Product Platform Modeling

Contributions to the discipline of visual product platform modelling

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PhD thesis 13.2010

DTU Management Engineering

Rasmus Pedersen
September 2010

DTU Management Engineering
Department of Management Engineering

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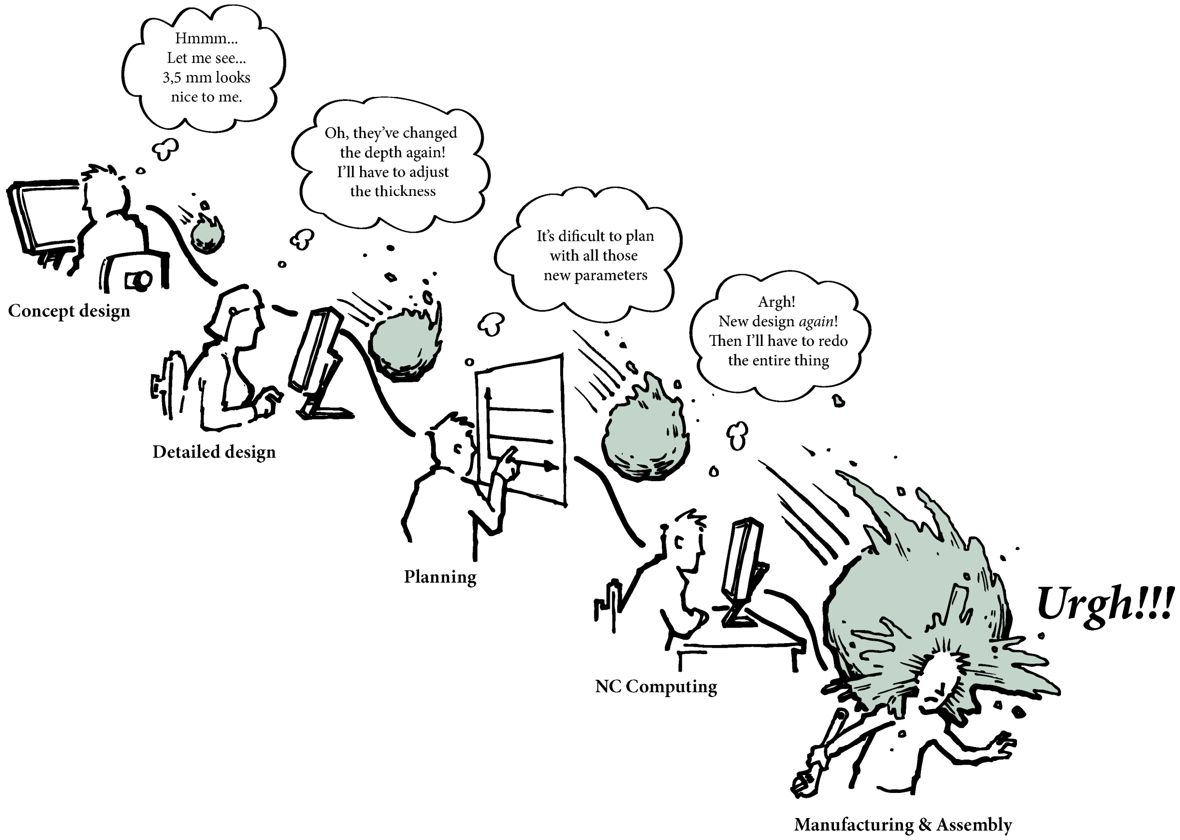

PhD Thesis

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Technical University of Denmark

DTU Management

September 2010

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Abstract

This PhD thesis has the title *Product Platform Modelling*. The thesis is about *product platforms* and *visual product platform modelling.*

Product platforms have gained increasing attention in industry and academia in the past decade. The reasons are many, yet the increasing globalisation and the change in the global economy seem to be major factors. Manufacturing companies have experienced an intensifying competition and many companies face increasing demands for reductions in costs and lead times in development and production. At the same time many customers have raised their demands for customisation of products. In many companies these changes in the business environment have created a controversy between the need for a wide variety of products offered to the marketplace and a desire to reduce variation within the company in order to increase efficiency.

Many companies use the concept of product platforms to overcome this challenge of balancing the external and internal performance demands. Product platforms are found in many different instantiations in various industries and companies, and the concepts and challenges are likewise diverse.

This PhD thesis documents a research project with two main purposes; First, various phenomena related to product platforms are investigated and secondly it is investigated how some of these phenomena can be visually modelled in order to support decision making in industrial platform projects.

The investigation of platform phenomena is based on the notion that *reuse* and *encapsulation of platform elements* are fundamental characteristics of a product platform. *Reuse* covers the desire to reuse and share certain assets across a family of products and/or across generations of products. Product design solutions and principles are often regarded as important assets in a product platform, yet activities, working patterns, processes and knowledge can also be reused in a platform approach. *Encapsulation* is seen as a process in which the different elements of a platform are *grouped* into well defined and self-contained units which are *decoupled* from each other. These groups can be varied and combined to form different product variants without increasing the internal variety in the company. Based on the Theory of Domains, the concept of *encapsulation in the organ domain* is introduced, and organs are formulated as platform elements. Included in this introduction is a discussion of the dispositional effects of organ and wirk element encapsulation. Unlike most present perceptions of platforms and modularity, the concept of organ encapsulation makes it possible to describe the system characteristics of a product platform in which reuse and encapsulation effects are obtained *without* necessarily introducing standardised physical interfaces between the varying elements.

By means of three industrial cases, in the companies Danfoss, Grundfos and Aker Solutions, it is discussed and exemplified how some of the phenomena and effects related to reuse and encapsulation can be visually modelled during product platform projects. A fundamental hypothesis in this project is that decision makers and important stakeholders have to be able to *see* the platform in order to *manage* it. Consequently, the thesis also investigates how visual models of important phenomena can support decision makers during a product platform project. The reaction from stakeholders in the case companies indicates that the decision base is improved by means of visual models. Another finding is that the sometimes rather theoretical and intangible phenomena can be instantiated in models and thereby made tangible and visual for decision makers and designers in the organisation.

Dansk resumé

Denne afhandling har titlen *Modellering af Produktplatforme* og berører emnerne *produktplatforme* og *visuel modellering af produktplatforme*.

Produktplatforme er i stigende grad genstand for interesse i industrien. Der er mange grunde hertil, men den øgede globalisering og den tilhørende ændring i den globale økonomi er en ganske betydelig drivkkraft. Industrielle fremstillingsvirksomheder oplever en tiltagende aggressiv konkurrence, hvori kravene til reducerede omkostninger og gennemløbstider i udvikling og produktion bliver skærpede. Samtidig kræver mange kunder i stigende grad individualiserede produkter. Mange virksomheder står derfor i et spændingsfelt mellem ønsket om at udbyde mange forskellige produktvarianter til markedet samtidig med behovet for at reducere den interne kompleksitet i organisationen, hvilket mange gange er en forudsætning for at reducere netop omkostninger og gennemløbstider.

En strategi baseret på produktplatforme er for mange virksomheder et middel til at imødegå udfordringen i at balancere kravene til ekstern produktvarians med ønsket om at reducere intern kompleksitet. Produktplatforme findes i mange forskellige former, afhængig af virksomhed, industri, produkttype og formål, og udfordringerne forbundet hermed er ligeledes ganske mangeartede.

Denne ph.d.-afhandling dokumenterer et forskningsprojekt med to overordnede formål: For det første undersøges og skildres forskellige fænomener, der relaterer sig til produktplatforme. For det andet beskrives det, hvorledes nogle af disse fænomener kan modelleres visuelt, således at grundlaget for beslutningstagning i industrielle platformsprojekter kan styrkes.

Undersøgelsen af forskellige fænomener baserer sig på den tanke, at *genbrug* og *indkapsling* er fundamentale karakteristika for en produktplatform. *Genbrug* dækker over ønsket om at genbruge og dele forskellige aktiver mellem produkter i en produktfamilie og/eller på tværs af produktgenerationer. Produktkoncepter, konstruktioner og konstruktionsprincipper, opfattes ofte som oplagte kandidater til genbrug i en produktplatform, men aktiviteter, arbejdsprocedurer, forskellige former for viden kan også være en del af en produktplatform. Indkapsling er et generelt systembegreb og dækker over en process hvorunder de elementer, der skal forme platformen, *grupperes* i veldefinerede og selvstændige enheder, der er *dekoblet* fra hinanden. Disse grupper af elementer kan varieres og kombineres og bruges til at skabe forskellige produktvarianter uden at den interne variation i virksomheden behøver at stige. Med udgangspunkt i Domæneteorien introduceres idéen om *indkapsling i organ domænet*, og organer opfattes herved som elementer i en produktplatform. En del af denne introduktion omfatter en diskussion af de dispositionelle effekter af indkapsling af organer og wirk elementer. I modsætning til de fleste eksisterende opfattelser af produktplatforme og modularisering, kan man med wirk element indkapsling forklare, hvorfor nogle produktplatforme tilsyneladende har success med indkapslings- og genbrugseffekter uden nødvendigvis at introducere fysiske grænseflader i platformen.

Med tre industrielle eksempler fra virksomhederne Danfoss, Grundfos og Aker Solutions, diskuteres og eksemplificeres, hvorledes nogle af de ovenstående fænomener, der relaterer sig til genbrug og indkapsling, kan modelleres visuelt i løbet af et produktplatformsprojekt. Der arbejdes ud fra den fundamentale hypotese, at beslutningstagere og vigtige parter i virksomheder må kunne se platformen for at kunne bestyre den. Derfor berører afhandlingen også, hvorledes visuel modellering af nogle af disse væsentlige fænomener, kan styrke denne beslutningstagning. Reaktionerne fra de involverede virksomheder indikerer, at visuelle modeller styrker evnen til at træffe beslutninger om produktplatforme. Et andet resultat fra studierne viser, at de til tider ganske teoretiske og uhåndgribelige fænomener, der følger i kølvandet på et platformsprojekt, kan gøres synlige og håndgribelige ved brug af visuelle modeller.

Preface

This PhD study has involved a number of people, whom I would like to thank.

First of all I would like to thank my colleagues at the Technical University of Denmark, and in particular Morten Kvist, Ole Fiil Nielsen and Lone Munk, with whom I have shared the years of PhD studies. I would also like to thank my supervisor, Professor Niels Henrik Mortensen, for positive, inspiring, and competent guidance during the years of study. I have been guided with a well balanced mix of research experience and focus on industrial applicability, and Niels Henrik has encouraged me to stay tuned on the project in good as well as bad times. Also thanks to my co-supervisor, Tim McAloone, for an always competent and readily available support. Professor Mogens Myrup Andreasen also deserves special thanks for sneaking into our office every now and then, and constantly observing and influencing our progress.

Another profound appreciation goes to Danfoss A/S who played a major role in this project. In particular I appreciate the support from Director of Operations Hans Eskildsen, Senior Vice President Søren Eskildsen, Vice President Hans-Erik Kiil, Technology Platform Manager Asbjørn Leth Vonsild and R&D Manager John Porland. They decided to host the project and to fund it with a significant contribution. By personally engaging in the project, they have provided the best possible industrial environment for a PhD student to hope for.

I would also like to thank my project colleagues at Danfoss, with whom I have worked for four years, and special thanks goes to design engineer Michael Birkelund, who has helped me from the first day in Danfoss. I would also like to acknowledge the support from the project manager, Arì Leifsson, who took good care of the daily management of my role in the company during several years.

At Grundfos I would like to thank Peter Høgh and Carsten Kammersgaard for support and cooperation during the project.

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My final appreciation goes to Anne – without knowing it, she made the greatest contribution to this work.

Copenhagen, August 2009

Rasmus Pedersen

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1

Research introduction

The concept of a platform model, the understanding of the underlying phenomena of platforms, and the visual modelling of the phenomena are the core topics within this research. This part of the thesis introduces the background of the research and the reasons to grant the subject of product platforms attention. Some major challenges in achieving a successful product platform utilisation are discussed. The complex challenge of decision making during a product platform project is also discussed and tied to the concept of a platform model as a means to achieve better decision making.

1.1 Introduction

This PhD thesis describes a research project within the topic of product platforms. The background and purpose of the work is shortly described on the following few pages, and thereafter a more thorough elaboration on the research background and the layout of the research project is provided.

A product platform is an instrument a company can choose to use in order to gain certain benefits. In most cases a product platform involves some kind of physical and tangible products. In such situations companies have developed a product concept enabling different parts of the products to be reused in various product variants for a variety of different reasons. A key challenge is to be able to reuse without limiting the available choices of the customers, and in some cases a platform concept may even enlarge the possibilities for customers to choose from, despite the reuse within the company. Typical main drivers for trying to reuse, is to gain a more efficient utilisation of resources such as material, equipment, and manpower, and also to speed up the internal processes and thereby get faster response to market needs. However, there are many more potential benefits, and they will be discussed in various contexts throughout the thesis.

Platforms is a diverse topic

There are many different kinds of platforms and therefore the term *product platform* - or simply *platform* - sometimes refers to other concepts than the one described above, i.e. it does not necessarily have to do with reuse of physical product parts. Apart from *product* platforms [Meyer & Lehnerd], there are *process* platforms [Sanchez & Collins], *service* platforms, [Sanchez & Collins, 1999], *knowledge* platforms

[Sanchez, 2000], platforms with *activities* [Miller, 2001], to name but a few. These different concepts all have in common the fact that *reuse and sharing* of parts, components, processes, activities, knowledge or other assets is essential, and in many cases the product is an essential part of the platform. In the rest of the thesis the terms *platform* and *product platform* is used to denote this concept of *sharing assets*, even if it includes intangible elements that are not a direct part of the physical products.

Decision making for product families

A common consequence of the reuse is the fact that several products are often developed in series or *families*. This makes product platform development very different from traditional single product development in many dimensions. A prime example of this difference is the risk associated with decision making, because decisions regarding the platform will propagate to many different product variants and because many of the decisions have to do with a trade-off between reuse and customer satisfaction. Platforms also serve as a *preparation* of design, in the sense that the platform in many cases is a design template from which *derivative* products can be designed. That complicates the decision making process even further, both in the *preparation* phase, where the platform is designed, and in the *execution* phase, where the derivative products are designed.

Research aim

The purpose of the PhD study is ultimately to improve the ability to navigate through the opportunities and strengths related to the complex decision making during a product platform project, by bringing about a contribution to the knowledge on the topic of product platforms. During the work different perceptions of platforms are discussed and the related *phenomena* addressed. The fundamental idea is that an improved understanding of the various phenomena, will lead to better decision making. Moreover, it is discussed how the sometimes intangible elements and phenomena within a platform can be *visually modeled* in an industrial project, and three industrial cases are used to exemplify and test the findings.

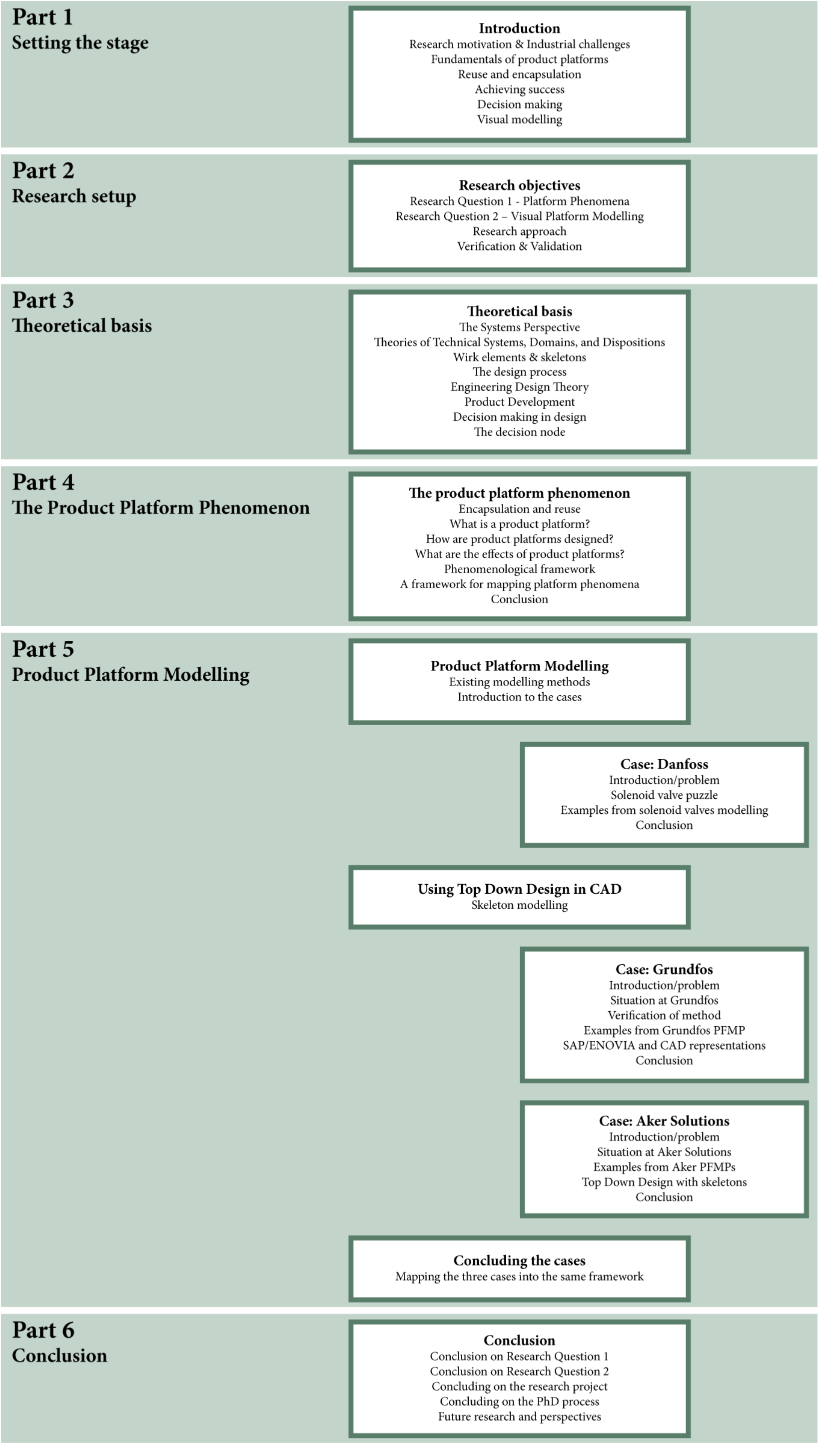
Potential audience of the thesis

The thesis is intended to be of interest for the academic as well as the industrial audience. After having read the thesis, the reader will hopefully have gained new insight into the topic of product platforms, and in the case of industrial practitioners, better be able to pursue a platform approach in a practical context. Apart from an academic study of product platform phenomena, the thesis includes examples from three industrial projects. The examples report how various phenomena have been modelled and visualised and thereby served as an integral part of decision making in industrial platform projects.

The structure of the thesis

This research project is based on an engineering design science tradition. This means that the research will seek to analyse a current state of knowledge in academia as well as in industry, seek to identify needs for improvement, suggest the improvements from a theoretical and practical perspective and finally discuss the validity of the findings. These steps form the basic structure of the thesis.

First, in Part 1, the research background, i.e. the challenges faced by industry and the current state of knowledge are discussed. Then the research project is laid out in Part 2 with a more elaborated discussion of the research aims and the approach and the research requirements. Thereafter, in Part 3, the fundamental theoretical viewpoints are listed, in the chapter that forms the theoretical basis. From that basis it is possible to review the current state of knowledge in the field of product platforms and discuss the phenomena in Part 4. Thereafter the challenge of modelling the phenomena and the three industrial cases are discussed in Part 5. Finally, a general conclusion on the project and suggestions for further research is provided in Part 6.



1.2 Fundamentals of product platforms

A result of the globalisation of the marketplace has been an intensifying competition amongst manufacturing companies. Over the past decade many a company has experienced an increasing demand for reductions in cost and lead times in development and production. At the same time the general growth in the economies worldwide has changed the habits of customers. There has been an increasing focus on personalisation and customisation.

In many companies these changes in the business environment have created a controversy between the need for a great variety of products offered to the marketplace and a desire to reduce the variation within the company in order to increase the performance of the company. In many company structures, variation leads to increased costs, lead times, mistakes and errors and other factors that decrease the performance of the company. Consequently, product variation and business performance tend to oppose each other, as depicted in figure 1.1;

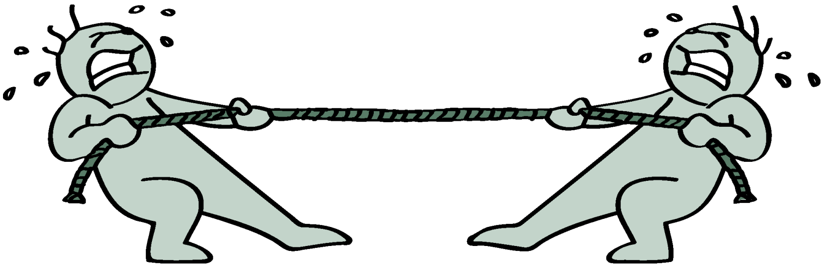


Figure 1.1: There is often a controversy between the demand for great product variety in the market and the desire to reduce product complexity and process variation within the company.

There is a common agreement in industry and academia that one way to help overcome the challenge is the use of product platforms as means to orchestrate product families and portfolio management. The concepts can help achieve the best of both worlds with the possibility to combine standardisation benefits from an internal company perspective with a diverse product portfolio from an external customer perspective [Meyer & Lehnerd, 1997], [Ulrich & Eppinger, 2000], [Claesson, 2006]. Two key aspects are *commonality* and *variety*, i.e. to achieve product variety from a customer viewpoint, and commonality from a product life phase viewpoint [Andreasen et al., 2001], see figure 1.2;

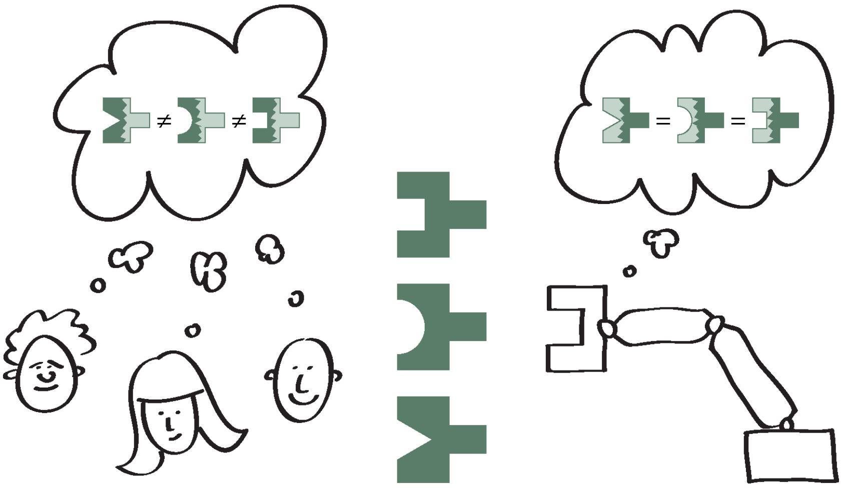


Figure 1.2: It is a challenge to obtain variety from a marketplace perspective and commonality from a company process perspective throughout the life phases.

The difference in *perspective* is important in the concept of commonality and variety. Commonality and variety are relative properties, and they happen in a relation between the products and something else. The same component may look different from a customer perspective yet seem similar in a manufacturing or distribution system. Thus, if the products are designed in a smart way, it is possible to achieve both commonality and variety in the same designs.

Joseph Pine [Pine, 1993] has introduced the term *economies of scope* as the next generation of the traditional perception of *economies of scale* (fig. 1.3). It phrases very well the potential benefits of platforms. In a product platform approach it is not about scale as it has been in traditional mass producing companies. Rather, it has to do with a partitioning of the product portfolio and business in a smart way while thereby gaining reuse effects which in turn increase the performance of the business without scale as the single key element. The keyword is instead scope, hence the term economies of scope.

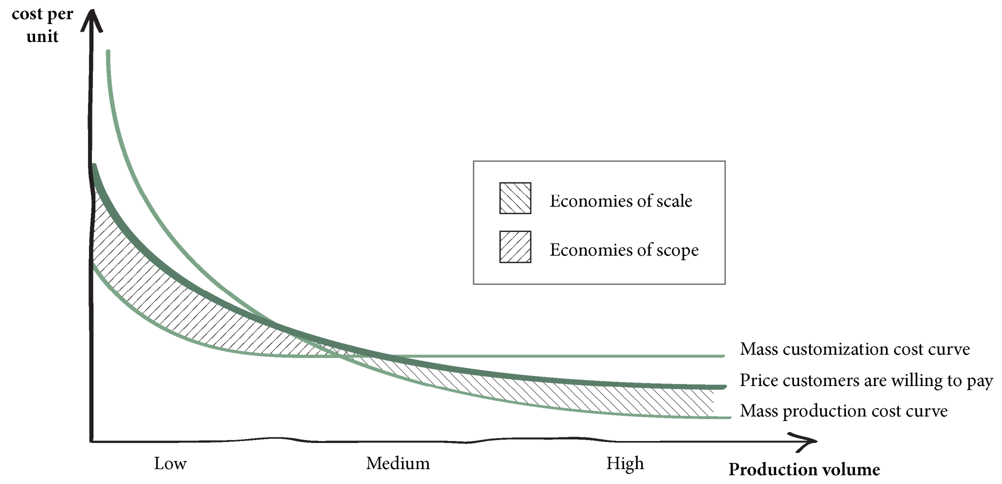


Figure 1.3: The figure illustrates how mass production has an advantage in high volumes where the actual volume can defray the often large investments in equipment. Because satisfying individual needs can be translated into higher customer value (and sales price) it is possible for companies with low-medium production volumes to get an advantage utilising increased flexibility built into modern manufacturing systems, [Jiao & Tseng, 1999].

Economies of scale and economies of scope can be very effective if they are combined. This can be illustrated by an example from the Danish door lock and key manufacturer, Ruko. When manufacturing their keys they make use of mainly two processes; a highly non-flexible stamping process from which they produce hundreds of thousands of identical base key elements and then a flexible milling process, which is used to make the keys distinctive individuals. Making the entire final product using either one of the processes would not be economically feasible. The important issue is to *decouple* the common features from the varying features. This example is further elaborated in Part 4, chapter 4.5.3.

1.2.1 Reuse and sharing

Commonality and scope is essentially about reuse and sharing. In figure 1.2, the interface to the production system is reused in the three products. Thus, it is an example of both reuse and commonality.

Many different assets can be reused depending on different aspects such as the company, strategy, scope, purpose or other relevant factors. Literature reports many different types of reuse from the very physical and tangible subassemblies or modules [Ericcson & Erixon, 1999], [Meyer & Lehnerd, 1997], production equipment and process plants [Miller, 2000], [Hvam, 2006], sometimes including design templates [Ulrich & Eppinger, 2000], ranging to more abstract levels of reuse such as functional blueprints for designs [Harlou, 2006] or potentially more intangible elements like different kinds of knowledge and processes [Sanchez, 2000].

Reuse is closely tied to the fact that product platforms are often a basis of more than a single product variant. Thus, the product platform is a basis of a family of products. The platform based approach is sometimes even referred to as “multi product development” [Roveda & Moffatto, 2000], [Andreasen et al., 2001]. The term denotes that several (and sometimes many) product variants are laid out during the development of a platform. The design decisions will propagate to several products and have an impact on a larger proportion of the future business and turnover. This is one of the reasons why platform development is regarded as a rather complex discipline.

Reuse is a common thing in the different available platform cases and references. Reuse is a key driver for utilizing resources as efficient as possible. Reuse gives repetitiveness that in turn creates a series of beneficial effects for the company.

1.2.2 Modularisation and encapsulation

A fundamental prerequisite for practicing reuse and sharing is to distinguish between assets which create the needed product diversity towards the market and the assets which should be reused in the product variants.

Encapsulation rather than modularisation

One of the aims of this research is to be able to describe some of the fundamental phenomena related to product platforms. In many references the split between variable and generic/reusable elements is seen as a fundamental characteristic of a product platform and closely tied to the concept of *modularisation*. However, there are two limitations to the concept of modularisation;

1. *Modularisation implies a physical split*

   Often, modularisation implies some sort of *physical split* between subassemblies [Ulrich, 1995], and modularisation is mostly a concept related to the *parts* of products, and not for example to the activities or knowledge elements in a product platform (although some authors talk about activity and knowledge platforms [Miller, 2001], [Sanchez, 2002]). The most widely acknowledged perception of modularisation is that it is about splitting the products into self-contained and interchangeable units from which the product range can be built and from which a set of effects can be attained. The physical interfaces between the units become highly important and can be used to alter the beneficial effects of the platform.

2. *A lack of consensus*

   There are many different perceptions of modularisation and of *modules*, and in that sense it is a rather ‘contaminated’ concept, without a generic consensus in literature.

Due to the above two reasons, it is decided not to use the term modularisation to describe the fundamental system characteristics of a product platform in this thesis. Instead, the more fundamental concept of *encapsulation* is used. Encapsulation is a systems engineering term, denoting the process of breaking down a system into smaller pieces and making these pieces relatively independent [Hitchins, 2003], however not implying how this independency shall take place, and thereby not implying a physical split. Moreover, the *system* can be perceived in a broader context, and does not necessarily have to do with a physical product or the parts in the product. From many perspectives, the traditional perception of modularisation is a certain kind of encapsulation.

The following quote describes the fundamental activity of encapsulation. Even though it is actually taken from a modularisation context, it is described in such a general and fundamental way that it will apply to systems, which do not necessarily have a physical split between elements, and does not even have to be physical products [Baldwin & Clark, 2000, p. 64];

“A complex system can be managed by dividing it up into smaller pieces and looking at each one separately. When the complexity of one of the elements crosses a certain threshold, that complexity can be isolated by defining a separate abstraction *that has a simple* interface*. The abstraction* hides *the complexity of the elements; the* interface *indicates how the element interacts with the larger system”.*

In this thesis, two aspects are emphasised as the generic characteristics of encapsulation. These are *grouping* and *decoupling*, and this point of view is further elaborated in Part 4, chapter 4.3. Encapsulation in this thesis will therefore be used to denote the process of *grouping* and *decoupling* of system elements, as explained here;

- *Grouping elements*

  Finding out which elements fits each other from a certain perspective, be it functional wise, fabrication wise, assembly wise etc., and then group these elements together.
- *Decoupling elements*

  Finding out how to decouple the grouped elements, be it using a certain assembly process, distribution set up etc. Decoupling makes sure that one group of elements can be manipulated without having the changes propagate to the rest of the system.

Grouping and decoupling are fundamental ways to achieve both commonality and variety, and grouping and decoupling is an approach that fits products as well as other assets in a platform.

1.2.3 Reuse and encapsulation are fundamental

Following the line of the above discussion, *reuse* and *encapsulation* are regarded as two fundamental characteristics of platforms in this thesis. However, reuse and encapsulation takes place in most companies even without a platform approach. What makes product platforms unique is the *deliberate* and *carefully planned* reuse and encapsulation, which enable a company to harvest effects across a family of products. The degree of reuse and the degree of encapsulation is different in a product platform approach compared to a traditional single product development approach.

1.2.4 The meeting

The carefully planned reuse and encapsulation takes place in order to gain certain *effects*. There is an *intention* behind the reuse and encapsulation. These intentions and effects are many and diverse [Ericsson & Erixon, 1999], [Miller, 2001], [Offermans, 2002]. An important thing to bear in mind is the fact that effects are relational – they occur in a relation between the platform and something else. This is often neglected in the present research on modularisation, because a modular design is seen as a goal and not a means to achieve a goal. A modular design is not in itself beneficial if the processes in the life phase systems do not benefit from the modular design. Returning once more to the simple example in figure 1.2, it is clear that the effects of reuse only arise in a *meeting* between the robot and the product. Without either of the two there is no reuse effect. The robot is a life phase system. The concept of *meetings* and the perception of effects and performance as a relative property are described in the Theory of Dispositions [Olesen, 1992]. According to the Theory of Dispositions, the fit between the product design and the product life phase systems determines the performance of the product in the different life phases.

Dispositions are decisions made in one life phase (in relation to this research in particular decisions made in the design phases) that influence, i.e. dispose, the type, efficiency and effectiveness of operations in other life phases. The benefits of a product design occur only in the different situations in which the product meets its life phases and life phase systems. Other examples of life phase systems are the product development system, the production system, the distribution systems, etc. The meeting between the product design and the life phase systems should be designed carefully to fit each other.

Figure 1.4 depicts the notion of effects in meetings. Reused and shared things are introduced in the product family in order to gain certain effects in one or more life phases.

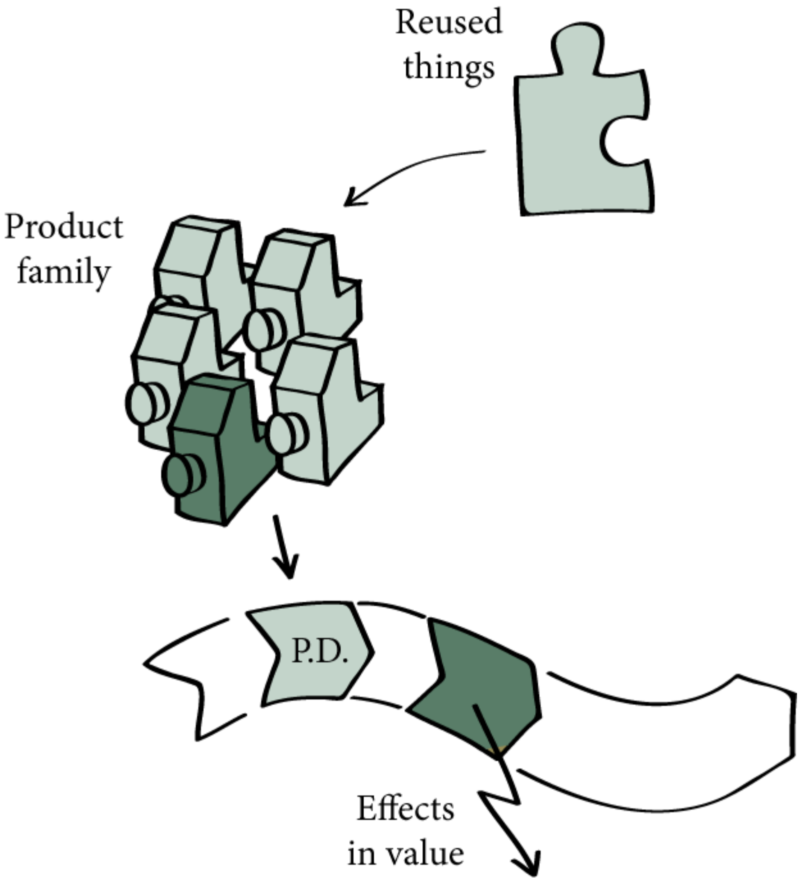


Figure 1.4: Reused 'things' are introduced during the Product Development, P.D., with an intention to create an effect in one or more of the product life phases.

Alignment

The term *alignment* [Andreasen et al., 2001] is sometimes used to denote the deliberate fit between the structural product characteristics and the different life phase systems. Alignment is about designing meetings by ensuring a *fit* between different levels of product descriptions and different levels of life phase systems, in particular the product leverage systems, such as the assembly system as depicted in figure 1.5;

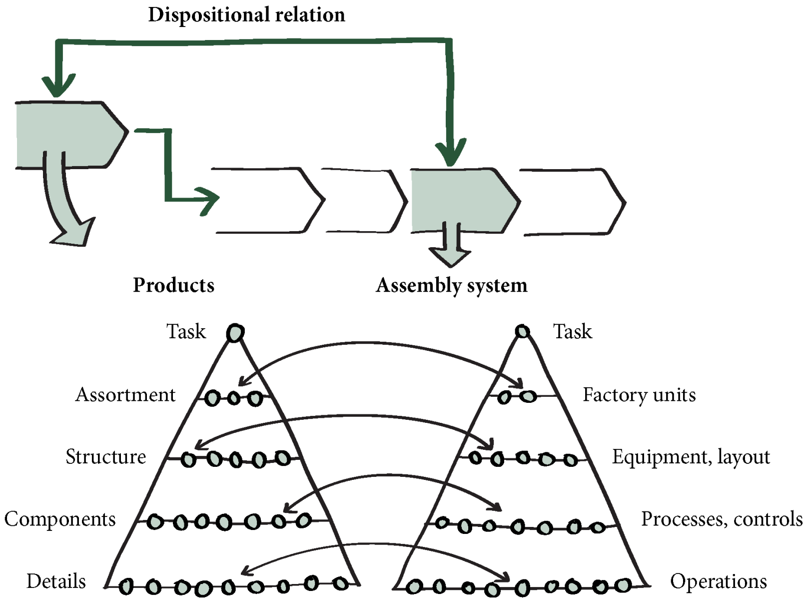


Figure 1.5: Alignment is a about creating a fit between the structure of the product family and the layout of different life phase systems, in this case the assembly system.

The fit between the structural product characteristics and the life phase systems determines the overall performance of the platform.

1.3 Achieving product platform success

Accepting the potential benefits of a product platform approach is one thing. Achieving the benefits of a successful product platform approach is clearly much more difficult. There is a very diverse set of experiences in industry. Some are rather famous, like the VW's expansion [Avishai, 1991], the Sony Walkman, [Sanderson & Uzumeri, 1995], the strategy of Hewlett-Packard [Feitzinger & Lee, 1997], among others. However, not all platform approaches are successful and there are great challenges on the road to success, [Harlou, 2006], [Meyer & Lehnerd, 1997], [Claesson, 2006], [Miller, 2001], [Andreasen et al., 2001], [Sanchez, 2004].

1.3.1 Platform challenges

The transition towards a product platform setup is difficult. Some companies struggle from the very beginning with the rather complex transition process when they change from a single product development focus to a multi-product focus. Others fail to fully implement a product platform at a later stage due to problems in the change process.

Of all the different challenges involved in a platform approach, a few main ones are emphasised in the following. They are the most evident changes a company may strive for in order to fully obtain the benefits of a product platform, while also some of the greatest challenges to overcome during the change process.

Following the argumentation that reuse and encapsulation are fundamental to product platforms, the main challenges can be categorised in three groups [Miller, 2001], [Sanchez, 2000];

- deliberate and carefully planned reuse and encapsulation of *product* elements
- deliberate and carefully planned reuse and encapsulation of *activity* elements
- deliberate and carefully planned reuse and encapsulation of *knowledge* elements

The first bullet point has to do with enabling product variety by the use of easily interchangeable elements. The key is to decouple the varying and generic elements in a product.

The second bullet point has to do with obtaining decoupling effects in the process of deriving product variety, e.g. in the design or production activities.

The third bullet has to do with standardising the knowledge in the company and making it available for various stakeholders, in order to avoid 'chimneys' in the organisation and a loss of knowledge exchange between stakeholders and decision makers.

The justification of seeing these three as the main challenges is further elaborated in Part 4.

In the following *product* and *activity* elements are discussed. In the succeeding chapter, *knowledge* about these two categories is discussed.

Encapsulation of the product elements

One of the most obvious changes when introducing a product platform is to encapsulate different parts of the product portfolio into elements that are shared and reused, and elements that are variable (fig. 1.6), i.e. distinguishing between:

- *Generic* elements
- *Variable* elements

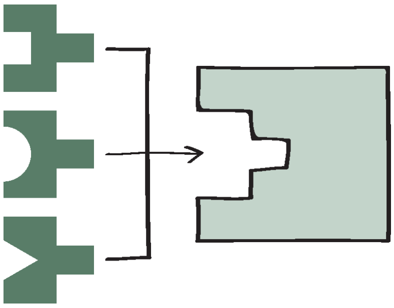


Figure 1.6: Splitting the generic and variable proportions of a product portfolio. The figure depicts two kinds of encapsulation. There is a clear physical decoupling between the green elements and the grey element. However, there is also a kind of decoupling between the left and the right part of the green elements, because the left part is allowed to vary while the right part is reused.

It is noteworthy that figure 1.6 depicts two kinds of encapsulation. There is a clear physical decoupling between the smaller green elements and the large grey element. However, there is also a kind of decoupling between the left and the right part of the green elements, because the left part is allowed to vary while the right part is reused. The right part of the green elements is encapsulated, yet without the use of a physical interface. Thus, there is an encapsulation type, which does not imply a physical split within the product. (This concept is further elaborated in Part 4, chapter 4.5.3).

Sharing and reuse may occur mainly in the generic elements of the product range while product customisation takes place by varying the variable elements of the product range. Consequently, standardisation and careful management of interfaces between different parts become important.

The core idea of defining generic and variable elements of the product portfolio has two dimensions [Martin, 1999], [Martin & Ishii, 2002]; meaning that elements can be:

- *Spatial* generic/variable
- *Generational* generic/variable

The term spatial refers to elements that are constant (generic) or change (variable) *within* a single product generation, i.e. at a certain point in time. The latter refers to elements that are constant or change over time, i.e. *across* product generations.

The terms spatial and generational refer to sharing and reuse, respectively, because reuse imply a change over time, while sharing does not. However, throughout this thesis, the term *reuse* is used as a synonym for sharing.

The challenges in the spatial and generational cases are somewhat different and the emphasis may lie on different issues. The product planning efforts and the exchange of knowledge, design ideas, concepts, subassemblies, parts, and features etc. may have different implications when used *within* and *across* generations respectively. This has a profound impact on the way product development projects are planned, prepared and carried out.

The transition process towards a product platform approach will also affect the way the company has to plan the life of different product variants, product introductions, and product upgrades etc., and thereby affect the long term product development process.

Encapsulation of product elements alone will – if done properly – enable possible cost reduction, better quality, etc. If the objective is to e.g. reduce lead time more drastically, then the *activities* in some of the life phases must undergo similar considerations.

Encapsulation of activity elements

When it comes to encapsulation and decoupling of the activity elements in different life phases, especially two motives should be considered [Meyer & Utterback, 1993], [Sanderson & Uzumeri, 1999], [Mortensen et al, 2008b];

- Separate *preparation* design phase from the *execution* design phases (fig. 1.7)
- Enable *parallel* activities in the different life phases

Both bullet points have to do with lead time reduction.

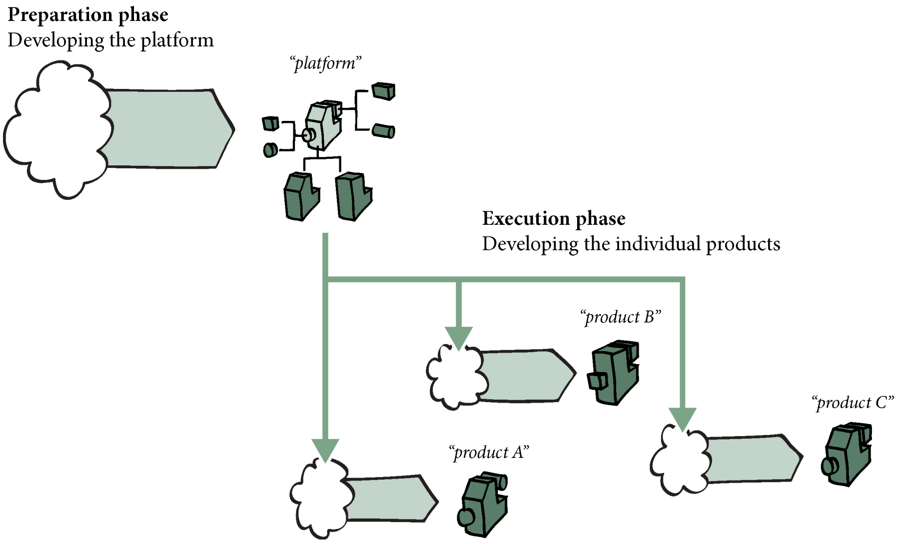


Figure 1.7: With a product platform it is possible to partition the development efforts in a preparation and execution phase. (Figure adopted from Mortensen et al, [2008b]).

In fig. 1.7 it is illustrated how the product development activities are split into a preparation phase plus a number of execution phases. The development that is done in the preparation phase is reused in the three different product variant projects. This split requires a long term forecast for the whole product family and expected future sales in order to plan what activities can (and should) be part of the preparation phase.

Enabling parallel activities in different life phases requires carefully specified interfaces which serve as a framework and ensure that results of the parallel activities go hand in hand. Besides lead time reduction, one major reason for decoupling activities into parallel courses is outsourcing – whatever the rationale behind the outsourcing might be (low cost labour, critical supply, focus on core competencies, etc.).

Not only the development activities, but also other types of activities are subject to reuse and encapsulation [Miller, 2001]. There are clear links between a platform approach and the possible changes in the production, [Salvador et al., 2002], [Ulrich, 2007].

One aspect that may have great impact on the platform design is the *customer order decoupling point* (CODP) [Madsen, 2001] or simply *order entry point*, i.e. at what point does the customer order enter the product leverage process (fig. 1.8). Furthermore, what should the customer at this point be able to specify, i.e. what options do the customers have?

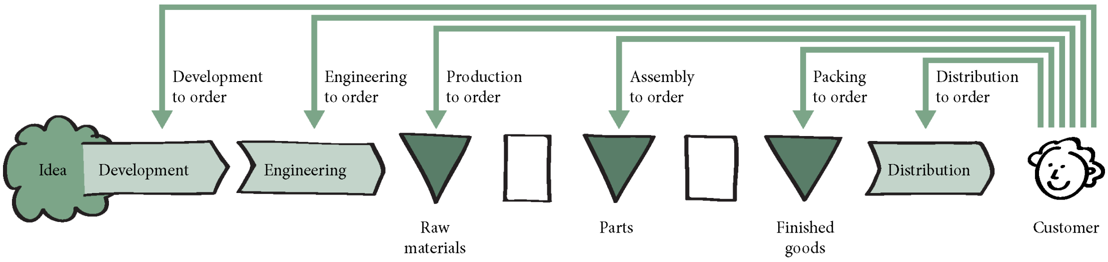


Figure 1.8: The placement of the customer order decoupling point and the available options will have great influence on the product platform design. (Figure adopted and redrawn from Madsen [2001] and Michelsen & Pagh [2002]).

To complicate the matter further it is - in fig. 1.8 – logic to consider different tracks for standard options and special options, where the latter will have an order entry point earlier in the process, thus requiring more work than standard options. Deciding what and when something is standard and special options, respectively, is not only a matter of strategic considerations but also influenced greatly by the technical solutions that are chosen, and vice versa.

Thus, the activities are grouped and decoupled in various ways and thereby subject to *encapsulation*.

Activity versus product decoupling

A decoupling of life phase activity elements, as it is described above, often has an impact on the design of the products. In some cases it can for example be necessary to introduce an interface, which from a use function viewpoint can't be justified but is required in order to decouple certain life phase activities. The opposite is also the case if a certain decoupling is the result of a market demand, and thereby has consequences in a life phase.

Thus, *encapsulation* of product and activity elements happens on an iterative basis and most platforms have combinations of both types.

1.3.2 Decision making in platform development

A great challenge in the transition towards a platform based approach is the complex pattern of decisions, which have to be made before, during and after the project. Managing a product platform is a fairly complex ordeal, and from many perspectives much more complex than the single product case, [Meyer & Lehnerd, 1997], [Sanchez & Mahoney, 1997], [Sanchez, 2000].

The various challenges related to reuse and encapsulation are difficult to manage, mainly because of the amount of information combined with the complexity of various trade-offs which complicate the basic decision-making process. The complex dispositional relations between design decisions and the effects achieved in various life phases are some of the important factors adding to the complexity of decision making. Because the platform is a basis for a whole family of products, the decisions become more complex and diversified than the case of traditional single product development. Many platform initiatives also bring about changes in the organisation, the manufacturing system, the distribution systems, in working procedures, and in the habits of employees. A platform approach is sometimes a major change process. Therefore, finding the optimum design of the product family is not always the hardest job in a platform project.

1.3.3 Know-how, Know-why, Know-what

A key player in any decision making process is knowledge, i.e. knowing what to decide upon. That is, knowledge on the key phenomena, desirable effects and knowledge on the controllable and uncontrollable factors. Basically, management and the designers have to know the desired product platform effects and possible ways to achieve these. Consequently, a good decision base must consist of an understanding of the problem in the minds of those involved in the design and use of the platform. These key persons are decision makers and have to have sufficient knowledge to be able to make the right decisions.

The necessary knowledge will often be characterised by vast amounts of information and data bound by relatively complex relations. And in the case of product platforms there are at least three main classes of knowledge;

- Knowledge on the technical aspects such as the design and manufacturing systems
- Knowledge on the building principles, possible combinations and design limitations, i.e. what one could call configuration knowledge
- Knowledge on the activities with which a successful platform is designed

The technical product related type of knowledge does not necessarily lead to the configuration knowledge. The design limits can be set by means of strategic decisions and not necessarily from a strictly technical point of view.

Other important issues are the different design variables and the different effects that come from altering the variables. If a parameter is changed in one place, then effects somewhere else may occur. These dispositional relations are also important to know about and to maintain an overview of.

There are many types of knowledge reported in literature, and knowledge management is a field of its own. Ron Sanchez, [Sanchez, 1996, 1997, 2000] discusses the need for an elaboration of the term know-how in relation to modularity and product platforms as an organisational business approach. A good decision base must consists of *know-how*, yet instead of just accepting the literal meaning of the word know-how, Sanchez adds the managerial terms *know-why* and *know-what* to the discussion on management of “modular knowledge” which is essentially equivalent to the required knowledge on encapsulation effects. In this thesis, know-how, know-what, and know-why are accepted as three fundamental classes of knowledge, which is regarded as a natural part of a decision base in a product platform development project.

Consequently, decision makers have to;

- Know *why* the platform is pursued, i.e. behavioural aspects
- Know *how* the effects are obtained, i.e. procedural aspects.
- Know *what* the platform contents and interrelations are, i.e. constitutive aspects

Know-how, know-why and know-what are fundamental prerequisites for any decision making process, and will – in whatever form it is expressed – be crucial in achieving success with a product platform approach.

The question is then how to achieve and maintain the right knowledge, i.e. the right know-why, know-how and know-what among decision makers?

1.3.4 Sharing and distributing knowledge

One can think of many different ways to attain and maintain the right level of knowledge among decision makers. A surprisingly large amount of design knowledge rests in the minds of people, and is seldom documented in a formal way in the organisation. Sharing and distributing knowledge in an organisation is much easier if the knowledge is tangible and not tacit, [Ahmed, 2000]. Due to the element of preparation and reuse, a platform approach has a lot to do with communication, because some people may design the platform (in the preparation phases) while others may use the platform (in the execution phases). Thus, communicating the rules, procedures and constituents of the platform throughout the organisation is a key task. Therefore, it is – for the purpose of this thesis - assumed that knowledge about a product platform has to be instantiated somehow, in order for people and decision makers to share it, and thereby use it.

Assumption:

Knowledge about a product platform has to be tangibly instantiated, in order for people and decision makers to successfully share it and use it.

So how do designers grasp this knowledge and how would efficient and effective instantiations of the know-how, know-why and know-what look like?

Visual product modelling

Several authors report success with the use of some sort of visual modelling as a means to support designers and decision makers [Tjalve, 1976], [McKim, 1980], [Andreasen, 1998], [Henderson, 1998], [Dahl et al., 2001], [Harlou, 2006], [Hvam, 2006], [Mortensen et al., 2008a + 2008b], [Kvist, 2009]. They recognise the value of visual modelling and graphical representations of products with sketches, drawings, etc. as a powerful means to hold information and to pass on knowledge to designers and decision makers – during conceptual work and later. Harlou [2006] argue that visual models are important, in product development as well as in product platform development.

Product modelling however, has many different instantiations in industrial applications, and may take many different forms.

Visual is meant in the way that an overview is easily obtained from the model. A common denominator for the above references is the problem of presenting data and information in a visually presentable way without losing the depth of the information – the key here is to have details and overview at the same time.

Product platform modelling

If the idea of a visual product model is brought into the context of a product platform, one may elaborate the assumption about tangible knowledge. Accepting that a visual model is one useful way to make knowledge explicit and tangible for decision makers, the following assumption can be formulated;

Assumption:

The ability to model and visualise a product platform is an important driver for a successful platform utilisation. Decision makers have to be able to see the platform in order to successfully develop and manage the platform.

From this assumption, a series of different questions emerge. How does a company visualise the product platform before, during, and after the development of the platform? What key decisions does the model have to support during such a project? How does the model have to change throughout a project while moving from a rather abstract and sketchy level to a more concrete and detailed level? And what are the phenomena that the model has to depict?

The answers to these questions are not readily available in literature or in industrial practice, despite the numerous cases and reports on product platforms. In fact, most companies still base their product platform development projects on the paradigm of “single product development”, without a way to grasp the whole product family and treat it as a united object and not just a set of discrete products.

Existing modelling techniques

Traditional everyday modelling techniques and design tools from the single product development case, such as technical drawings, CAD models, Bills of materials etc, are not sufficient to describe the complex aspects of a product platform. The combination rules, the constraints, the design limits within the platform, the encapsulation, the rules of reuse, the different kinds of responsibilities and roles in a product platform decision making context, are all examples of aspects that have to be dealt with to some degree.

Literature and industrial cases provide very few reports on how to *visually* model a product platform in detail while maintaining a sufficient overview. Most available models are rather schematic representations of the product functions, product interfaces, or other abstractions. They do not represent the product in a visual way i.e. a way that allow for easy recognition of design variables and effects for a diverse set of decision makers with different backgrounds – and with a background outside that of the engineering department. The most common ways of expressing product platforms is on a sketchy level such as boxes, squares, arrows and matrices, [Harlou, 2006], [Miller, 2001], [Stone et al., 2000], and in some cases platforms are merely verbal expressions of a phenomenon [Gershenson et al., 2003]. There are few tools that enable a product manager to visualise the platform in an easy and presentable way in order to communicate the platform and to the engineers, sales personnel, and production managers and other important and diverse stakeholders and decision makers within the organisation.

A more in-depth resume and evaluation of existing literature on the topic of product platform modelling can be found in part 5.

1.3.5 Visual modelling of platform phenomena

The introduction has identified a potential research task, in the sense that there is room for improvement in the available tools for product platform modelling and the possibility for models to support decision making. Tseng and colleagues [Tseng et. al, 2003, p. 814] have coined the problem very well, and despite the age of the reference, it is still relevant, judging on the current state of literature;

"It has been common practice that different departments in a company have different understandings of product families from their individual perspectives. Such incoherence in semantics and subsequent deployment of information embodies a formidable hindrance "…" It is necessary to maintain different perspectives of product family representation in a single context".

In the quote the needs for a common understanding of product families and the needs for a common context are emphasised. The aim of this research is quite close to these two needs. Based on the discussion and the assumptions in the introduction, the aim of this research is to *clarify various phenomena* related to product platforms, and to investigate how such phenomena can be *visually modelled*, assuming that a visual representation will improve the decision base in industrial platform projects.

In Part 2 this aim is brought into a research context and further elaborated.

2

Research setup

In this part of the thesis, the motivation of the research is rephrased as research questions. The research approach and the setup of industrial cases and verification & validation efforts, is described. The scope of the research is discussed as an integral part of the discussion leading to the research questions.

2.1 Introduction

The following chapters elaborate on the introduction in Part 1 and describe how the challenges listed in the introduction can be brought into a research context. First the research objectives are discussed, and two research questions formulated. Then the research approach is discussed including a short discussion on the cases and the validation within the cases. This gives the following structure of Part 2;

Chapter 2.2: Research objectives

Including the two research questions and a discussion hereof.

Chapter 2.4: Research approach

A discussion of different approaches, all of which are part of the research design of this particular work.

Chapter 2.5: Research validation and verification

A discussion on how verification (i.e. internal logic) and validation (i.e. research impact) of the work is sought after during the project. The limitations of the validation and findings are also discussed.

Chapter 2.6: Research design

A discussion of how the above research approaches have contributed to the research design in this project.

Chapter 2.7: Concluding the research setup

A short conclusion on the setup of the research project and the research approach.

2.2 Research objectives

2.2.1 Phenomenon versus model

In the introduction in Part 1 it is stated that the aim of this research is to contribute to the current knowledge on platforms, by means of a clarification of some of the phenomena related to product platforms. It is also stated that it is important to be able to visually model these phenomena in order to manage the platform, and in order to perform successful decision making. From a research perspective, these two aims constitute two studies, which are closely related yet rather different. The first study is of a relatively theoretical and phenomenological nature, while the second study is of a more practical nature.

The phenomenological understanding of a product platform can be seen as a prerequisite for modelling the product platform. The model is an instantiation of the phenomena, and the model builds on a certain theory, modelling principle or understanding of the object of study.

Duffy & Andreasen [1995] discuss different modelling classes in relation to engineering design and the development of computer based design support tools. They divide models into three classes; *phenomenon* models, *information* models and *computer* models (fig. 2.1).

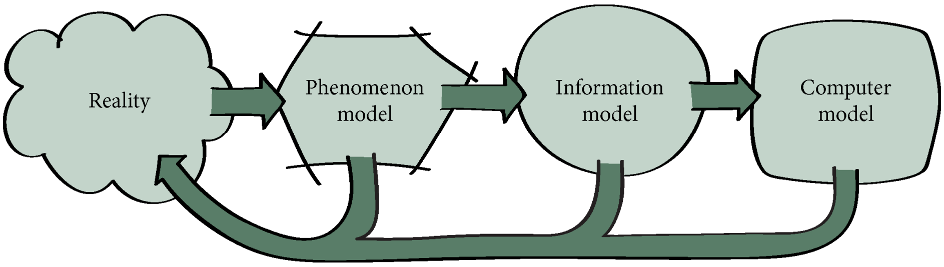


Figure 2.1: Models come in different classes with different modelling paradigms [Duffy & Andreasen, 1995]

These modelling classes provide a relation from different models to the underlying *reality*. Reality is in this case the product platform itself. It is the modelling object. The phenomenon model is a representation of the phenomenon based on a theory (fig. 2.2).

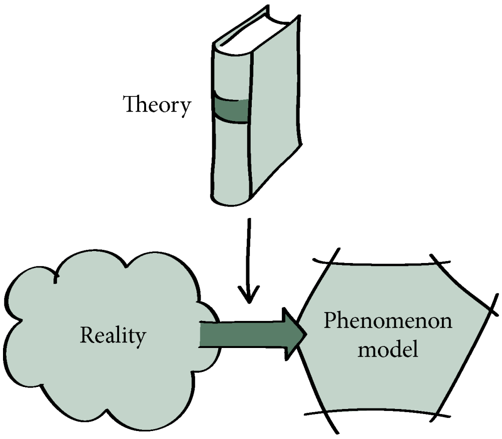


Figure 2.2: A model depends on the theory that is used to describe and understand the phenomenon.

When moving from left to right in figure 2.1, the theories behind the models may change and each model is related to distinct theories. It changes from an artefact and constitutive theory towards information and computer theories. Moving from right to left is the process of validating the models - based on the different theories - as the models are confronted with reality based on empirical observations as to whether the models represent the expected reality or not.

It is not the intention to provide a sharp distinction between the modelling classes in this work. Rather, the models presented later in the thesis have elements of both phenomenon, information and computer models.

2.2.2 A phenomenological study

The study of phenomena related to platforms will have to be based on theories and viewpoints (fig. 2.2). A certain theory will lead to a certain perception and representation of the platform. Thus, the nature of a product platform model is dependent on the theoretical framework.

One of the basic points of view in this research is the notion of reuse and encapsulation as fundamental characteristics of product platforms. The rationale of this point of view is given in the introduction in Part 1 and further elaborated in Part 4, chapter 4.3.

The study of product platform phenomena is based on the *Theory of Technical Systems* [Hubka & Eder, 1988] and in particular the *Theory of Domains* [Andreasen, 1980]. The Theory of Domains is used as the main theoretical basis because it provides rather handy ways to describe the phenomena of reuse and encapsulation.

Research question #1

In the introduction in Part 1, a point of view is presented which sets the stage for the study in this thesis. It is the viewpoint that an understanding of product platforms consist of *know-why*, *know-how*, and *know-what.* In other words, decision makers have to;

- Know *why* the platform is pursued, i.e. *behavioural effects*
- Know *how* the effects are obtained, i.e. *activities leading to the effects.*
- Know *what* the platform contents and interrelations are, i.e. *constitutive elements of a platform*

The behaviour is considered to be the effects which arise from the meeting between the platform and its life phase systems, according to the Theory of Dispositions [Olesen, 1992] (see Part 1 chapter 1.2.4, and Part 4, chapter 4.6 and 4.8). The activities are mainly design activities, i.e. the fundamental synthesis steps in a product platform project. Finally, the constitutive elements are the elements that make up a platform.

Given that *reuse* and *encapsulation* are accepted as fundamental characteristics of a platform, the first study seeks to answer the following research question;

> ***Research question 1***
>
> What phenomena are related to the encapsulation and reuse of *constitutive elements* in a product platform, the expectable *behavioural effects* arising from reuse and encapsulation, and the *activities* leading to reuse and encapsulation effects?

Focus shall be kept on the investigation of *constitutive elements* within a platform with emphasis on the nature of these elements, the reasoning behind various encapsulations, and the means by which reuse and encapsulation can take place in domains *other than* the part domain (following the terminology of the Theory of Domains). The study of behavioral effects is included in order to know the effects of reuse and encapsulation and the study of activities is included in order to understand how reuse and encapsulation are obtained.

There are two main reasons to stress the necessity for a clarification of encapsulation and reuse *outside the part domain*;

1. *Encapsulation and reuse of assets other than product parts*

   Many platforms are reported to consist of assets, which are not constitutive parts of the products and thereby not in the part domain (activities and knowledge for example).

2. *Encapsulation of products assets*

   Many successful product families have reuse and encapsulation benefits within the product which does not arise from a classic modularisation, i.e. an encapsulation (with physical interfaces) in the part domain. The products are encapsulated in other domains, and the research must clarify the reasoning behind such phenomena, in which the encapsulation does not necessarily follow the boundaries of parts.

Comments to the research question

Constitutive platform elements

The investigation will take a starting point in existing platform perceptions and clarify the lack of reasoning on the subject of reuse and encapsulation of assets that are not necessarily *part* related (as in the part domain of the Theory of Domains).

Activities leading to reuse and encapsulation

It is the intention to discuss phenomena related to the general patterns in a design process leading to reuse and encapsulation. This is relevant in order to understand the context in which the models of various platform elements have to fit, and the context in which the *decisions* have to be made.

Behavioural effects

In the investigation of behavioural effects, it is the intention to clarify the most fundamental patterns in the effects of a platform approach, and not to give an exhaustive list of benefits in all possible contexts. The discussion on effects will include some aspects from various life phases and in particular those activities related to production (fabrication and assembly). Research fields like Mass Customization, Lean Production, and Supply Chain Management are kept in the periphery of the project. The concept of postponement however, is discussed more extensively as a potential effect of encapsulation.

Research Question 1 is dealt with in Part 4, in which reuse and encapsulation as phenomena are further discussed, and in particular the concept of reuse outside the part domain is accounted for. (Chapter 4.5.3).

2.2.3 Visual platform modelling

Understanding the phenomena within product platforms will not necessarily lead to improvements in industrial practice. Another core problem from a practical point of view is the lack of ability to visualise the product platform and to use it actively for design and decision making purposes [Harlou, 2006]. The introduction in Part 1 provides a basic assumption, which impacts the work in this thesis. It is stated that decision makers have to see the platform in order to manage it. On the basis of this assumption, the second research question is phrased. It extends Research Question 1 into a modelling context.

Research question #2

Given that a visual model may support decision making, answer the following;

> ***Research question 2***
>
> What possible ways exists to visually *model* the phenomena related to reuse and encapsulation of *constitutive platform elements*, inside as well as outside of the part domain - in order for decision makers to experience an improved decision base in platform projects? Ideally, such models should provide decision makers with knowledge on potential *behavioural effects* arising from the meetings between platform elements and life phase systems.

Decision base

Judging whether the decision base is improved, is based on reactions from stakeholders in the three case companies. Notice that the research question seeks to determine the *experienced improvement*. This is a very important limitation of the study. Since decision theory and decision making as a field of research, is held outside the scope of the research, the question focuses on how a visual model can improve the experienced or perceived improvement of a decision base. A consequence of this has been that the validation of the findings is of a qualitative nature, based on feedback from the stakeholders, who have been involved in the three case projects.

Existing models

A product platform model – in whatever form it may have – will have to somehow interface with existing modelling and design tools. An important point to make here is that the product platform model should not necessarily be seen as a complete model of all possible information and data about the platform. Instead, a platform model – by interfacing with existing modelling and design tools – has the potential to provide an overview of the platform while serving as an information directory.

Computer modelled representations of products like the ones present in CAD systems (Computer Aided Design), PDM systems (Product Data Management), ERP systems (Enterprise Resource Planning) and PLM systems (Product Lifecycle Management) are already widely applied in industrial practice.

Product models are found in many places; CAD systems store geometrical models. PDM systems store bills of material and documents in general. ERP systems hold information on production aspects such as routings and stock levels. PLM systems have the prime purpose to combine different viewpoints and often a role of integration between the domains of the other IT systems (CAD, PDM, ERP etc.) The company may even have a product configuration system that also has its own product model. Configuration product models are very likely to hold information on the combinations of variants but they do not necessarily hold information on geometrical or structural variation, nor the embodiment design.

The different commercially available IT- systems provide many strong opportunities in relation to product platform modelling, yet the *use* of them often results in shortcomings in a product platform context. The below statements are based on experience from several years of engineering design research and consultancy work at the Technical University of Denmark, and is also an experience from the three case companies within this study;

- The use of commercial IT-systems is often at a concrete and detailed level, making it somewhat difficult to work on a conceptual level
- Several systems are often used to serve the same purpose, e.g. two different CAD system brands, with a parallel set of models
- Similar yet different product models are sometimes found in different IT systems e.g. different bills of materials in the PDM and ERP systems
- The various systems are rarely well integrated and a lot of manual information exchange between systems often takes place. As the IT system portfolio in manufacturing companies often evolves in many tempi and without a predetermined plan the result is little or no integration between the different systems.

There is a large body of research on various product models, with the intention to build computer models and computer systems for handling the modelling task [Malmqvist, 1997], [Männistö et al., 1998], [Jensen, 1999], [Mortensen, 2001], [Johanneson & Claesson, 2005], [Claesson, 2006], [Haug et al., 2009]. However, the computer models often serve very specific purposes and are not flexible. Moreover, it often takes time and resources to implement a new IT system in a company.

The answer to Research Question #2 is therefore scoped in order to keep emphasis outside the computer domain. Instead, the visual models are thought as mainly paper based visual models, while the modelling object can be parts of the IT system models. A model kept outside the computer modelling domain would have the ability to tie the different IT systems together, regardless of the type and standard of the systems and without great investments (fig. 2.2).

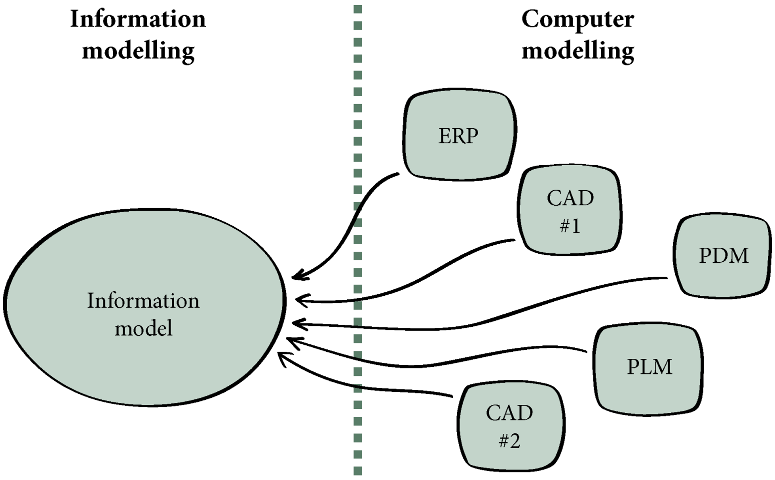


Figure 2.2. An information model outside the computer modelling domain has the potential to be independent of the different IT systems and may serve as a help to orchestrate the information in the different systems.

Figure 2.2 depicts the idea of a low-tech solution keeping track on the information in the already existing systems. This makes it possible to create an overview and improve the decision base relatively fast. The Grundfos case in Part 5 is an example of such a low-tech platform model, and it was implemented over a relatively short period.

2.3 Research scope and limitation

A PhD study is characterised by two major limitations; it is mainly done by a single person, and it has a limited time frame. This has had an impact on the scoping of the project. Another governing factor has been the case companies and their situation since they have been a provider of both empirical information and possibilities of validation. The following section discusses the scope and delimitation of the research.

2.3.1 Business and product types

The research has a focus on manufacturing companies within the mechanical engineering area. Product platforms are particularly interesting when there is a certain amount of product variety, and a certain amount of repetitiveness in order for reuse to be beneficial.

Three companies have participated in this research work; Danfoss, Aker Solutions and Grundfos. The three case companies are further described later in Part 2 (chapter 2.3.2) and much more thoroughly in Part 5 (chapters 5.5, 5.7 and 5.8). All three case companies are characterised by two of the basic challenges of platform projects, which is described in the beginning of the introductory part;

- There has been a desire to *group* and *decouple* generic and variable (spatial and generational) properties in the products and/or the activities and processes.
- There has been an ambition to obtain a decoupling between *preparation* and *execution* in the design and development work and/or in manufacturing.

All three projects are – in their own way – platform projects, yet they are quite different from a product and business point of view. Therefore, they serve as very beneficial cases showing the different instantiations of a platform approach as well as three rather different ways of working with and implementing product platforms. Because they are so different, they add to the consistency of the validation. Moreover, they serve as a validation of correctness of the product platform phenomena indentified in the work on Research Question #1 and the modelling approaches identified in the work on Research Question #2.

2.3.2 Case companies

The three companies are;

- ***Danfoss***
  Product range of solenoid valves. Relatively simple products made in several thousand different variants. Typical annual sales volume from 10 pieces on some product variants ranging up to 250.000 and more for other variants.
- ***Grundfos***
  Injection moulding equipment. Medium complexity with an annual volume of around 10–20 pieces. Thus, the repetitiveness is much smaller than that of Danfoss.
- ***Aker Solutions***
  Drilling equipment for oil and gas exploration. Large complex installations consisting of different hydraulically operated mechanical machinery. Each machine is quite complex with mechanical, electrical and software dimensions involved in the design process. Annual sales volume less than 10 pieces for each machine.

The three cases have the potential to give evidence and validity to the applicability of a visual product platform modelling approach over a broad range of different industries. Apart from the very different businesses and product types, it turned out during the studies that there are great similarities in some dimensions.

2.3.3 Scoping the studies

During the work, the cases have had an influence on the final framing of the work. Rather than spending time in one company and trying to understand their processes in detail, it has been a part of the approach in this research, to incorporate different industries with different organisations, working patterns, and products. Therefore, some details have been left out, or kept on a shallow level of exploration.

The first obvious limitation is constituted by the companies, which would benefit from a product platform approach. In general it takes a certain level of product variety, complexity and sales volume for a product platform to be beneficial. Annual sales volume, product complexity and product variety are three factors that can be used to somehow classify different companies and product types, and thereby become part of a delimitation of the research. The three factors are quite different and incomparable while also rather hard to quantify, and therefore it provides a qualitative rather than quantitative delimitation. From the three factors, it is possible to visualise a three dimensional space in which to delimit the research (fig. 2.3)

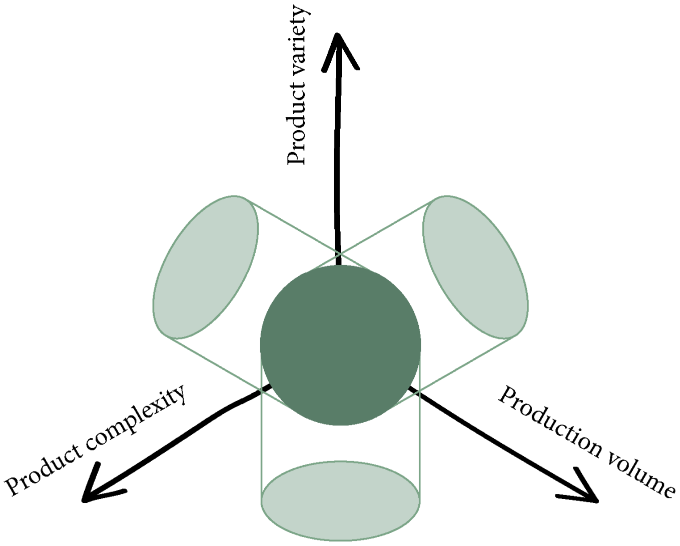


Figure 2.3: Products with high volume, extreme complexity or extreme variety is kept outside the scope of this thesis. The case is the same for very simple products and the cases with low variety one off installations with no repetitiveness.

Figure 2.3 depicts the limitation of target companies. The three case studies all lie within the green sphere. The Aker Solutions case is a special case because it has to do with large one-off installations. However, the product in the case apply to the requirements in figure 2.3.

The following aspects, which are closely tied to the research objectives, are held outside the research contribution and scope;

Computer modelling

Following the argumentation is figure 2.2, it is considered to be outside the scope of this thesis to give detailed insights and research contributions to the computer modelling discipline i.e. to study the use of

PLM, PDM, CAD and ERP systems and to contribute to those subjects. It is still important to interface with these systems and the related models, and the three industrial cases described in part 5 all have discussions on the use of CAD systems and some implications of a visual modelling approach for product platforms on the structuring of data in ERP and PDM systems. However, it is not the intention to provide a research contribution to the use or development of commercial IT systems, nor theoretical/abstract computer modelling. In Part 5 there is a discussion of Top Down Design in CAD systems, and the Aker Solutions case provides an example of the use of a certain CAD modelling approach. However, this example is included as an example of the interface between the CAD system and a visual, paper based model. The findings regarding the use of CAD models are not tested or compared to alternative modelling techniques.

Development process

The contribution in this thesis lies within product platform modelling. The modelling discipline is seen as a part of the development process of a product platform. However, it is not the intention to prescribe a certain stepwise methodology for product platform development.

Organisation and management theory

A product platform can have profound implications on many of the different activities within a company, and may be perceived accordingly. Depending on the viewpoint and the perception of a product platform and a product platform model, the subjects also have the potential to be seen as organisational constructs, business models, information sharing methods, management tools etc. Thus, there are many different potentially relevant research approaches and theoretical foundations in relation to the subjects of this thesis. The focus in this thesis is kept within an engineering design context and the other disciplines are kept outside the research focus. This is mainly due to the skills and background of the author, and the time constraints of the project.

Decision making

Decision making and decision theory is a field of its own. It is assumed that a visual model will improve decision making. However, it is considered outside the scope of the research to study theories on decision making or contributing to these. Instead, the object of study is the *perceived* decision base, i.e. that different decision makers are asked whether they felt an improvement in their decision base. Clearly, this is a deliberate choice imposing some limitations on the findings of the study. The reason not to include theory on decision making is mainly that of resources and the background of the author. Moreover, there was no empirical input available that would make it possible to state, that the decision base is actually improved. The only measurable criteria are the decision base, as it is perceived by the stakeholders in the three case companies.

2.4 Research methods

The engineering design discipline is a rather complex affair to conduct research studies on. It is a widespread discipline with many different stakeholders involved. It is rarely possible to set up laboratory studies or to create an artificial environment in which to study the phenomena and later on to test the effects and applicability of new research contributions. Thus, many studies within product development and engineering design research are done in the field, in industrial practice. Add to this the complexity of the subject of product platforms, the wide impact from a product platform approach on a business and the numerous factors that influence and are influenced by a change process of that scale. It then becomes evident that it is hard to identify the right research object and indicators, and hard to design a study with a bullet proof verification and validation of postulated effects and assumptions.

There is not a single unifying research approach that fits the task of the two research questions in this thesis, and the questions have different requirements for a suitable research approach;

1. *Research question 1* is rather theoretical yet it does have a practical applicability as an underlying driver for research question 2.
2. *Research question 2* on the other hand, has the opportunity to become more practical, in the sense that models can be implemented in a company (as opposed to a phenomenon or theory, as in the case of research question 1). Research question 2 resembles the traditional engineering design research setup, in which an initial state is desired to change. That change is often sought after through the development of tools and supports [Blessing & Chakrabarti, 2002]. In this case the *state* is the current situation in which companies struggle to visualise product platforms, and the notion that the decision base can be improved.

The two studies thereby constitute a mix of feasible research methods. The research work in this thesis is a mix of different approaches. These approaches are discussed in the following chapters;

- *Chapter 2.4.1: Research viewpoints*
  A fundamental discussing on how different points of view can influence the study and the outcome of the research.

- *Chapter 2.4.2: Applied Research*
  Dealing with a theory and a problem base in the same research project

- *Chapter 2.4.3: Engineering Design Research*
  Introducing a method or “support” in a company and testing the contributions from this method

- *Chapter 2.4.4: Case studies*
  Dealing with cases as a source of empirical input to a research project

- *Chapter 2.4.5: Action Research*
  Taking into account the presence and active involvement of the researcher during the research

2.4.1 Research viewpoints

It can be feasible to give a few thoughts as to what kind of research, the research questions induce. Verschuren & Doorewaard [2004] provides a list of *research viewpoints*;

- ***Theory-developing research***
  Giving contributions to a theory and then testing whether these contributions has consistency and usefulness.
  Parts of the work on Research Question #1will imply theoretical contributions to existing theories, and from that perspective this work has elements of theory-developing research.

- ***Theory testing research***
  Testing a theory against practice using hypothesis based on the theory
  If Research Question 2 is perceived as a concretisation of the phenomena identified during the work on Research Question 1, then theory testing is part of the validation of the usefulness of the product platform model, i.e. part of the case studies.
- ***Problem-finding research***
  Identifying important subjects for a given matter.
  The problem base in this research is mostly based on the work of other authors, however slightly rephrased (such as the assumption on reuse and encapsulation and the postulated need for visual models). However, this study is not considered to be of a problem-finding nature.
- ***Diagnostic research***
  Searching for the cause of a dysfunction.
  This research builds upon a number of different assumptions. It is already assumed that there is a need for visual product platform models, i.e. it is assumed that the dysfunction or inefficiency in present product platform approaches can be partly overcome by means of a visual product platform model as a means to improve decision making. This fundamental assumption is in fact not thoroughly tested in the work, and therefore the research is not of a diagnostic kind. Otherwise, the research task would have been to establish an understanding of the different possible explanations to the lack of success in product platform approaches, maybe by using unsuccessful projects as the research object. This is not done in this work.
- ***Design-oriented research***
  Developing a plan or model for a design process.
  Most engineering design research has a strong affiliation to this research viewpoint. This thesis has a starting point in engineering design research. The product platform model is perceived as a design support, and the nature of the research viewpoint in Research Question 2, resembles that of design-oriented research. However, as it is stated in the scoping, the intention is not to build a prescriptive, stepwise method for product platform design. Instead, the product platform model - as a concept - is seen as a support during a product platform design process.
- ***Intervention-oriented research***
  Comparing a desired process with an actual process as it is carried out, by monitoring the process as is.
  Since there are no real existing workflows to monitor in the three case companies, the intervention viewpoint is not very relevant in this work.
- ***Evaluation research***
  Evaluating the comparison in an intervention-oriented study based on assessment criteria.
  Like the intervention-oriented research, evaluation research is not a direct part of the work in this thesis.

The question is then how to set up a study that ensures the right research contribution and answers to the research questions. The following chapters discuss the interplay between theory and practice and different research approaches, all of which have contributed to the setup of this research.

2.4.2 Applied Research

This study has been carried out in close cooperation with industrial practitioners in companies. Apart from the mainly theoretical work on Research Question 1 (which is documented in Part 4), the author has engaged in a study in three case companies. Jørgensen [1992] presents a framework for a research approach that ensures the fit between theoretical and practical drivers in engineering design research (fig. 2.4).

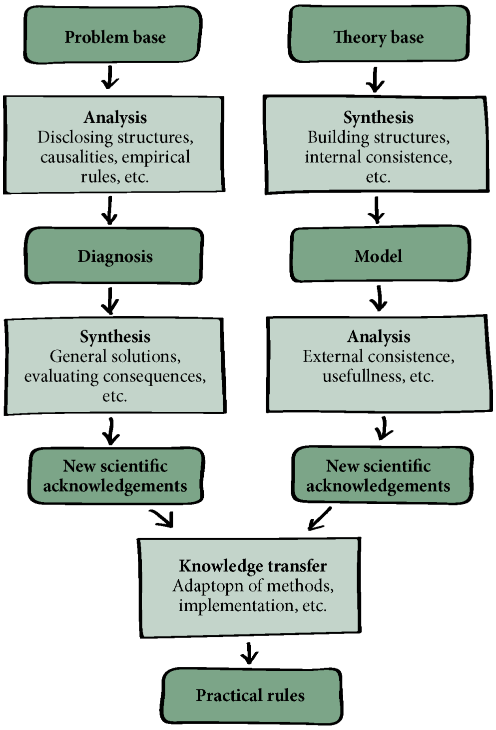


Figure 2.4: The fit between theory and practice in engineering design research [Jørgensen, 1992].

The framework accepts a basic need that is of either practical or theoretical kind – or in many cases a combination thereof. The two research questions somewhat represent the two tracks in fig. 2.4, even though both research questions has its starting point in a combination of a problem base and a theory base;

- Research Question 1 deals with various phenomena within the subject of product platforms, and is mainly – but not only – starting in a theory base, as seen in the top of fig. 2.4.
- Research Question 2 deals with the modelling of these phenomena and test it in an industrial setting, and the starting point of the cases are mainly – but not only - that of a problem base as seen in the top of fig. 2.4.

The theory base and problem base are closely related and not strictly separated. During the studies, present theory has been reviewed (in the theoretical base in Part 3, the study of phenomena in Part 4 and partly in the beginning of Part 5, in the study of present modelling approaches), new theoretical inference and models have been built (in Part 4 and Part 5 respectively) and finally the effects of the models have been assessed by observing the use of them in industry (in Part 5).

During the project, the discussions have been confronted with academia through conference and journal papers, and the industrial practitioners in the case companies, during the day to day work and in workshops.

2.4.3 Engineering design research

Blessing & Chakrabarti [2002] propose an engineering design research framework in which a series of three successive studies follow each other during a research project. See figure 2.5

In this framework, a set of criteria is formulated. These criteria represent the aim of the research. One of the challenges is to identify measurable criteria in order to be able to assess the validity of the research later on. Then, a preliminary descriptive study is made in order to observe the research object and gain knowledge about relevant challenges to study. This process leads to a concretisation of the research objective. A prescriptive study holds the response to the identified challenges. In most cases within engineering design research, the prescriptive study is a methodology or development model, i.e. a concrete tool. Finally, a second descriptive study is undertaken, in which the effects of the tool is observed and – if possible – measured in a more or less quantified manner.

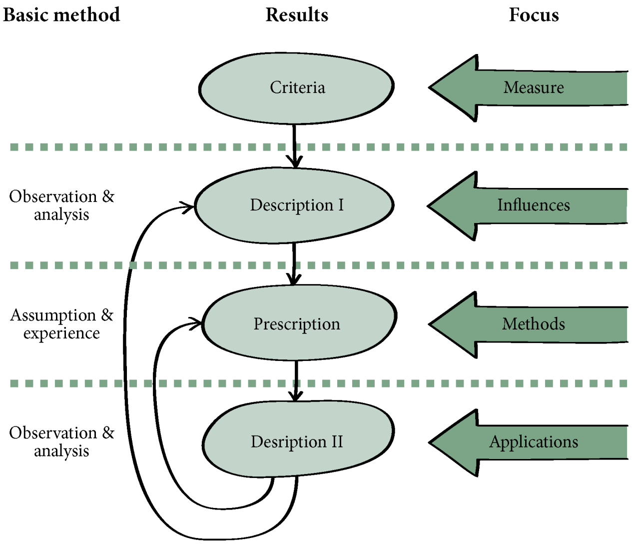


Figure 2.5: Engineering design research framework [Blessing & Chakrabarti, 2002]

The engineering design research framework is addressing the discipline of studying engineering design processes. In most engineering design research studies there is an initial assumption that a *support*, i.e. tool, a method, a mindset etc. utilised by engineering designers, will lead to some sort of improvement of the development process or the outcome (the products), e.g. higher efficiency in the use of engineers, better manufacturability of the products, better usability of the products, faster development, fewer design flaws etc.

The engineering design research framework is considered to be relevant in this study, for two reasons;

1. A better understanding of the phenomena of platforms is assumed to improve the decision making within a product development project.
2. Visual models are assumed to be the means to anchor the understanding of phenomena in the organisation.

It is noteworthy that fig. 2.5 depicts the iterative nature of a design setup. Rather than seeing the framework as three consecutive studies, it should be perceived as three different classes of studies. The work has not been carried out as three different and independent chronological phases. Instead, the studies have evolved over time, and through iterations covered all three aspects, i.e. a study of the phenomena, a suggestion as to how the present situation may be improved, and an implementation of a future state and an observation of the effects. That is the basic order of the studies in the three case companies, while a fundamental literature study has been carried out as a starting point (in Part 3 and 4).

Formulating research criteria

Ultimately, the desired practical implication of most engineering design research is to improve the state of companies, more specifically by improving the instruments available to designers. However, Blessing & Chakrabarti [2002] note that it is often quite difficult to measure the effects of a single research contribution on broad success criteria like the overall profit or the lead time in product development. Since engineering design research is often based on case studies, the studies tend to be blurred by a number of different uncontrollable factors in the case companies. Therefore it can be hard to isolate the effects of the research contribution on the performance of the company.

When validating and verifying the research there is often a need for a set of concrete and measurable criteria.

Modelling the research criteria

A reference model is a tool proposed by Blessing and Chakrabarti in which rather broad research success criteria are broken down into more concrete and measurable criteria, see figure 2.6.

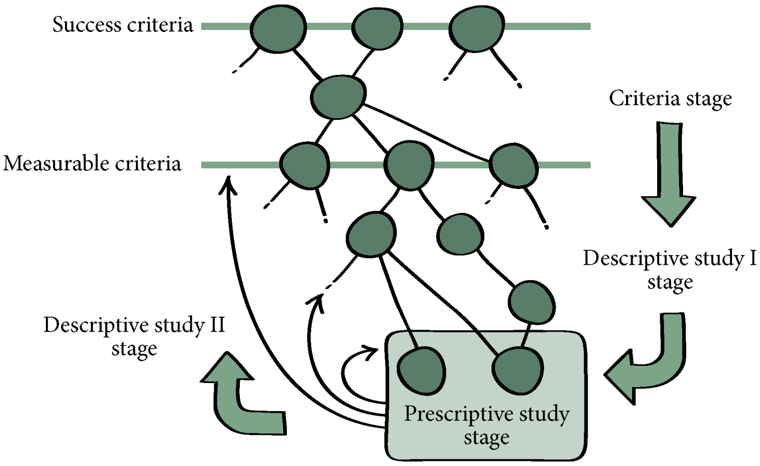


Figure2.6: The network of influencing factors. Success criteria are concretised and translated into measurable criteria.

2.4.4 Case studies

The problem base in Jørgensens model (fig. 2.4) is closely related to the design of the research. Three cases serve two purposes; they have been used to concretise the research questions and identify detailed problem areas while at the same time served as “test grounds” or laboratories in order to add validity to the research results.

The case study as a research methodology is described by [Yin, 1994]. It allows the researcher to study the phenomenon under its real circumstances. The strength of the case study is that it applies a real environment to the study. A drawback is the limited ability to use inductivism and claim general conclusions and validity based on a single or few case studies. The case study somehow resembles action research, yet the researcher does not necessarily have to intervene with the studied object. In the studies in this thesis however, the researcher has taken up a rather active part of the project cases.

Choosing the type and number of case studies in a PhD project like this one, is influenced by a number of different factors. In this case, obviously the availability of willing companies played a vital role, and somehow the research objective was affected by the reality in the companies. There is also a trade off between the number of cases and the depth and detail within the cases. The boundaries of a PhD study contain a certain amount of time, research experience, and resources. Therefore, there is a contradiction between the level of detail within each case study, and the number of cases. In this case it was decided to work with three companies, and from these three companies induce general applicability to some extend within the scope of the research.

2.4.5 Action Research

Acknowledging and accepting that the researcher actually takes part of the study is one thing. Another issue is the fact that some phenomena would never have occurred, was it not for the presence of the researcher. That was partly the case in the three case companies, as they had little or no experience in the field of product platform modelling and the product platform approach in general – at least not as conscious and explicit phenomena. The researcher participated in projects in which a product modelling approach was implemented. Without the research project there would have been no product platform model to study.

The method of *action research*, [Coghlan, 2007], deals with this issue, i.e. the studies of phenomena that would not have occurred without the *influence* of the researcher. In this thesis this also implies not only an influence but an active participation and presence of the author.

This is one of the reasons that the Engineering Design Research framework of [Blessing & Chakrabarti, 2002], has been altered a bit and does not follow a strict consecutive structure of descriptive and prescriptive studies.

The Action Research part of the study has been carried out in three different projects, in three different companies. The action research characteristics of the project make way for two potential shortcomings when it comes to validation;

- Strictly speaking, the results have not been tested without the presence of the researcher, and it is therefore only out of inference, that a long term applicability and implementation is claimed.
- The reactions from the stakeholders in the company are biased due to the fact that most of the employees eventually got to know the researcher as a colleague.

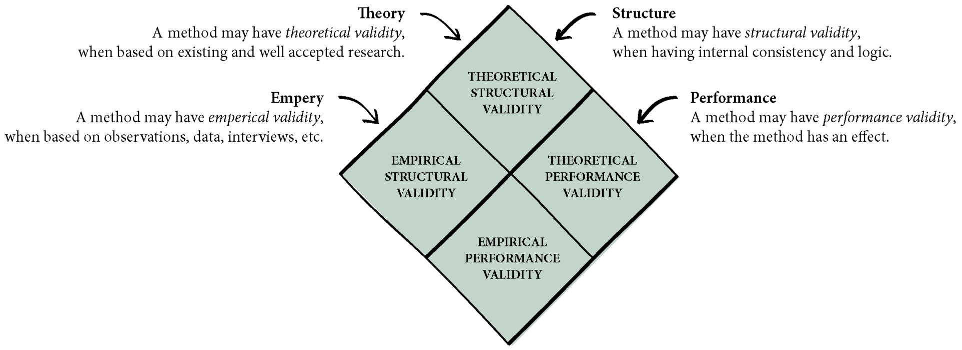
Validation and verification is further elaborated in chapter 2.5.

2.5 Research validation and verification

One of the greatest challenges in this kind of research is to obtain an unbiased an objective verification and validation. This chapter discuss some the methods, which have inspired the efforts to verify and validate the findings in this research.

From the literal meaning of the words, verification is in this case is considered to be acceptance of the logical internal consistency of the research, and the way the contributions have come about. Validation is considered to be the acceptance of the usefulness of the research and the effects of the contributions. In popular terms: Verification is the answer to the question *"Did we do things right?"*. Validation is the answer to the questions *"Did we do the right things?"*. Some of the authors listed in the following references do not distinguish between the words verification and validation; however the concept of internal/external acceptance is present in the references.

Due to the nature of the case projects, it has not been possible to set up a perfect test environment nor to compare the effects of the research contributions with a status quo situation. Pedersen et al. [2002] propose a framework for validation of engineering design research, often denoted the *validation square* (fig. 2.7). It takes in to account the fuzziness of the subject and the sometimes very qualitative measurable criteria, one have to address. Often, engineering design research is characterised by few quantitative indicators, making it hard to ensure a strict validation based on observations. That is indeed the case in this study, where, first of all, the measurable criteria are of a very qualitative nature, and secondly, the case projects are characterised by many factors involving the overall performance of the projects. This means that the project environments have changed due to uncontrollable and external factors. The Danfoss case project, for example, has – at the time of writing – had a duration of some 5 years. During that period, many other initiatives went on in the company; the financial climate changed, employees where changed and so on. Thus, isolating the effects of this research on the overall project is near impossible.



Theory
A method may have *theoretical validity*,
when based on existing and well accepted research.

Structure
A method may have *structural validity*,
when having internal consistency and logic.

Empery
A method may have *emperical validity*,
when based on observations, data, interviews, etc.

Performance
A method may have *performance validity*,
when the method has an effect.

Figure 2.7: The validation Square, [Pedersen et al., 2002]. The two dimensional framework spans theory as opposed to empery, and structure as opposed to performance. Validity is perceived as confidence in usefulness.

Pedersen et al. [2002] further elaborate the framework and provide a link between the square and the design method, i.e. in that case the research result that is to be validated. Note that the method in the top, in the case of this research, is considered to be the product platform model.

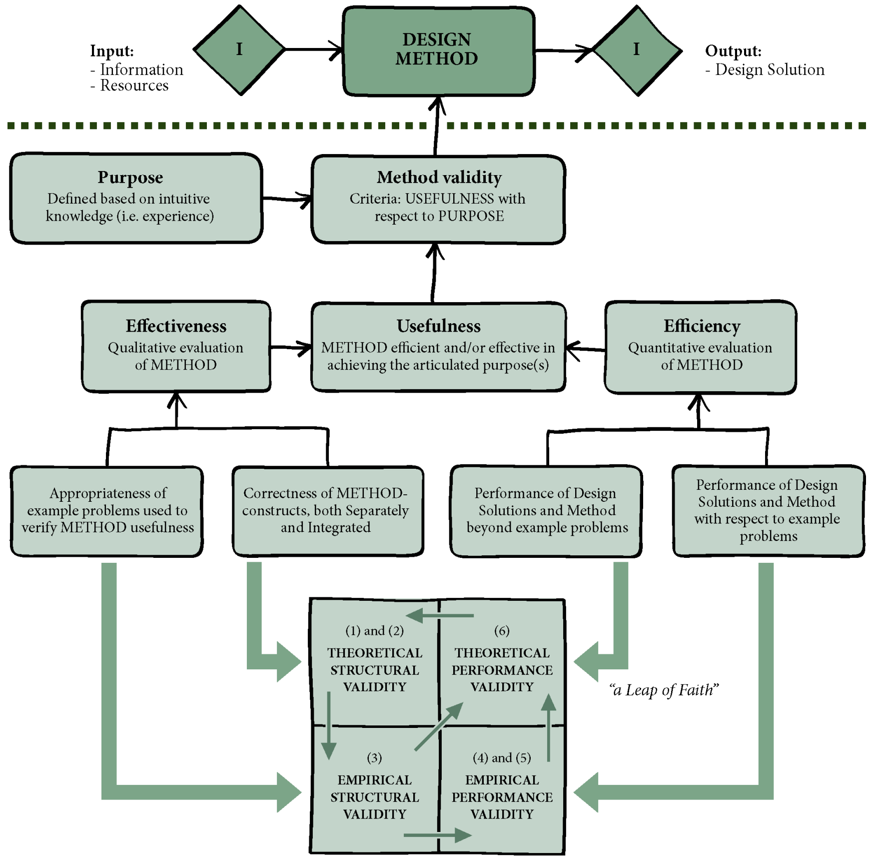


Figure 2.8.: The validation square framework. Linking the validation approach with the research result, in the top [Pedersen et al., 2002].

This approach holds six steps while navigating through the validation square. The numbers refer to the square in figure 2.8;

1. Accepting the validity of the construct
2. Accepting the consistency of the method (research result)
3. Accepting the cases involved
4. Accepting usefulness of the method within the cases
5. Accepting that this usefulness relates to the application of the method
6. Accepting the usefulness of the method in broader applications "outside" the cases (i.e. inductivism).

All six steps are not always possible to go through, yet the list is useful to obtain an overview of the state of validity – i.e. in which dimensions the study can be claimed to be valid, and in which dimensions further studies are necessary.

Using the framework in this project

The validation square is intended for the validation of *design methods*, and in the top of figure 2.8, a design solution is seen as the change of state. Nevertheless, the validation square framework is considered to be useful for the research questions in this thesis even though the two questions are not directly targeting a prescriptive design method. The six steps in the validation square are still considered to be relevant – at least in the case of Research Question 2. Research Question 1 is more questionable, as it has to do with theory development.

In each of the cases in Part 5, it is discussed which of the steps in figure 2.8, the cases fit.

2.5.1 Verifying the theoretical aspects

Research Question 1 deals with rather theoretical aspects. The validation square somewhat deals with theoretical aspects in the steps 1, 2, and 6. Pedersen's definition of validity is "*confidence in usefulness*". How does one proof the confidence in usefulness of a *perception* of a phenomenon, which is basically the nature of the contribution in Research Question 1. The answers to Research Question 1 are *perceptions* of phenomena (and phenomenon models) rather than methods. Jacob Buur, [Buur, 1990], suggests two approaches on how to verify a design theory. It is well aligned with the internal/external validity of the validation square framework, and would apply to the theoretical contributions in the work on Research Question 1 (Without claiming that the research contribution to research question 1 is a theory, but more contributions to a Theory).

Buur suggests two approaches to verification:

Logical verification

- A theory must be consistent: Internal conflicts between the theory constituents are not accepted
- A theory must be complete:, The theory must explain or reject observed phenomena of relevance
- A theory has to support established and widely accepted methods as well as specific design problems

Verification by acceptance

- A theory must be accepted by a relevant scientific community
- A theory must be accepted by industrial practitioners

The formulation of theoretical contributions is – hopefully – built upon a rationale that rests on existing theories and has a sufficient degree of internal consistency. However strictly speaking, all the work in this thesis is not truly verified by means of the above logical or acceptance verification.

The intention with Research Question 1 is not to formulate a united and complete theory. Rather, the intention is to contribute with explanatory elements within the phenomenon of product platforms, and a formulation of and justification of the relevance of the concepts of *reuse* and *encapsulation*. That is, to explain constituents of a theory but not claiming to have provided a whole theoretical framework.

An elaboration on the above verification approach is given by Olesen [1992]. He states five characteristics that a research result may have in order to be valid;

- *Internal logic*
  A research result is internally logic when consistency between the research motivation, the hypothesis and the research results exists. In addition, the research has to comply with known theory that is accepted.
- *Truth*
  A research result can be claimed to be true when the theoretical and practical implications of the result can be used to explain phenomena that are founded in reality and not just theory.

- *Acceptance*
  A research result has to be accepted by a research community and industrial practitioners in order to be valid.
- *Applicability*
  The research result has to be applicable in practice in a real industrial setting.
- *Novelty value*
  The research result has to have newness, i.e. have to provide new approaches or new realisation.

It is notable that both the *internal logic* and *external acceptance* are two fundamental ways to obtain verification/validation in the above approaches. It is seen in the split in a theory base and problem base of Jørgensen's model, and the description and prescription studies of Blessing and Charkrabati's model. To some extent, Research Question 2 is a concretisation of research question 1. Proving the applicability of the models related to Research Question 2 will add some sort of validity to the phenomena discussed in relation to research question 1, yet the theoretical consistency does not evolve from practical applicability. It has been the intention to gain internal consistency in the line of argumentation in Part 4, and from the fact that the theoretical contributions are based on existing and well established theories. This has to do with the intention to explain the phenomenon of reuse and encapsulation on the basis of the Theory of Domains.

2.5.2 Concluding on verification and validation

The fundamental efforts to verify and validate the findings are based on *internal logic* and *external acceptance*. Since the findings are either theoretical or qualitative, there is no quantitative measure to compare with in order to clarify whether or not the findings are valid. Instead, it is a mix of different evaluations.

Ideally, all the findings should have been confronted with external parties, and only some of them have been published, peer reviewed and confronted with external parties not directly related to the author (such as colleagues, professors at the same university etc.). Due to time constraints, it has not been possible to publish all the findings during the course of the project. Therefore, the final judgement of the validity has to be left to the scientific community and the reviewers of this thesis.

2.6 Research design

The research has been set up as a mix of descriptive and prescriptive activities, in a combination of case and literature studies. The case studies have been carried out using action research. The combination of literature studies and case studies somewhat have elements of applied research, with analysis and synthesis elements, and both diagnostic and modelling activities leading to new scientific contributions.

The activities in the study have been a combination of the following;

- Literature studies in journals, proceedings and other academic sources – this is both part of the initial criteria formulation and the *descriptive* activities
- Inferring about important phenomena on the basis of the literature study – a combination of *prescriptive* and *descriptive* activities
- Observing a current state in industry on the basis of findings in literature, working experience in companies and the experience from the cases, i.e. mainly a *descriptive* activity.
- *Prescribing* various modelling methods and using them during the three cases

- *Describing* and reporting the use of the models.

And from a validation point of view;

- Confronting ideas, perceptions and models with academia through journal and conference papers and presentations
- Gaining input on the acceptance of the results in the industrial cases, based on reactions from stakeholders involved in the case projects and their perception of the results.

As a consequence of the iterative nature of the study, it is not possible to describe the different activities using a strict division between prescriptive and descriptive studies.

2.7 Concluding the research setup

In Part 2 it is described how the problem statement in the introduction (Part 1) is brought into a research context. The introduction in Part 1 states that the *decision base* in a platform project can be improved by means of an improved understanding of various phenomena related to product platforms and by means of visual models, which represent these phenomena. Figure 2.9 depicts a model of a simplified line of argumentation based on the statements in the introduction.

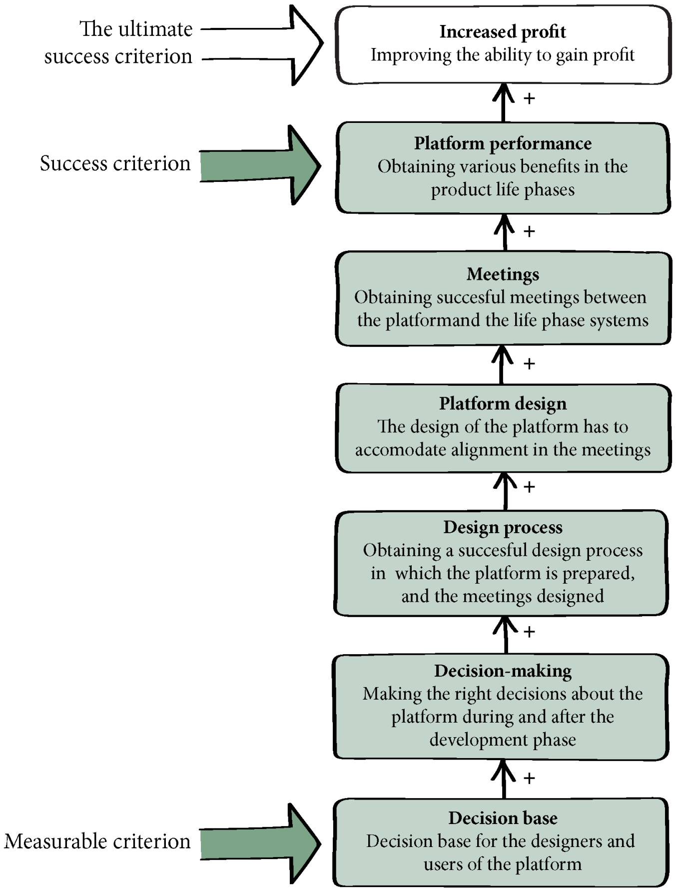


Figure 2.9: Platform performance eventually calls for a better decision base for decision makers.

In figure 2.9 the success criterion of the research is shown as the desire to improve the *performance of the platform*. The performance of the platform is rather loosely defined as the ability to reach certain desired effects from the platform – it depends on the context and scope of the platform. (The effects of platforms are addressed in Part 4, chapter 4.6).

At the bottom of figure 2.9, a measurable criterion is shown – it is the *decision base*. The decision base is chosen as the measurable criterion because it is the focal point of the observations in the three case studies, and because the reactions from stakeholders in the three companies mainly have to do with the decision base (following the formulation of the two research questions).

Figure 2.9 is a very simplified model since many other factors have a potential influence on the performance of a product platform. A lot of factors are left out. The basic arguments in figure 2.9 are the following (which is a short version of the argumentation in Part 1 and Part 2);

- The platform performance is depending on the effects of the meetings between the platform and the life phases.
- Successful meetings occur when there is a *fit* between the platform and life phase systems, and the setup in different life phases are *aligned* with the platform and vice versa.
- The platform design is a key constituent of the meeting and a fundamental assumption is that successful meetings take a successful platform design to be realised.
- The need for a successful platform design puts demands on the design process, and the next assumption is that a successful design process is a prerequisite of a successful platform design. This design process is referred to as the *preparation phase* in order to distinguish it from the *execution phases*, which are the later stages, in which engineering designers start to build products on the basis of the platform.
- In order for the design process to be successful, team members have to make the right decisions, and so *decision making* is a key issue.
- The final assumption in the chain of arguments is that – in order to make the right decisions – decision makers have to have a basis to build the decisions upon. This *decision base* is then the starting point of the research. Research Question #1 seeks to identify important phenomena that can be part of an improved understanding, i.e. a part of the decision base. Research Question #2 seeks to identify ways to model these phenomena, a visual representation of the decision base.

Research aim and objects

In the introduction, the concepts of *reuse* and *encapsulation* are considered to be fundamental characteristics of product platforms. Reuse is the process of reusing platform elements. Platform elements are considered to be the elements, which a platform consists of. Encapsulation is considered to be the *grouping* and *decoupling* of platform elements.

In the introduction it is also stated that the decision base is founded on knowledge and that this knowledge can be perceived from three different points of view, i.e. know-how, know-why and know-what.

- *Know-WHY* has to do with the effects of the meetings and the drivers for the platform approach. It thereby corresponds to the *behavioural* aspects of the platform
- *Know-WHAT* has to do with the platform itself, and, i.e. the *constitutive* aspects of the platform, that is essentially the question of what a platform “is made of”.

- *Know-HOW* has to do with the way the WHAT and WHY are obtained, i.e. what activities lead to a successful manipulation of the platform in order to obtain the effects.

Provided that reuse and encapsulation are regarded as the two fundamental characteristics of a product platform, the model in figure 2.9 can be further extended. This is done in figure 2.10, in which the decision base is further elaborated. Combining the know-how, know-why and know-what with an understanding of reuse and encapsulation gives the following visualisation of the influencing criteria that have an impact on the decision base;

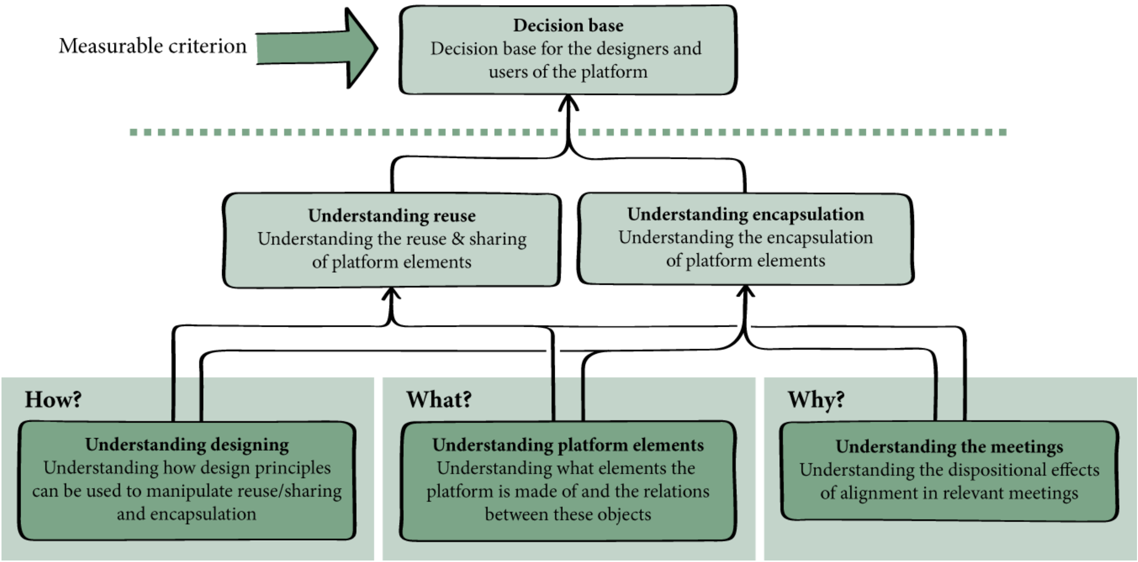


Figure 2.10: The decision base is influenced by a number of different factors. In this thesis, there is an emphasis on the understanding of reuse & sharing and encapsulation, by the means of know-how, know-what, and know-why.

Figure 2.10 depicts that a successful decision base is influenced by the understanding of reuse and encapsulation. The knowledge provided by a model has to consist of know-how, know-what, and know-why. The research aim is to investigate how this knowledge can be improved and provided to decision makers.

Figure 2.10 has to be seen from two perspectives;

1. Decision makers have to have an understanding of the phenomena.
2. Decision makers have to get that understanding from somewhere

These two perspectives are reflected in the two research questions (see chapter 2.2.2 and 2.2.3). These two perspectives govern the research, in the sense that the understanding of the boxes in figure 2.10 has two dimensions. Therefore, the research aim is to provide contributions to the knowledge in a *phenomenological* dimension, and a *modelling* dimension. Thereby, the research has two research objects;

1. A set of phenomena related to the nature and effects of reuse and encapsulation of platform elements and the platform elements themselves.
2. The use of visual modelling of product platforms.

The fundamental research aim

Basically, research is about building knowledge. If a tool or method evolves from the work, the research contribution is not the tool/method itself, but the knowledge and confidence that it will pay off to use that kind of method. The consciousness and knowledge about the phenomena behind the model is also part of the research contribution. From the new knowledge and the documentation of a research project, other people should then have the opportunity to build on the knowledge and expand it into other applications or studies.

Hopefully, this thesis will provide a sufficient documentation to serve that purpose.

3

Theoretical basis

The theoretical basis is the fundamental viewpoint from which the research objects are perceived and the research aims are striven for. Many different viewpoints can be related to the subject of product platforms, and consequently, many different research fields are relevant for the subject. However, the thesis has its starting point within engineering design science. It has a systems and design perspective on the topic of product platforms. This starting point forms and limits the theoretical basis upon which the research is founded. The following section describes this theoretical basis of the thesis.

3.1 Introducing the theoretical basis

A product platform is the basis of a product family. The individual products within the product family can be seen as systems. Thus, one natural viewpoint when exploring the subject of product platforms is that of a *systems* perspective.

Many of the interesting phenomena related to platforms have to do with design activities, and a design theory perspective is also relevant. Basic problem solving and design processes form the *context* in which the research fits, because the decision making efforts described in Part 1 and Part 2 takes place during design processes.

This gives two fundamental viewpoints, from which the research can be studied;

- Theories of systems
- Theories of design processes

The following section will discuss fundamental viewpoints and theories of systems and design processes, as it forms the basis for the viewpoints on the research object and research task. As a subset of the discussion on design processes, product development and product platform development processes are discussed.

Finally, the topic of decision making during design is shortly discussed, since the research questions has to do with supporting decision making in a product platform context. This gives the following structure of the chapter;

Chapter 3.2: The Systems Perspective

- *Chapter 3.2.1: The Theory of Technical Systems*

  A description of the fundamental viewpoint on a technical system, the constituents of a system, and the inputs, outputs and effects.

- *Chapter 3.2.2: The Theory of Domains*

  The Theory of Domains is very important for this research, as it provides the concept of organs. Organs are abstractions that make it possible to talk about physical function carriers which are realised by several parts. The Theory of Domains is used later in Part 4, to introduce the concept of encapsulation in the organ domain.

- *Chapter 3.2.3: Wirk elements and skeletons*

  The concept of wirk elements is included in the theoretical basis because it provides the opportunity to elaborate the concept of organs and talk about wirk element encapsulation – which is done in Part 4.

- *Chapter 3.2.4: Theory of Dispositions*

  The Theory of Dispositions deals with the effects in various life phases, which are consequences of design decisions in the design phase. The Theory of Dispositions also coins the concept of meetings, which is used in Part 4 to describe various effects of platforms.

- *Chapter 3.2.5: The Genetic Design Modelling System*

  The GDMS is included because it gives a way to describe the difference between encapsulation in the parts and organ domains respectively in Part 4, chapter 4.5.3. It also distinguishes constitutive from behavioural modelling.

Chapter 3.3: The design process

- *Chapter 3.3.1: Theory of Design Processes*

  General patterns in various design theories are discussed.

- *Chapter 3.3.2: Product planning and development*

  The task of product planning and the concept of integrated product development is described, as they form the general context in which many platform projects occur.

Chapter 3.4: Decision making in design

- *Chapter 3.4.1: The decision node*

  The decision node is included as a fundamental way to model the decision activity.

- *Chapter 3.4.2: The decision map*

  The decision map is included to model the decision node in the context of product development

- *Chapter 3.4.3: Decision making for product platforms*

  Here, it is shortly discussed how decision making for product platforms is different from the case of single product development

Chapter 3.5: Concluding on the theoretical basis

3.2 The systems perspective

The systems perspective is dealt with by several engineering disciplines. The European engineering design community is largely based on the Theory of Technical Systems and the Domain Theory as a way to understand and perceive industrial products. Systems Engineering is another discipline also providing useful viewpoints on systems. These disciplines are described in the following sections.

3.2.1 The Theory of technical systems

Theory of technical systems (TTS) has been formulated and elaborated by Vladimir Hubka and Ernst Eder in various references; [Hubka, 1973], [Hubka & Eder,1987], [Hubka & Eder,1988], [Hubka & Eder, 1996]. TTS is a framework for describing products as technical systems.

A *Transformation* of an *Operand* takes place on the basis of a relational between the *Technical System*, the *Human System*, the *Information System,* and the *Management & Goal System*, all of which are affected by the *Environment.* The operand is the object of transformation, i.e. the object changes state during the transformation.

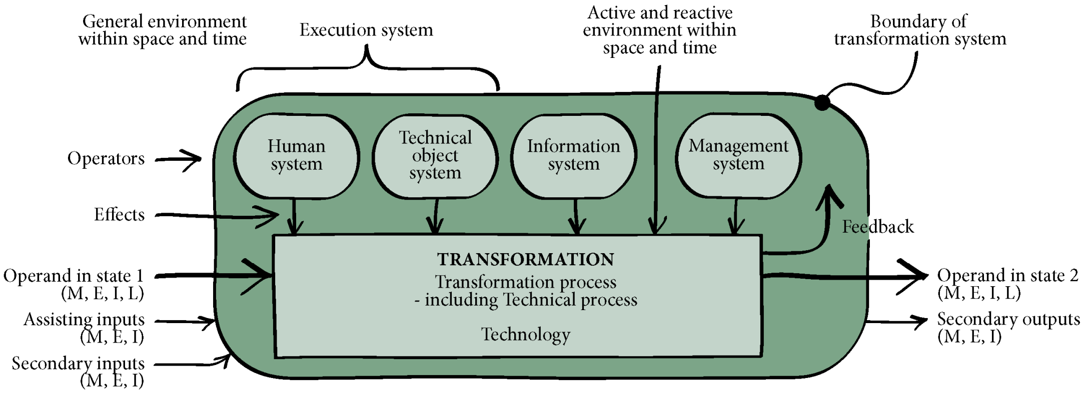


Figure 3.1: The Theory of Technical Systems: The Transformation takes place in interplay between different operators, an operand and the environment. The Technical Systems, Humans Systems are called operators, while the operand is the object of transformation, changing state during the transformation, [redrawn from Hubka & Eder, 1996].

- ***Transformation*** – changes certain properties of the operand (as passive participants in the process). A transformation originates as a mutual interaction between the object being transformed, and means of causing the transformation.
- ***Operand*** – WHAT is being transformed? Object that is being changed in the transformation process(passive participant in the transformation) from an input state (1) to a (preferably more desirable) output state (2).
- ***State*** – sum (vector) of the values of all properties of a system at a certain time. When observing a system , only the state of the selected group of properties is reported.
- ***Technology*** – HOW is the operand being transformed? Knowledge about the transformation, formulates the (input) effects needed to achieve the transformation.

- ***Effects*** – WITH WHAT is it being transformed? Means of transformation – effects acting (actions exerted) on the operand, including supply of the necessary energy, auxiliary materials, regulation, and control.
- ***Secondary inputs*** – all necessary (desirable) additional inputs to the process, and all undesired inputs (disturbances, contaminants, products of the environment, etc.).
- ***Secondary outputs*** – mostly undesirable outputs of the process, their nature and composition depend on the chosen tecvhnology.
- ***Operators*** – WHO and WHAT delivers the necessary effects (as active participants in the process) to the operand: (output effects = desired effects + secondary effects);
  - *Human system:* living things, particularly humans, also animals, bacteria, etc.
  - *Technical system:* Technical (artificial) means, systems
  - *Information system*
  - *Management system:* Management & goal system (directing, setting and achieving goals)
  - *Active environment*
- ***Active environment*** – WHERE is the operand being transformed? takes part in the transformation (desired and undesirable effects).
- ***Space*** – the main property of the environment (surroundings) of the transformation.
- ***Time*** – WHEN is it being transformed? – time period during which the transformation occurs.
- ***Type of effects*** - (acting on the operand), secondary inputs, secondary outs, etc:
  - *materials*
  - *energy*
  - *information (including signals)*

Distinguishing constitutive and behavioural aspects

An important aspect of the theory is the fact that the transformation takes place as a *relative* process. The transformation only takes place in a meeting between the Technical System (what would be called the product in most cases), and the other elements in figure 3.1. Thus, the technical system does not perform the technical process alone. The technical process is an effect of the interplay between the technical system and the other elements. From a product design perspective however, the product (technical system) is the only object of the designer to actually manipulate directly. The product is designed, whereas the transformation is a derivative of the characteristics of the technical system and the interplay with the other elements.

This is also discussed by [Tjalve, 1979], in which product characteristics and product behaviour is clearly distinguished. Product characteristics is a derivate of the physical design (such as dimension, material, surface quality etc) while behaviour is a result of the way the product acts in a context.

The same fundamental issue is further discussed in the Theory of Dispositions, [Olesen, 1992], (chapter 3.2.4) in which a product is said to generate a number of different effects in different *meetings* throughout the life phases of the product. A meeting is a context in which the product operates.

A *function* is often perceived as a purposeful effect related to the use of the product. However, a product also generates other effects, and these effects are not only generated in the use phase, but also in the production, when recycling, etc.

Andreasen [1980] and Mortensen [2001] elaborate on the differences and links between the physical/constitutive and functional/behavioural aspects of a product, by the introduction of the Theory of Domains and the revised Chromosome model respectively. (see chapter 3.2.2 and 3.2.5).

All of these different theoretical contributions deal with the same fundamental issue, namely the nature and relation of *constitutive* and *behavioural* perceptions of a product. This is important in a product platform modelling context, because many platform initiatives have to do with an ambition to create a certain mapping between the physical and functional layout of the product [Ulrich, 1995], [Erens & Verhulst, 1997], [Miller, 2001]. This is further elaborated in Part 4, chapter 4.5.2.

Theory of Technical Systems as a basis for the research

The Theory of Technical Systems provides a fundamental abstraction for the description of product platforms, because product platforms are systems of elements that in the end form different products. Products can be perceived as technical systems. The theory provides the basis to describe the relations between elements in a technical system, and between a technical system and its operands, as well as other technical systems. The idea of a meeting – which is phrased in the Theory of Dispositions – is used extensively throughout the thesis, and the Theory of Dispositions lay the grounds for that perception.

The notion of a technical system is somewhat focused on single products. However, many of the characteristics of a single product are also found in a product platform. The platform has life phases, the platform engages in meetings, the platform is the basis of products and parts that take part in transformations and are themselves transformed as operands. Therefore, the Theory of Technical Systems serves as the basic perception of a system in the thesis.

The theory is applicable on several levels of decomposition of a product, because the technical system view is applicable on subassemblies as well as 'whole' products. Thus, it can be used in a recursive way on several levels of abstraction and detail, depending on the viewpoints from which the system is perceived.

Finally, a product platform can be perceived as a set of technical systems that can be altered and/or combined into instantiations (configurations) of single products. However, aspects like the combination rules are not supported by the Theory of Technical Systems. It only states the nature of systems.

3.2.2 Theory of domains

Product platforms have constitutive and behavioural elements, and the links between the physical and functional viewpoint is a common denominator in many platform perceptions.

The theory of Domains was introduced by Mogens Myrup Andreasen in 1980, [Andreasen, 1980], and it holds strong means to describe the links between the physical and functional domain, with the introduction of the notion of organs.

Four domains

The Theory of Domains identifies four descriptive domains for a mechanical system [Andreasen, 1980], [Mortensen, 2000], [Hansen & Andreasen, 2002];

- ***The Transformation domain***
  Transformations correspond to the transformation in the Theory of Technical Systems, i.e. the overall purpose of the machine/system that takes place in an interaction with operands and operators. The state of the operand's material, energy or data is changed in the transformation.

- ***The Function domain***
  Functions are the subordinate transformations that take place in order to make up the total transformation of the product. Functions are abstractions of the necessary effects taking place within the machine. The functions are the tasks of the organs and are thus realised by organs. Functions are not included in all Theory of Domain references, as they are somehow obsolete, once the organs are clearly defined.
- ***The Organ domain***
  The active elements, which create the required effects in the mechanical product, are the organs. An organ can be further subdivided into so-called wirk elements [Hansen & Andreasen, 2002]. (Wirk elements are explained in section 3.2.3.) Organs are physical yet they do not necessarily belong to a specific component.
  Thus, an organ can reside in several components, and several organs can reside in one component, and this characteristic makes it a strong abstraction when mapping between a functional and a physical domain.
- ***The Part domain***
  The parts are the physical components that make up the product and realise the organs. Parts interact and are often structured in a hierarchy of subassemblies. Parts are defined by their form, material, dimension, tolerance, and surface. A model in the parts domain would also include the relations between the parts. Models in this domain are often geometrical and focus on constitutive rather than behavioural composition. According to [Mortensen, 2000] behaviour in the Part domain is denoted *task.*

The domains are a basis for the research

There is some discussion as to the existence of the function domain. The original Theory of Domains included a function domain, whereas later elaborations of the theory have omitted the function domain. The reason is that the domains are structural viewpoints, and there is no functional structure of a product [Andreasen, 1998]. In fact, one cannot talk about a function structure, without knowing the function carriers, i.e. the organs. Therefore, the functions become obsolete in a complete description of a single product on the basis of the other three domains.

However, in the case of multi products the functions makes sense for one simple reason; A product family may have the same sub function realised by different organs and different parts. Often, complex product assortments are burdened with the presence of non value adding variety [Fiore, 2005], [Harlou, 2006]. It happens when different designs in different product variants serve the same purpose. From Theory of Domains perspective, it is the function – not the organ – that is constant throughout the product range, and therefore it somehow makes sense to revitalise the function domain and keep it in the case of multi products, and thereby in the case of product platforms.

It is not within the scope of this research to determine whether a function structure and thereby a domain exists or not. The ability to talk about organs as function carriers are provided in the revised Genetic Design Model System [Mortensen, 2000], which is described later in this chapter, and the ability to map functions and organs will be discussed from that starting point.

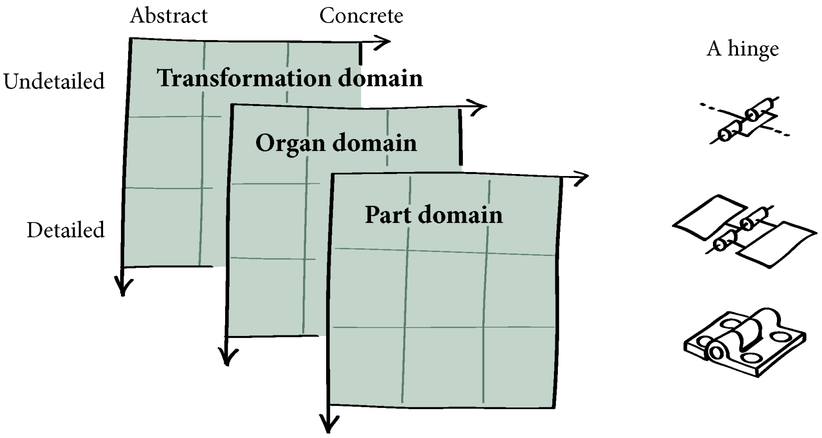


Figure 3.2: The transformation, organ and part domains. To the left, a transformation, organ and part representation of a hinge is visualised. (Redrawn from Hansen &Andresen, 2005, originally in Andreasen [1980]).

Figure 3.2 depicts three different viewpoints on a hinge; from a fundamental point of view, the overall *transformation* of the hinge is to give two objects a constrained rotation around the same axis. Looking at the hinge as an *organ* is then to depict the principal function carriers. In this case the coaxial elements that constrain the rotation and the connections to the two objects. Finally the *parts*, in which the organ resides, is modelled in the bottom. In the characteristics structure, form, material, dimensions, and surface quality determine the properties of the hinge. Figure 3.3 depicts principal differences in the organ and part domains for a snap fit joint.

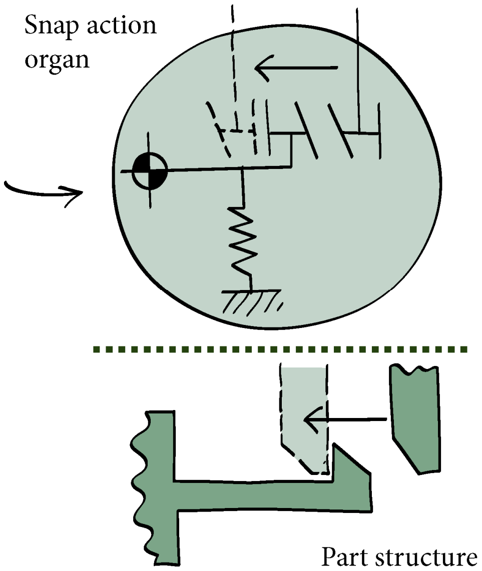


Figure 3.3:A visualisation of an organ and its snap fit joint. The organ is the principle function carrier, realised by the part structure. (Redrawn from Hansen & Andresen [2005], originally in Andreasen [1998]).

3.2.3 Wirk elements and skeletons

The concept of wirk elements can be used to elaborate the Theory of Domains further and more specifically to break down the organ domain into a higher level of resolution. Wirk elements or similar concepts are proposed by several authors [Rodenacker, 1970], [Ersoy, 1975], [Birkhofer, 1980], [Jung, 1989], [Koller, 1994], [Pahl & Beitz, 1996]. They all share the generic understanding of wirk elements as low-level geometrical shapes, surfaces, volumes or bodies of uniform material, which serve a specific functional purpose. Wirk is German for *effect*, and the elements are thus denoted wirk surface, wirk volume and wirk field etc. because they serve the purpose of making an effect happen. A wirk surface is the active surface of one or more parts in which an organ resides, e.g. the surface of a tooth of a gear wheel. The tooth itself would constitute a wirk volume transmitting a moment. An example of a wirk field is the interior volume of the cylinder in a combustion engine. Several components are making up a volume that is somewhat "empty", yet serving a very important purpose. The organ consists of a wirk field and the wirk surfaces of the piston, cylinder interior and other components. This is an example of an organ residing in several components, i.e. another example of the difference between the organ and parts domain.

When the concept of wirk elements are matched with the Theory of Domains, [Jensen 1999], [Hansen & Andreasen, 2002], they become the lowest level of decomposition in an organ domain. The reason (or relation) is that wirk elements are function carriers, just like organs are function carriers, only on a higher level.

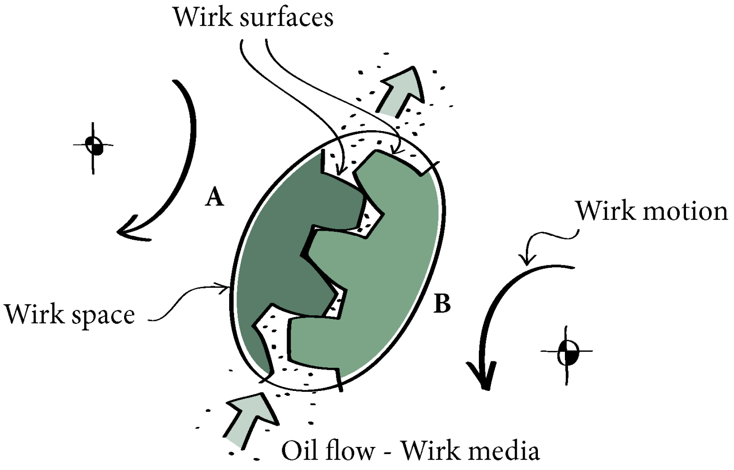


Figure 3.4: Wirk elements: A workspace constituting the borderline between two gear wheels. The wirk surfaces on the teeth are wirk elements. The oil is a wirk media. (Redrawn from Andreasen & Mortensen [1994]).

Figure 3.4 gives some examples of wirk elements. An interesting example is the oil, which serves as a wirk media. Oil, air and other non solid media often play vital roles in the product but are seldom included in product models because they are not directly part of the production process, and product representations tend to focus on the parts that are to be produced in the end. Yet most gearboxes without oil would not work properly. The concept of wirk elements and organs provide a chance to perceive these media as a part of the functionality of the products. The paradox of oil as a non existing part of product models is discussed by Jensen [1999].

Organ skeleton

A skeleton is an abstraction that can be used to describe the relations between wirk elements. These relations are often spatial, i.e. geometrical. An explanation of a skeleton is given by Andreasen & Mortensen [1994]: "*The skeleton carries the spatial relations between the entities of organs*". If it is accepted that the entities of organs are in fact wirk elements, the statement can be rephrased;

The organ skeleton carries the spatial relations between wirk elements

Jensen [1999] further elaborates on the skeleton and see it as "*a non-existing element of an organ to which the spatial arrangement of the wirk elements refers*".

If the pair of gear wheels is again used as an example, one can add the skeleton to the visualisation. In figure 3.5, the skeleton carries the entities of organs;

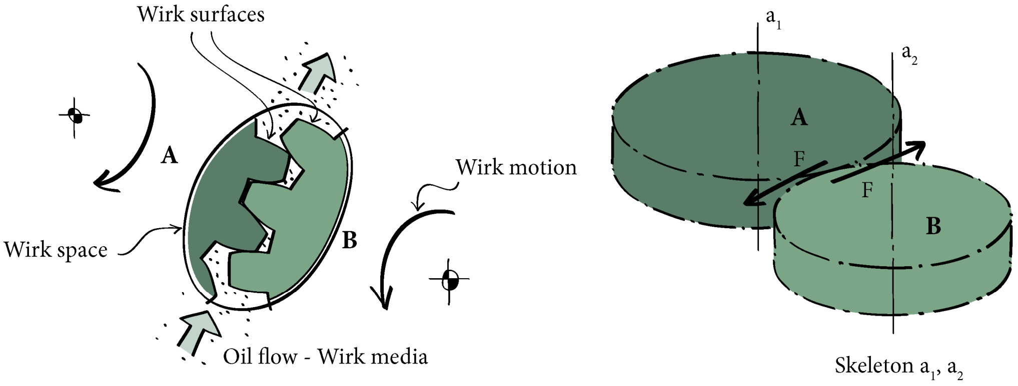


Figure 3.5: The idea of a skeleton as a carrier of spatial relations between the entities of organs. (Redrawn from Andreasen & Mortensen [1994]).

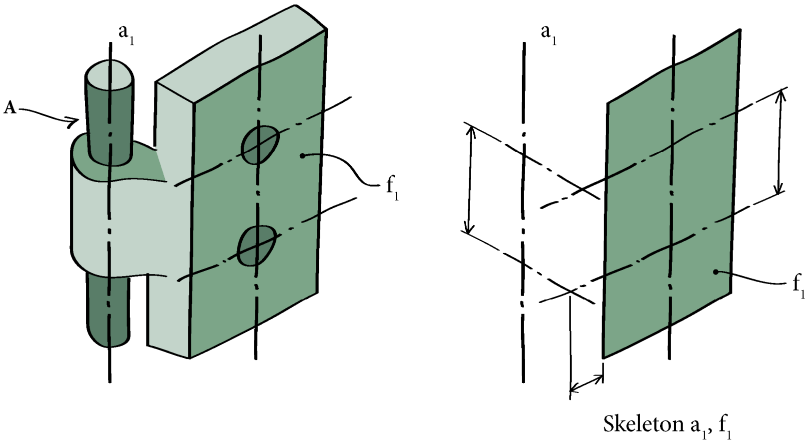


Figure 3.6. An example of a skeleton of a hinge. The skeleton carries the relation between the wirk elements of the hinge. (Redrawn from Andreasen & Mortensen [1994]. If the viewpoint changes from a functional (wirk) element to a geometrical (form) element, one can also find skeletons that carry relations between form elements, and therefore belong to the part domain.

Part skeleton

The above skeleton perception belongs to the organ domain, since the elements of study are based on a functional point of view – as function carriers. If the point of view changes to the part domain, other elements such as form features and surfaces are found. They are also spatially related, and thus they may also have a skeleton. This is widely used in CAD systems. (See Part 5, chapter 5.7 for an elaboration of the form feature skeleton and its use in CAD modelling).

For the use in this thesis – and following the argumentation of the organ skeleton in the above, the following perception of a skeleton in the part domain is used in this thesis;

The part skeleton carries the spatial relations between form feature elements

The skeleton is different from a part structure, in the sense that the skeleton carries the relations between entities of parts – i.e. on a potentially finer decomposition. A part structure defines the relations between parts.

3.2.4 Theory of Dispositions

A product or technical system has different effects depending on the context in which it occurs. From a TTS perspective, the inputs from the environment and human operator, can change, and does not necessarily have to do with intentional and purposeful functions in the use of the design. The weight of a product is often an expensive property during transportation and shipping, and not really desirable in that context.

The Theory of Dispositions [Olesen, 1992], discusses the effects from the product design in a certain context throughout the life phase of the product. A disposition is that part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas. Functional areas refer to the different disciplines involved in bringing products to the marketplace, all the way from development, engineering design through production and distribution, during use, maintenance and scrapping & recycling and so on. Dispositions are decisions about a product design that later create certain effects in the life phases. All decisions create effects, and some are more desirable than others. These dispositions are often made well in advance, early in the process of design and development, and it can be hard to predict the precise effect of these decisions. The theory states that the overall performance of the product and life phase systems must be optimized by creating a fit between the dispositions and the life phases.

The various life phases of the Theory of Dispositions are illustrated in figure 3.7.

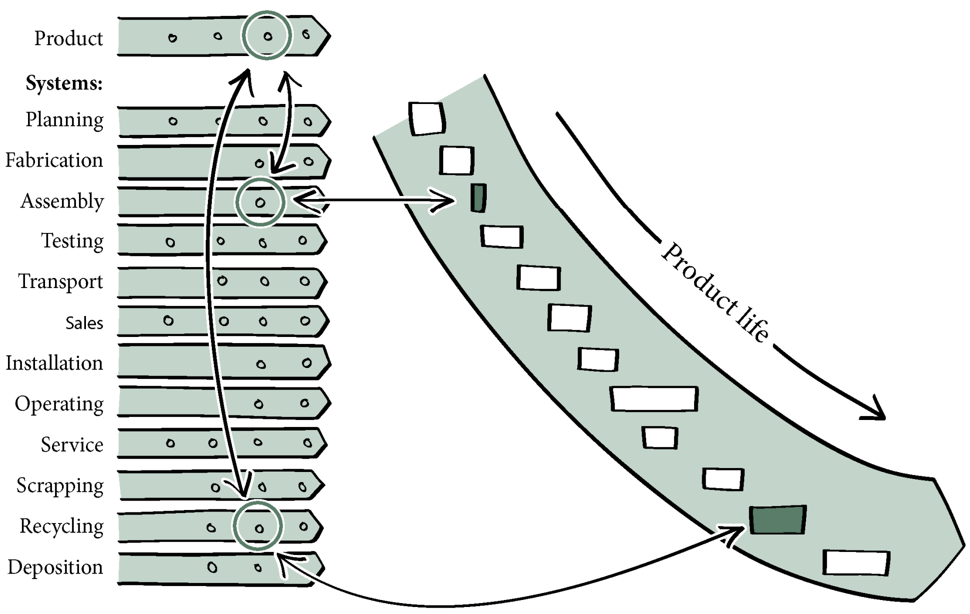


Figure 3.7: Decisions taken in the early phases of a product development process has effects throughout the whole life cycle of a product. The effects occur in the meetings between the product and a certain context and the relations are called dispositions.

The concept of meetings is essential in the Theory of Dispositions. It stresses that the effects of a design are relational effects, i.e. they take place when the product meets a certain context in one of the life phases. This idea of meetings is important to this thesis for a number of different reasons.

First of all, it stresses that the characteristics of a product platform must be aligned with a number of different life phases. The consequence is that the performance of a product platform has to be evaluated in relation to something – in relation to the use phase, the production phase or other important aspects. This is somewhat neglected in many references within the field of product platforms. There is a whole school of studies in the US in which commonality indices are calculated as indicators of the performance of a design [Thevenot and Simpson, 2004]. However, commonality should not be the goal of a design phase but a means to achieve an effect – and this effect only occurs in the meeting. A commonality index based only on the product itself does not tell the full story of the performance of a design.

Secondly, it builds on the fundamentals from the Theory of Technical Systems and the Theory of Domains, in which the constitutive built up of a design, generates effects in a meeting with operators. The Theory of Dispositions takes it one step further by not only focusing on the use phase (the intended transformations) but also all the other transformations and effects that takes place during the life phase of a product. The performance of a product platform often has to do with the production and specification/engineering/design/configuration phases. In order to evaluate a product platform one must take other things into account than just the *use* phase.

3.2.5 Genetic Design Model System

An elaboration of the above theories is found in the Genetic Design Model System (GDMS), proposed by Mortensen [2000]. It incorporates elements from the Theory of Technical Systems and the Theory of Domains, while also handling the idea of meetings in different life phases from the Theory of

Dispositions. The origin of GDMS is found in the chromosome model proposed by Ferreirinha and colleagues [1990], which again is based on the Theory of Domains.

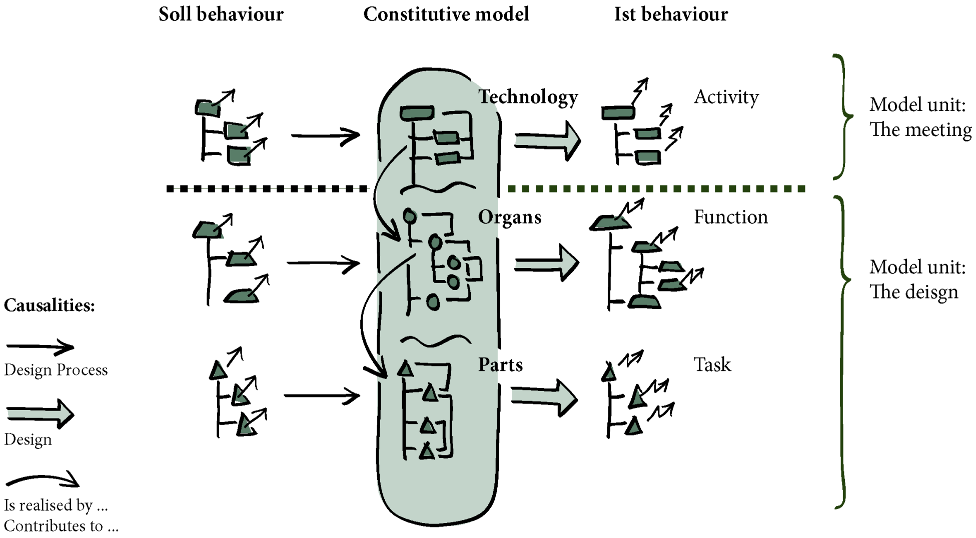


Figure 3.8: The GMDS provides a constitutive and behavioural description of a product model (Figure redrawn from Mortensen [2000]).

Constitutive and behavioural modelling

The model contains a constitutive and behavioural part, while at the same time mapping the transformation, organ and part domains from the Theory of Domains. The introduction of the term *task* adds to the functional/physical split in the domain theory. A task is the purposeful job done by a part in the part domain. The parts accommodate organs that again carry functions. The functions belong to the behaviour class, as seen in the figure. Behaviour is split in a before (*Soll*) and after (*Ist*) situation. Thereby functions are included as the behaviour of organs and not as a separate domain, as it was the case in the original Theory of Domains.

Another important split is the clear demarcation of modelling units, i.e. the *meeting* and the *design*. In the case of the transformation (i.e. the top level effect carrying out the activities of the product), the modelling unit is the *meeting*, as described in Olesen's Theory of Dispositions. Thus, the modelling unit is not the product itself but the effects that are created by the meeting between the product and a life phase system, and is somewhat product external. In the organ and part domains, the modelling focus is somewhat product internal.

This makes it feasible to talk about two kinds of attributes when describing the nature of a design. We have the constitutive/structural attributes, the *characteristics*, and the behavioural attributes, the *properties*, which is a basic part of systems theory and systems engineering disciplines [Klir & Valach, 1967], [Chestnut, 1967].

The following attribute classes are defined (see figure 3.9);

- ***Characteristics***
  The direct object of the design process. These are the only attributes, a designer can determine directly during design. Eskild Tjalve lists the characteristics (yet using the word basic property)

[Tjalve, 1979]; Structure, Form, Material, Dimension and Surface i.e surface quality. Hubka and Eder, [Hubka & Eder, 1988], add Tolerance and Manufacturing methods to these direct characteristics

- ***Inherent properties***
  Are the derivatives of the design and are determined by the characteristics and the environment.
- ***Relational properties***
  Relational properties are the related to the meetings between the product and its life phase systems.
- ***Qualities***
  Is a stakeholder's perception of an artefact (or product).

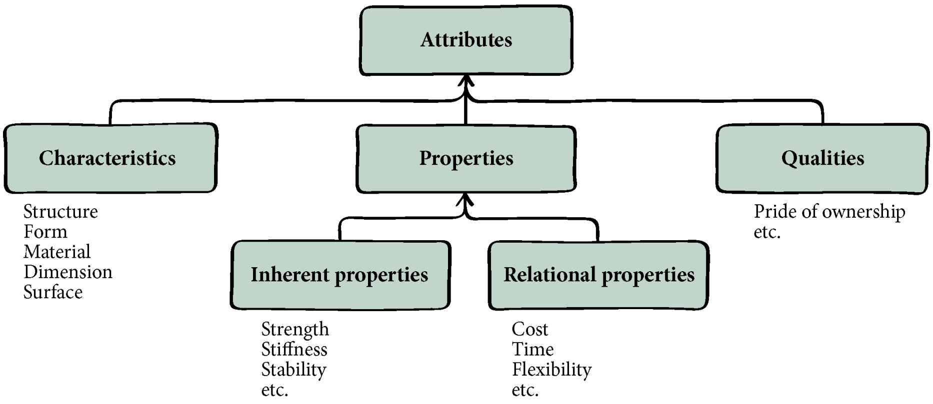


Figure 3.9: Different classes of attributes. (Redrawn from Miller [2001], based on Mortensen [2000].

The main point is that properties and characteristics are different, and that – in a product platform context – the *behaviour* of the product platform is considered to the effects arising in meetings. From the Theory of Dispositions, it is clear that these meetings are not only taking place in the use phase.

3.3 The design process

The origin of product platform development is that of general problem solving and single product development, even though product platform development is a very different task from the single product case. However, there are numerous similarities between these.

From a general point of view, the overall theories of product planning, product development and portfolio management all have aspects that fit the early preparation phases of a product platform development project. The later phases in which the technical details are elaborated, resemble that of an engineering design task more.

The following section will briefly discuss some general topics within design in a product platform context. The reason is that the research questions fit in a context of product platform development. Once again, it shall be emphasised that the research contribution does not lie within prescriptive design methods of product platforms.

3.3.1 Theory of Design Processes

There are some general patterns in most design processes. Most of these have the intension to establish an overview of the required functions of the product and then create solutions to these functions using general problem solving techniques. All of these different approaches have one general challenge in the fact that sub functions are not always known, if the means (solutions) on lower levels are not know either. Thereby the process of detailing the product is an iterative one moving back and forth between a functional viewpoint and that of the physical design.

Design process described by means of the Theory of Domains

The Theory of Domains also provides a framework for describing design processes [Andreasen, 1980], [Hansen & Andreasen, 2002], see figure 3.10;

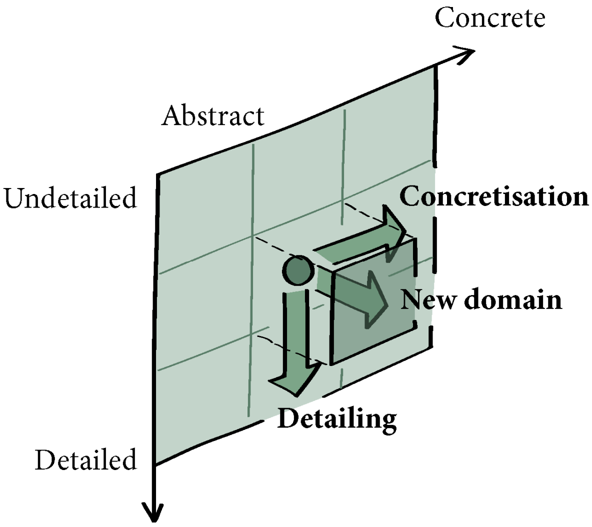


Figure 3.10: Product synthesis as a process of detailing and concretising the domains, while gradually specifying the parts domains, which in the end will provide the final design of the product. (Based on Andresen [1980], figure redrawn from Hansen & Andreasen, [2002]).

The transformation, organ and function domains are gradually detailed and made more concrete during the design task. When progressing through the design project, designers will 'jump' from the transformation domain, to the organ domain and then finally ending up specifying the part domain to the last detail in order for the manufacturing to be able to take place.

Product synthesis and design process theory

A very basic model, depicting these general steps, is shown in figure 3.11, [Tjalve, 1979]:

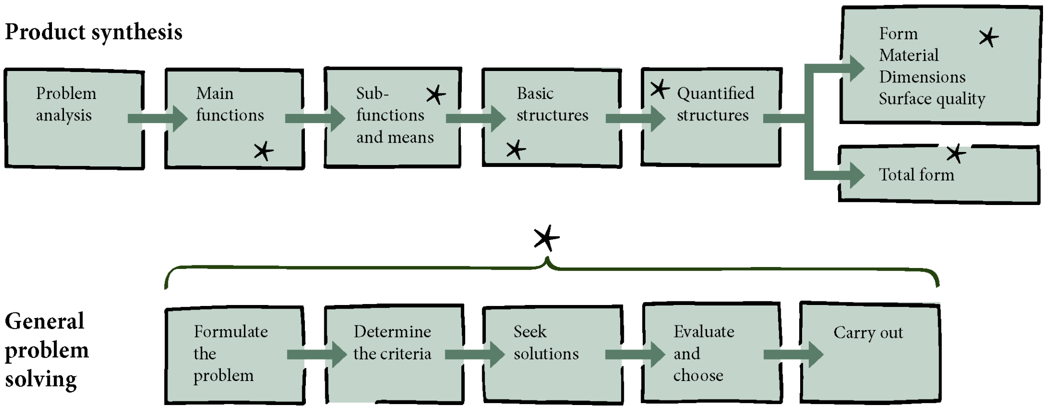


Figure 3.11: The Product Synthesis process, consists of a concretisation of the problem from the main functions, ranging to sub functions and their means (solutions), moving further in to the embodiment design, with the basic and quantified structures.

In the product synthesis model in figure 3.11, the structural considerations are split in two activities; the basic structures and the quantified structures. The basic structure is largely to be perceived as a structure of functional surfaces and elements, largely corresponding to the concept of organs and wirk elements. The characteristics are not established before the quantified structures are made – hence the name quantified, i.e. that the elements are placed in spatial relations to each other and the detailed design starts, when assigning the last two steps to the right in the model.

The following model (figure 3.12) depicts a more general flow in a design process based on the Theory of Technical Systems, and the Theory of Design Processes [Hubka & Eder, 1996]. Note that Tjalve's sequences of product synthesis generally correspond to the pattern found in the *Design Operations* and that the same thing applies for Tjalve's general problem solving, which is partly recognised in the *Basic Operations*, although slightly rephrased. Hubka and Eder then break it further down and add two more levels of *Elementary Activities* and *Elementary Operations*;

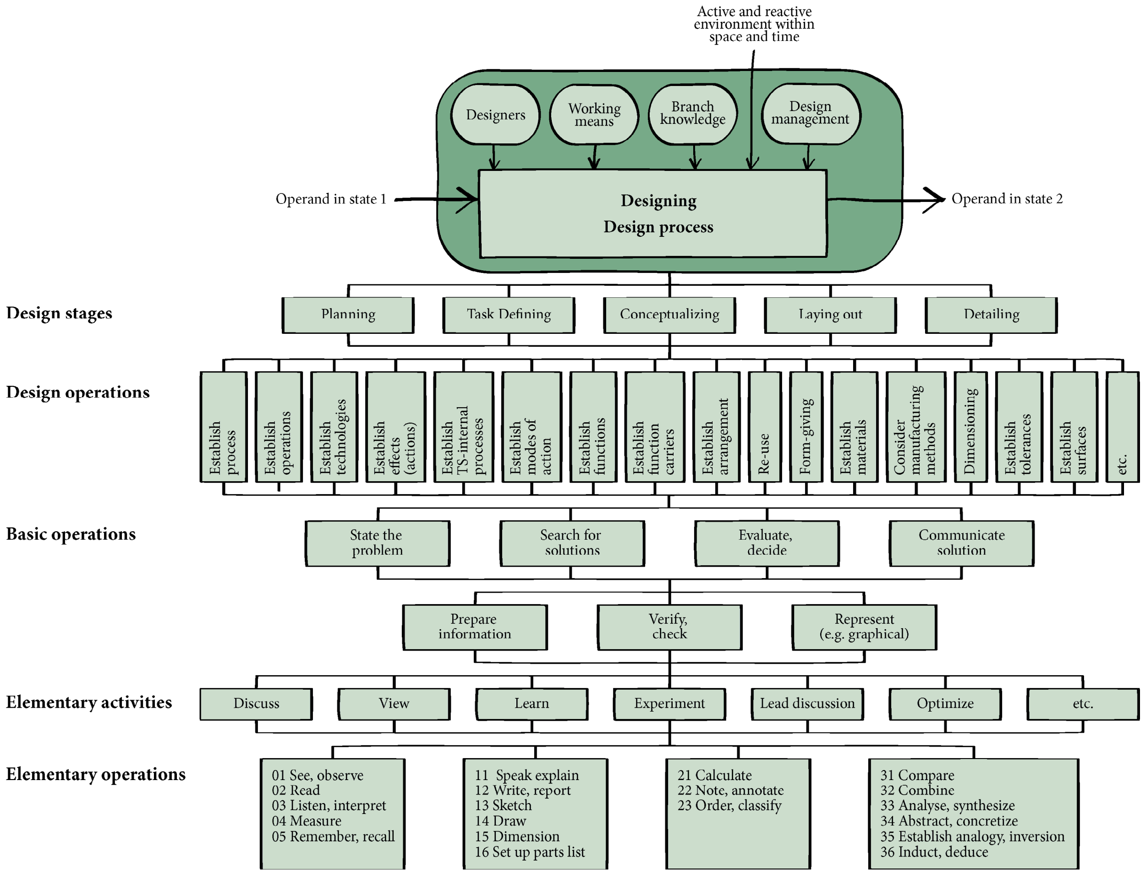


Figure 3.12: A general (and hierarchical) model of the design process, [Hubka & Eder, 1996]. Each step in a level contains the steps of the lower levels, forming a hierarchy of iterative activities.

Figure 3.12 depicts the iterative nature of the design process. Several arch types of activities are repeated during the process of adding resolution to the design specification.

General comments on the design process

There are many more models and methodologies describing the process of solving problems and making a physical design that satisfy a certain set of functions, examples are the design guidelines from VDI [VDI, 1987], general product design models [Pahl & Beitz, 1996], [Ulrich & Eppinger, 2000], [Otto & Wood, 2001], and the concept of axiomatic design [Suh, 1998]. From a general viewpoint however, the product synthesis model provided by Tjalve (figure 3.11), somewhat covers the most fundamental steps from all of these different models and concepts: the path from formulating the functions (on the basis of knowing the needs of the customer/user) to gradually detailing a structure, the elements in the structure and the interactions between elements in an iterative process using general problem solving.

3.3.2 Product planning and development

Engineering science has a product focus, that is, a focus on the embodiment and detailed design activities, sometimes taking the concept design into consideration as well. However, there are many more issues to address when bringing new products to the market place. Product Development in general is often understood as the more business oriented approach to gathering needs from the market place, planning the product portfolio, introducing new products in a certain sequence, designing the sales processes, together with the physical design of the products, the production processes, the distribution processes etc. The engineering design task is a subset of these activities. Again there is a multitude of models and concepts within product development, [Clark & Fujimoto, 1991], [Pahl & Beitz, 1996], [Andreasen & Hein, 2000], [Ulrich & Eppinger, 2000], [Otto & Wood, 2001], Wheelwright & Clark [1992, 1995, 2007], [Cooper, 2001] of which only the general patterns are discussed here.

The product planning and design framework [Pahl & Beitz, 1996];

The framework of Integrated Product Development [Andreasen & Hein, 1987], seeks to combine the efforts of the market, product and production design tasks in a planning scheme, and may serve as a general model, that raise the basic questions in most product development activities;

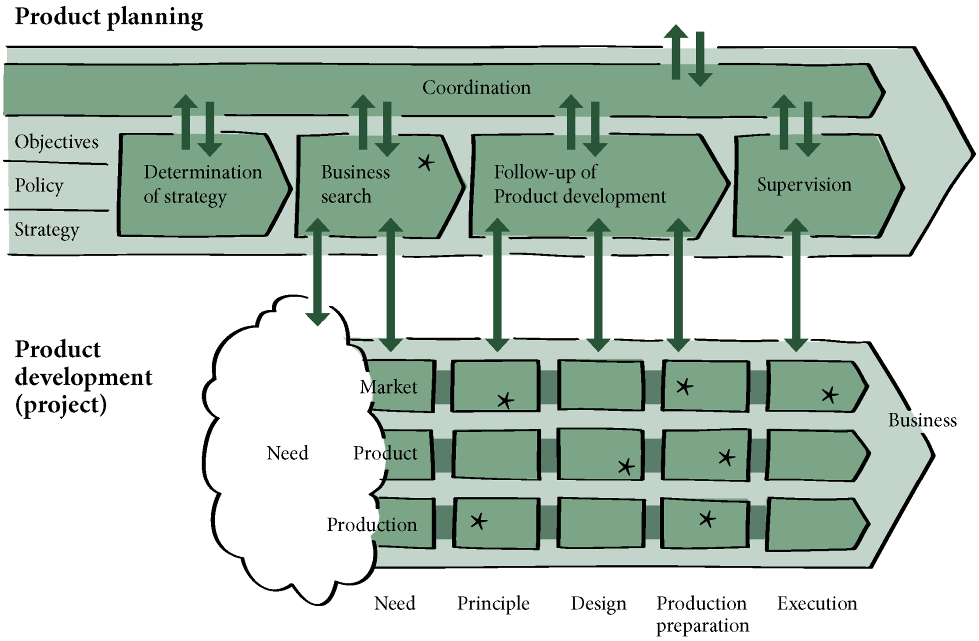


Figure 3.13: Integrated Product Development. The Market, Product and Production needs are accounted for in a concurrent approach, which is part of a high level product planning process. Each star represents the general problem solving model from Tjavle, [1979] see figure 3.11.

Figure 3.13: Depicts the Integrated Product Development scheme. The key issue – in relation to this research – is that the product development task is a subset of a product planning task that has to do with overall strategic decisions. Product development fits as the operational execution of the company's strategy. Recognising the *meeting* as an important driver for product success, also emphasise that products cannot be developed without a strong eye on the market, which will eventually receive the product, and the production system, which has to handle and produce the product.

3.4 Decision making in design

Decision making in engineering design is a complex task, and takes place on different levels and throughout the whole design process. Designers have to know their design degrees of freedom and their "handles" i.e. what opportunities they have to control the product design. They also have to know the derivative effects and dispositions of their designs. Often, the design is the easiest to have a clear picture of for the designers, while the dispositions can be harder to envision. That is a paradox because the effects of the meetings are actually the reasons for the product to be.

There is a whole lot written on decision making, and it constitutes a research field of its own, to fully cover this topic. Hansen & Andreasen [2004] provides a review of different decision making perceptions and strategies, and elaborate the work of Hansen & Andreasen [2000] and puts the *decision node* and the *decision map* into an engineering design context. These two topics are described on the following;

3.4.1 The decision node

The decision node is a model of a decision episode in a product development project [Hansen & Andreasen, 2004]. It is the generic basis of decision making throughout the design process in which numerous subsequent decision episodes take place. Figure 3.14 depicts a decision node;

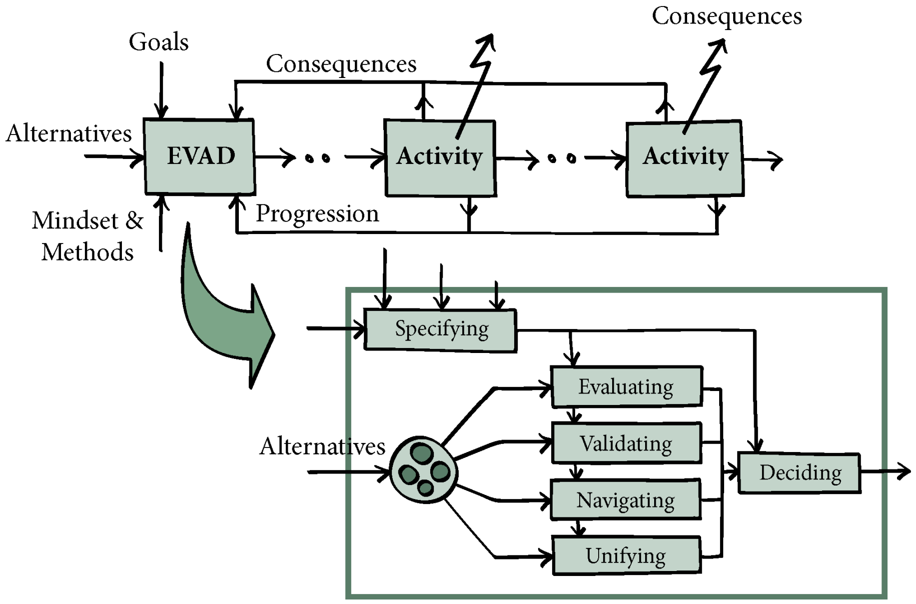


Figure 3.14: The decision node, EVAD. EVAD is an abbreviation for an EVAluation and Decision making activity.[Hansen & Andreasen, 2000].

The decision making activity consists of six sub-activities;

- ***To specify***
  ..i.e. to specify the object of the decision and the success criteria for the decision to be made
- ***To evaluate***
  …i.e. to evaluate the alternatives that have to be decided upon

- ***To validate***
  …i.e. to validate the alternatives in order to make a decision that will hold
- ***To navigate***
  …i.e. to through the solution/activity space
- ***To unify***
  …i.e. to unify the current decision into constituent context or whole
- ***To decide***
  …i.e. to make the final decision within the decision activity based on the above sub-activities.

The decision node is a generic activity, which is replicated many times during a design funnelling activity, in which a sketchy design problem becomes more concrete and detailed.

3.4.2 The decision map

The decision map is a model of the object of synthesis. Hansen & Andreasen [2000] provides a set of design objects:

- The product
- The life phase systems
- The meetings between the products and life phase systems
- The business
- The design process

The point is that designers, when making decisions, have to be aware that their design decisions have implications in these five dimensions.

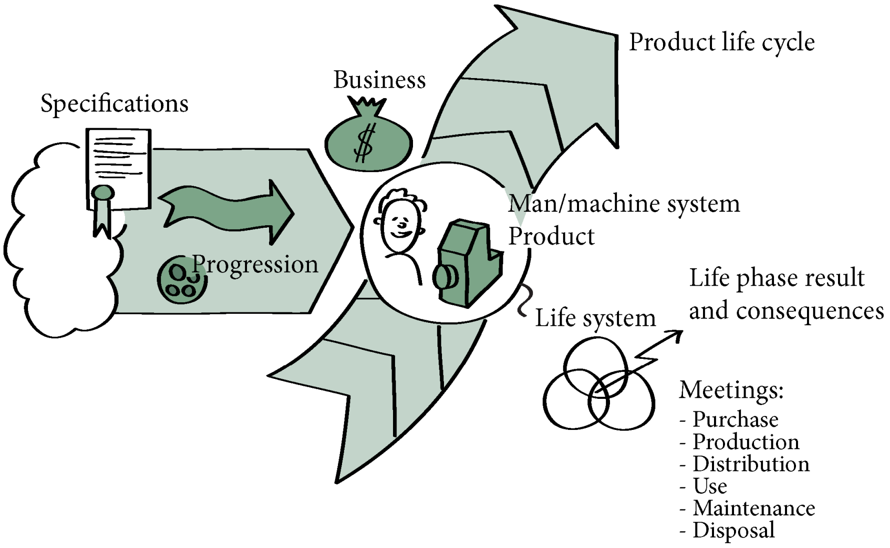


Figure 3.15: The decision map. Engineering design decisions have the potential to not only affect the product, but also the life phase systems, the meetings, the business and the design process itself, [Hansen & Andreasen, 2000].

3.4.3 Decision making for product platforms

The main point to bring forward from the work of Hansen & Andreasen [2004] is that engineering designers with a proper understanding of the design context makes better decisions. Having an understanding of the elements in the design node and the design map will enable designers to improve decision making.

It is assumed that the case is the same for product platforms, yet only more complicated. The fundamental difference is that the basis of several product variants is designed as a whole, making the dispositional effects and tradeoffs more complex to gain an overview of.

From a product design reuse point of view, one may anticipate that the five sub-activities of the generic decision node are the same for product platform development, only with the addition that the "product" is not a single instantiation, but also a reused part of the platform. The designers have to understand the meetings between the platform and the life phase systems, and thereby also understand what is actually reused.

3.5 Concluding on the theoretical basis

The viewpoint on this research comes from an engineering design and technical system perspective. The theoretical basis is a derivative of that viewpoint, and forms the fundamental assumptions and perceptions regarding the research aim and object, as well as the research approach.

The concepts of technical systems, domains, meetings and dispositions are regarded as important phenomena in explaining and elaborating on the subject of product platforms. Moreover, the 'classical' single product development scheme is perceived as an important starting point to explore the product platform development context in which the answers to the research questions have to fit.

The product platform as a topic is not included in this theoretical basis. The reason is that it is the object of the research and not as such regarded as a theoretical foundation upon which the viewpoint of the research can be based. Therefore product platforms and product platform development is the topic of the following chapter, in which various phenomena related to product platforms are discussed.

4

The Product Platform Phenomenon

This part of the thesis will explore different phenomena within the subject of product platforms and identify aspects that are relevant for a product platform model. The identification of aspects is based on current literature, commonly known cases and examples from industry, and partly on the basis of the three cases, which are elaborated in the following Part 5.

4.1 Introduction

The purpose of Part 4 is to provide answers to Research Question 1. This is done by means of a review of various works from the literature and industrial cases on the topics of *product platforms*, *product architectures* and *modularisation*.

For reading convenience, research Question 1 is repeated here;

> ***Research question 1***
>
> What phenomena are related to the encapsulation and reuse of *constitutive elements* in a product platform, the expectable *behavioural effects* arising from reuse and encapsulation, and the *activities* leading to reuse and encapsulation?

It is also stated in Part 2 that the three aspects in the research question are to be understood in the following way;

Different types of phenomena

- *Constitutive phenomena*
  The *what* question: This refers to the constituents of the platform, i.e. the question of what a platform ‘is made of’.
- *Behavioural phenomena*
  The *why* question: The behaviour refers to the behaviour of the platform in various meetings, that is, the effects of the platform.
- *Activity phenomena*
  The *how* question: How do we manipulate the platform in order to get the effects?

In Research Question 1, *reuse* and *encapsulation* of platform elements are assumed to be fundamental aspect of product platforms. In the introduction it is further added that the reuse and encapsulation has to be deliberate and carefully planned. In the following two chapters first encapsulation and then reuse & sharing are explained, and it is argued why the words and concepts are highlighted in the research questions.

4.1.1 The structure of Part 4

In the conclusion on the research setup in Part 2, the following figure is given to illustrate the elements of a decision base, as it is given in the research questions (originally figure 2.10);

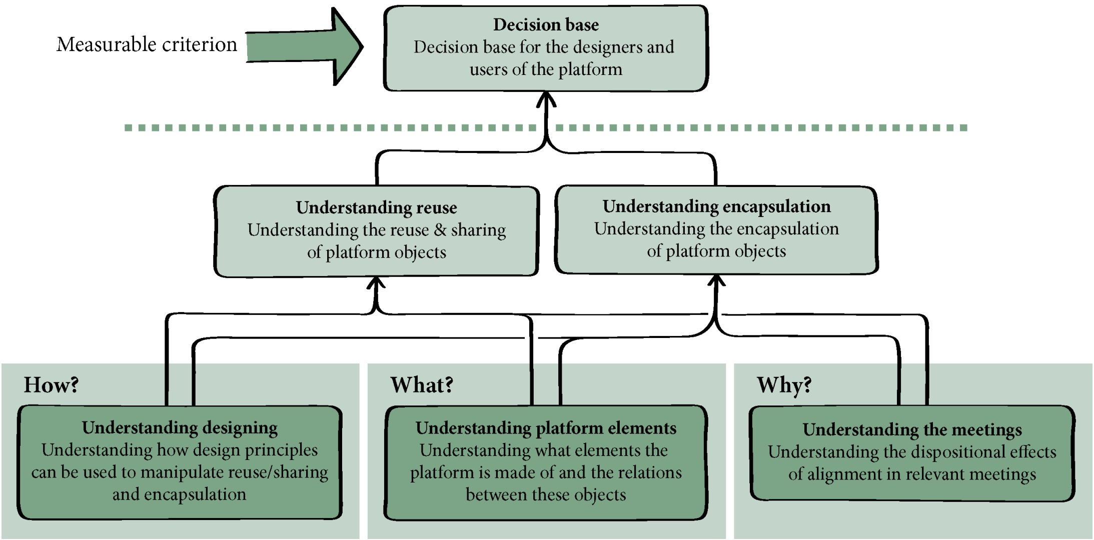


Figure 4.1 (same as 2.10): The research criteria are formulated on the assumption that know-how, know-why and know-what on the aspects of reuse and encapsulation are fundamental prerequisites for a decision base in a product platform context. The know-how, know-what, and know-why corresponds to the phenomena related to activities, constitutive elements, and behavioural effects.

Basically, the following chapters go in to the five boxes below the dotted line in figure 4.1. The aspects are used as a disposition for the following chapters.

- *Chapter 4.2: Short introduction to platforms*
  In order to understand the review of various aspects, this first chapter will provide an ultra brief overview of the topic of product platforms in order for the reader to better follow the argumentation in the rest of Part 4.
- *Chapter 4.3: Encapsulation*
  Encapsulation is a fundamental aspect of virtually any product platform perception. Encapsulation is discussed from a general perspective.
- *Chapter 4.4: Reuse*
  Carefully planned reuse (and synonymous sharing) across a product family or across product generations is an aspect that make a platform approach different from single product development and tailor-made product development. Reuse is often the reason to perceive a group of products as a product family.

Then the constitutive, behavioural and procedural phenomena are discussed in the following three chapters. Reuse and encapsulation are aspects in all three dimensions, and will thus be exemplified during the chapters;

- *Chapter 4.5: Constitutive platform phenomena*
  The chapter discusses various perceptions of what a platform is, and a discussion of encapsulation of various platform elements is provided. In this discussion the concept of encapsulation in the organ and part domains are discussed. The topic of product architectures is also dealt with in the chapter.
- *Chapter 4.6: Behavioural phenomena – the effects*
  The chapter discuss various perceptions of why platforms are pursued, i.e. the effects. This is mainly based on a review, and is the results of other researchers. The concept of postponement is stressed as a specific and important effect of encapsulation and reuse.
- *Chapter 4.7: Activity phenomena*
  The chapter discuss various perceptions of how a platform is designed and what changes
- *Chapter 4.8: Phenomenological framework*
  The exploration of the research question is given in chapters 4.6, 4.6, and 4.7. On the basis of these chapters, a pattern is recognised and a framework for identifying product platform phenomena is proposed. The framework is used in Part 5 to compare the three cases (see chapter Part 5, chapter 5.9).
- *Chapter 4.9: Concluding on Part 4*

  Some general conclusions from the findings in Part 4 are discussed and summarised.

4.2 Short introduction to platforms

Despite the various perceptions of platforms, which is presented in the following, a few general notes is provided here as a brief introduction, in order for the reader to hopefully better follow the flow in the following chapters. Some of these points are also raised in the beginning of the thesis in Part 1.

A product platform is an instrument a company can choose to use in order to gain certain benefits. Often a product platform involves some kind of physical and tangible products. In such cases companies have developed a product concept enabling different parts of the products to be reused in various product variants for a variety of different reasons. A key challenge is to be able to reuse without limiting the available choices of the customers, and in some cases a platform concept may even enlarge the possibilities for customers to choose from, despite the reuse within the company. Typical main drivers for trying to reuse, is to gain a more efficient utilisation of resources such as material, equipment, and manpower, and also to speed up the internal processes and thereby get faster response to market needs. However, there are many more potential benefits, and they will be discussed in various contexts throughout the thesis.

There are many different platforms reported in literature and from various industrial cases, and therefore the term *product platform* - or simply *platform* – is used interchangeably in various references and not always to denote reuse of product parts. The concept of product platforms is widened in some references to include *process* platforms [Sanchez & Collins], *service* platforms, [Sanchez & Collins, 1999], *knowledge* platforms [Sanchez, 2000], platforms with *activities* [Miller, 2001], and so on. These different concepts all have in common the fact that *reuse and encapsulation* of parts, components, processes, activities, knowledge or other assets are essential. However, the physical products are often a central core among these assets.

These above terms mainly refer to the elements in the platform, i.e. what the platform is made of. Terms like *modular* or *integral*, [Ulrich & Eppinger, 2000], *parametric* or *configurational* [Farrel & Simpson, 2003] are also used on platforms, depending on the way they are built.

This thesis has a starting point in engineering design and product development, and the following review will therefore look at the more product related aspects, i.e. perceiving the core of a platform as a (mainly) physical product embodied in a mechanical design. It has also previously been stated that products work and interact in meetings with life phase systems (Part 1, chapter 1.2.4, Part 3, chapter 3.2.4). The consequence of the presence of meetings is that the life phase systems have to be taken into account when perceiving a product platform.

Kristjansson et al., [2004], have provided a basic perception of platforms that generally cover most of the various perceptions in literature. They perceive a platform like this;

"...a collection of core assets that are reused to achieve a competitive advantage".

This basic perception is a good starting point to have in mind when reading through the remainder of Part 4.

4.3 Encapsulation

This section will elaborate on the statement that encapsulation is a fundamental characteristic of platforms, and explain how encapsulation is to be perceived.

4.3.1 Encapsulation from a systems perspective

The Systems Engineering disciplines provide useful viewpoints on technical systems [Sage & Armstrong, 2000], [Hitchins, 2003], [Chestnut, 1967]. From many perspectives, Systems Engineering is a paradigm close to the paradigm constituted by the Engineering Design Science tradition. From a research perspective this thesis builds its phenomenological understanding on the Theory of Technical Systems and the Theory of Domains. However, two useful concepts are taken from Systems Engineering. These are the concepts of *encapsulation* and *elaboration*, [Hitchins, 2003]. Some engineering design science references use the concept of encapsulation in product platform context, [Andreasen et al, 2004], [Riitahuhta & Andreasen, 1998b]. Figure 4.2 depicts an example of encapsulation versus elaboration;

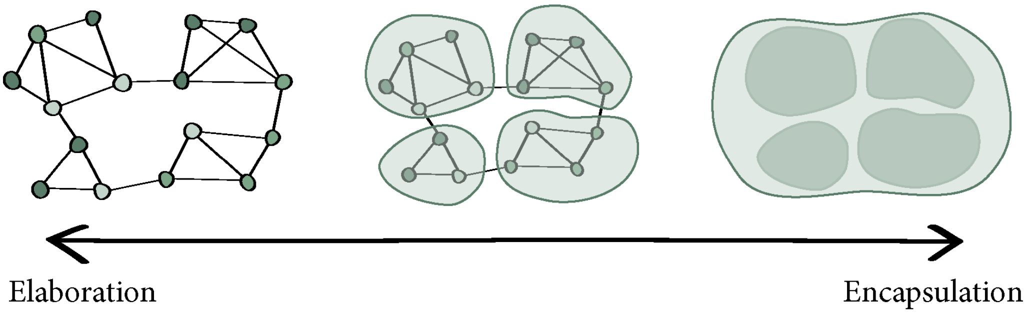


Figure 4.2: Encapsulation and elaboration are different ways of altering the perception of a system. Moving from left to right is encapsulation in which details are concealed in larger design chunks. Elaboration is the opposite process. (Figure redrawn from Hitchings [2003]).

Encapsulation and elaboration are processes in which the viewpoint on a system is changing. A very simple way to distinguish the two processes is that encapsulation seeks to create a broader resolution of the design, i.e. to encapsulate design details into larger chunks. Elaboration is the opposite, in which a finer resolution makes way for a more detailed level of description.

Technical systems are made of numerous elements in a hierarchy. This hierarchical relation is often perceived as a recursive relation [Mortensen, 2000]. Depending on the viewpoint on a system, the system may appear more or less detailed. If system elements are grouped together, they can be perceived as a single element in a certain level of resolution.

One can see encapsulation and elaboration as different ways of describing the same underlying system structure. Encapsulation can also be seen as a process in which a system is changed from a relatively elaborated layout towards a more encapsulated layout, i.e. not just changing the viewpoint but actually changing the system.

Encapsulation is about grouping and decoupling

In their seminal book "Design Rules - The Power of Modularity", which is one of the most cited within the literature of product platforms, Baldwin and Clark provide the following description of the basic break down of a system – another way to express the process of encapsulation, [Baldwin & Clark, 2000, p. 64];

"A complex system can be managed by dividing it up into smaller pieces and looking at each one separately. When the complexity of one of the elements crosses a certain threshold, that complexity can be isolated by defining a separate abstraction *that has a simple* interface. *The abstraction* hides *the complexity of the elements; the* interface *indicates how the element interacts with the larger system".*

From this quote, and from a general observation of the principals laid out in figure 4.2, encapsulation is – *in this thesis* - considered to consist of the two different processes of *grouping* and *decoupling*, and it is noteworthy to keep them apart.

1. *Grouping*
   Grouping is the process of deciding which elements that fit together as a unit. The grouping can be done from several viewpoints, in order to achieve several different effects, and the subject of the grouping (i.e. the elements which are grouped) may be different as well. These different elements are discussed in Chapter 4.5.

2. *Decoupling*
   Decoupling is the process of finding means to decouple the groups from each other. Depending on the nature of the grouped elements, the means can be different. In the case of parts, the decoupling is often taking place by means of a physical interface, i.e. a certain design solution. If an activity or production step is grouped, the decoupling is of another kind.

Following the argumentation in the quote from Baldwin & Clark, grouping resembles the process of choosing which elements to divide, while decoupling is about how to divide them, i.e. establishing useful interfaces.

Grouping and decoupling are further discussed in the following two chapters.

4.3.2 Grouping

Grouping is a strategic discipline. Grouping is essentially the decision on what elements, attributes and characteristics to separate. In the three cases in Part 5, grouping is an important part of the decision making during the projects.

Grouping is governed by the desired effects, and the grouping will depend on the drivers for the platform approach, i.e. whether product customization, upgrading, or outsourcing etc. is the main reason for the grouping to take place. Consequently grouping has a strong relation to the strategic reasons behind a platform. Grouping is the task of deciding which characteristics to group and which characteristics to separate.

Deciding on the reusable and variable proportions of the product often has strong ties to the product design and production capabilities, because they largely determine which attributes are easy to decouple, which again has an impact on the grouping.

4.3.3 Decoupling

Returning once more to Baldwin and Clark, a strong description of decoupling is provided, in their perception of a module, [Baldwin & Clark, 2000, pp. 63];

"A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. Clearly there are degrees of connectivity, thus there are gradients of modularity".

If structure is not taken too much for granted as a physical coherence but rather as a set of relations, this perception may serve as a rather fundamental description of decoupling in a product platform context. Decoupling has to do with designing the system so that elements are related to each other in a certain pattern, in order ensure, for example, that reusable and variable attributes are relatively independent of one another. The term module, however, is not used as such in this thesis due to the reasons pointed out earlier.

Another point about decoupling is raised by Ron Sanchez who gives the following comment on different types of decoupling;

"Note that tight or loose coupling of components in a product design is different from tight or loose coupling in an actual (usually) physical product. A personal computer design, for example, may have loosely coupled components in that different microprocessors or hard disk drives may be substituted into the computer design without requiring a redesign of the other components. Nevertheless, the components in the physical computer will be tightly coupled in the sense that all components must function properly for the computer to function as a system." [Sanchez & Mahoney,1996, note 3 on page 61]

The point here is that decoupling has to do not only with physical detachment but also with the functional layout. Keeping the Theory of Domains in mind, the point of Sanchez & Mahoney is that decoupling in one domain may occur without decoupling in another domain.

Decoupling in several domains and the mapping between domains is a topic of extensive research, mostly within the concept of product architectures. See chapter 4.5.2 for an extensive discussion on mappings of various domains.

Potential benefits from decoupling in for example activities, may be [Miller, 2001];

- improved performance
- independency in work elements
- parallel, distributed work
- reduction of work complexity

Decoupling is a fundamental activity of virtually any platform approach.

4.3.4 Why emphasise encapsulation?

Some readers might argue that the concept of encapsulation is very close to the concept of modularisation. However, there are two reasons to use the word encapsulation instead of modularisation in this thesis;

1. Some of the most widely cited definitions of modularity have to do with grouping and decoupling of physical elements, i.e. what is often called *modular products*. Thus, modularisation often implies that modules are perceived as physical sub assemblies and that physical interfaces are used as a means to obtain decoupling. One of the aims of Research Question 1 is to highlight that this is not always the case, and that there are in fact other ways to achieve reuse benefits.
2. There are many different understandings and definitions of modularisation, thus the word is difficult to use in a *fundamental* description of various phenomena. Encapsulation however, covers a more fundamental systems understanding.

Encapsulation as a generic concept

Encapsulation also seems to be useful as a generic term in describing several different kinds of platforms. A few general examples of platform types and the related encapsulation are given here;

1. The classical modular product platform is often a concept in which modules make up a system, from which various product variants can be built [Erixon, 1998]. The modules are grouped mainly in a variable and reused proportion, and in order to be able to change the varying parts without changing the rest of the product, the elements are decoupled.
2. Encapsulation will fit other platform concepts, such as the perception of a knowledge platform as *a set of decoupled knowledge elements* [Sanchez, 2000].
3. Within management science, the subdivision of tasks is reported to be beneficial [von Hippel, 1990]. Subdivision of tasks again imply *grouping*, and if the tasks are to be done interdependently of one another, they have to be somewhat *decoupled*. Consequently, *activity platforms* [Miller, 2001], [Andreasen et. al, 2004] are also characterised by decoupling and grouping.

Therefore, encapsulation is considered to be a generic characteristic in a wide range of platform cases.

4.4 Reuse

From a very fundamental viewpoint, reuse (and sharing) is the main drivers for encapsulation and thereby for a platform approach. Most product ranges have some kind of sharing or reuse between product variants, between production lines, in activities and so on. The conscious strive towards certain strategic effects through reuse is what makes a platform approach different from a more traditional setup. The reason for reusing is basically to use resources in a more effective way, and thereby gain a variety of different effects, such as reduced lead time, reduced cost and a higher focus on value adding activities in product development, to name a few. Regardless of these different effects, reuse is the fundamental characteristic driver, and as such a fundamental means in all known platform cases reported in literature.

There are all sorts of reuse types reported, such as reuse and sharing of components, [Nobeoka & Cusumao, 1998], of knowledge [Sanchez, 2000], of design concepts [Harlou, 2006], of parametric designs, i.e. sets of parameters, [Claesson, 2006], etc. These are accounted for in a more elaborate way in the following chapters.

4.5 Constitutive platform phenomena

This chapter is a review of various platform perceptions, and as such a current state of knowledge within the field of what a platform *is*, what a platform *consists of*, i.e. what the *elements* in a platform are.

The chapter consist of several sections;

- *Chapter 4.5.1 Platform perceptions*
  The first section will present a general review of the field, using statements and perceptions from various authors. This is done to present various different perceptions of platforms, and to give a first overview of the wide area – and some of the phenomena related to the subject.
- *Chapter 4.5.2 The Product Architecture*
  The concept of a product architecture is discussed, because it is an important aspect in many references in literature. Product architectures are mainly regarded as either a characteristics of products/product families/platforms or as a model. The various perceptions are discussed, and in particular the concept of domain mapping as an important part of product architectures.
- *Chapter 4.5.3 Modularity and encapsulation*
  The role of encapsulation is discussed relative to the concept of modularity. Modular and integral architectures are linked to process and assembly flexibility and the role of organs and wirk elements in encapsulation is discussed. This chapter holds some of the most important discussions on phenomena related to reuse and encapsulation and is therefore specifically important for the answer to Research Question 1.
- *Chapter 4.5.4.Organs and wirk elements as platform elements*
  Organs and wirk elements are further discussed, and it is stated that organs and wirk elements can be regarded as constitutive platform elements, i.e. that they are subject to reuse and encapsulation in a platform.
- *Chapter 4.5.5 Interfaces*
  The role of interfaces in a product platform context is discussed. Various constitutive and product related interface classes are discussed, and finally interfaces between activities are shortly mentioned. Interfaces are often reported as a means to achieve decoupling, and interfaces are specifically important for encapsulation in the part domain.

- *Chapter 4.5.6 Concluding on the constitutive phenomena*
  Finally, a conclusion of chapter 4.5 is provided.

4.5.1 Platform perceptions

The topic of product platforms is used in many different industries, for a variety of different purposes. Research within the field is carried out by various researchers from both a technical/engineering background and a managerial background. This could be one of the reasons why there are so many different perceptions of the concept. However, there are a few common phenomena, of which encapsulation and reuse & sharing have already been emphasised.

The platform elements

The term *platform element* will be used in the following, and is therefore explained here. Generally, the term is used in this thesis to denote what the platform consists of. The term *element* is used in this thesis to avoid implying preconceptions about the nature of the elements, i.e. whether the elements are tangible, physical subassemblies or components or more intangible objects like procedures, technology or other non physical aspects.

Asset is another term used in literature about the reusable constituents of a platform, however asset is a biased word in the sense that asset imply a benefit or advantage.

The word "platform elements"

The *platform elements* are the constituents of the platform. It is the elements that are reused and encapsulated to some degree in order to gain effects in various life phases.

This is not a definition, only an explanation to the use of the term *platform element* in the following. In other words, the platform elements are the objects of the design activities during a product platform development project. The platform elements are the elements that are subject to decision making, and thereby an essential aspect in relation to the two research questions.

Product platforms

The word platform is very often preceded be the word product, thereby forming the phrase *product platform*, and somehow implying that a physical, tangible product of some kind is involved - sometimes more intangible products like software and services are also part of the product perception. There are several definitions of product platforms, and a lot of them have something to with sharing of components, elements and technology;

"A product platform is a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced" [Meyer & Lehnerd, 1997].

This rather famous quote – which has become a seminal classic within literature- is taken from Meyer & Lehnerd's book "The Power of Product Platforms". It has served as a basis for many succeeding pieces of work. Despite the rather strict focus on subsystems, Meyer & Lehnerd also notice the importance of product planning and the strategic implications of a platform. But the perception of the concept is that of a set of *subsystems* and *interfaces.*

Meyer and Lehnerd's perception has been added with *intention* and *planning*, which is in fact in many perspectives, what makes a platform different from product development – the intention and the carefully planning;

"A product platform is a set of subsystems and interfaces intentionally planned and developed to form a common structure from which a stream of derivative products can be efficiently developed and produced." [Muffatto, 2002].

The intention reflects the desired effects, and as it has been discussed several times in the introduction in Part 1, and again in the introduction to Part 4, encapsulation comes with an intention, i.e. a desired effect somewhere in the life phases of the platform. Thereby, Muffatto's addition is rather important, and not just a matter of words.

Some suggest that parameters and features are within the perception of a product platform, thereby breaking it down to a lower level of decomposition than a subassembly level.

"The set of common parameters, features, or components that remain constant from product to product within a given product family is referred to as the product platform", [Farrel & Simpson, 2003].

Some include *technology,* as a shared element in the platform;

A product platform is a " ...collection of the common elements, especially the underlying core technology, implemented across a range of products" [Jiao & Tseng, 1998].

The platform elements in all of the above perceptions and definitions of product platforms have a rather product and technology centred focus. There are more perceptions, some of which are rather industry specific, and again many of which originates in the automotive industry. They include the under-body of a car or very specific components such as drive unit, parts of a cockpit, axles, suspension, and fuel tank into the definition of a product platform, [Muffatto & Roveda, 2000]. Muffatto and Roveda argue that such descriptions are too narrow.

Broader product platforms

The perspective of a product platform can be broadened to incorporate more than just "bits and pieces";

"..the product platform is described as the collection of assets that are shared by a set of products. These assets can be divided into four categories: Components, Processes, Knowledge, and People and relationships. Taken together, these shared assets constitute the product platform." [Robertson & Ulrich, 1998].

Based on a review of various platform definitions, Kristjansson et al, [2004], use Robertson & Ulrichs definition to propose a generally applicable perception of a platform:

They see a platform as "*a collection of core assets that are reused to achieve a competitive advantage*".

..and adopt then assets from Robertson & Ulrich [1998], namely that of *components*, *processes*, *knowledge* and *people & relationships*.

In their perception of a platform, Kristjansson and colleagues include the following elaboration of the core assets;

- *Components*, include functions, CAD tools, circuit designs, and software.
- *Processes* include the equipment used to make components into products, assembly system, and the design of the associated supply chain, and material
- *Knowledge* includes and the design know-how, material know-how, technology applications and limitations, production techniques, mathematical models, and testing methods.

- *People & relationships* include teams, relationships within and across teams in the organisation, alliances in- and outside of the company and relations to suppliers.

A similar perception is proposed by Miller [2001] and Andreasen et al. [2004], in a perception of the foundation for a product family, consisting of *activities* (i.e. processes), *products* (i.e. components), and *knowledge*. A case from Phillips Consumer Electronics, [Niewland, 1999], reports the use of a platform definition comprising three aligned architectural constructs within *Hardware, Knowledge and Activities.*

Following that line of argumentation, Andreasen [2003] further describes a platform like this;

"A platform is a means for rationalisation of the product development and product realisation seen in relation to the business process, based upon a smart, fitted interrelation between products, knowledge and activities".

An equivalent to Robertson & Ulrich's *"People & Relationships"* is not found in these three latter perceptions of product platforms. However;

Different classes of platform elements

The aspects of *products*, *activities* and *knowledge* seem to reflect three fundamentally different classes of platform elements, all of which a platform may consist of.

Sanchez [2000], talks about *loosely coupled knowledge domains*, as a part of the platform, i.e. to decouple knowledge, and document knowledge in order to be able to reuse and share it.

Other broader perceptions include the *core capabilities* of the company as the *foundation for* – not the definition of - the platform [Meyer & Utterback, 1993].

The platform as a planning and business instrument

Some perceptions of platforms include descriptive elements, in the sense that the platform is a planning tool or a model, rather than just physical or technical *things*;

"A product platform in a firm has a twofold meaning, i.e., to represent the entire product portfolio, including both existing products and proactively anticipated ones, by characterising various perceived customer needs, and to incorporate proven designs, materials and process technologies" [Tseng, et al., 2003].

"A platform can be seen from a strategic, an organizational, and a technical perspective", [Muffatto, 1999].

"A product platform is not a product but a planning construct"..."platforms must be a business concept and not solely an engineering concept", [Yang & Jiang, 2006]

Sawhney [1998], being from a marketing science background, denotes a platform as the *shared logic* underlying a product family, that is, logic by *common design*, *manufacturing processes*, *brand strategies*, *distribution* and *promotion* methods. He also bring about the concept of platform thinking (as opposed to portfolio thinking) as; "*the process of identifying and exploiting the shared logic and structure in a firm's activities and offerings to achieve leveraged growth and variety*". Thereby also including activities and the planning of these, that perception of a platform is somewhat broader than the strict product/process focus of some of earlier of the listed definitions.

Some authors emphasise the planning challenges *across company borders* and emphasise that a platform approach may lead to new types of competition and opportunities in a business. They deem *modular* and *architectural* business opportunities as two different approaches a company may choose [Baldwin & Clark, 1997]. The point is that a company can either;

1. try to set an *architectural* standard (i.e. rules on designs and interfaces) and then encourage sub suppliers to supply within the design rules.
2. ..or excel in delivering modules that fit within the architecture of another company.

The computer industry is an often used example of such an industry wide architecture in which several standards flourish among various vendors and suppliers. Many of those trends started in the 1960'ies on the basis of the systems developments from IBM in the US. These architectural rules later propagated out in the business and became worldwide standards of design. The automotive industry is another example. In fact, an interesting difference in that type of competition is that of the European/US approach versus of the Japanese car industry. In Japan, automotive companies make rather loose specifications of the subsystems they get from vendors, and then let them compete about the best solution, whereas the "Western" automakers tend to give much more rigid specifications, thereby loosing the opportunity to exploit the competencies and creativity of vendors who may even have a better domain knowledge on the sub system they provide. Some of these principles are known as set based concurrent engineering, [Kennedy, 2003].

Other initiatives extend beyond the borders of the company. Reusing *order* and *lot sizes* is another opportunity for companies to excel in encapsulation [Bartezzaghi & Verganti, 1995], in the sense that orders are grouped and decoupled in the order flow and then reused.

Service platforms

Meyer & de Tore list five principles for evolving "Platform Thinking" into an extended enterprise context, also including services in their perception of products;

"First principle: the conventional definition of product platforms is that they are common architectures spanning multiple products that are implemented with common subsystems and subsystem interfaces.

Second principle:"*… the more effective approach, is to view the major subsystem and the interfaces between subsystems as the product platforms. This may be referred to as a non monolithic or modular approach to platform development, our second principle of platform thinking."*

Third principle:"*platforms extend beyond technology to both markets and business models."*

Fourth principle "*...common product architecture, subsystems, and interfaces all have within them deeper insights, technologies, and processes that are the crown jewels of the corporation."*

Fifth principle "*…this approach to product architecture and components, like any other, has important implications for the organization of the enterprise."*

Joseph Pine, [Pine, 1993b], incorporates services into the perception of mass customization and talks about "point-of-deliver-customization", in which the process of specifying the final product (service) is delayed as much as possible, following the principles of postponement (see chapter 4.6.2 for a discussion on postponement).

Platforms as models or descriptions

It is not always absolute clear when authors perceive a platform as a model or as a tangible, physical part of the business. Some note that the *design* – i.e. the rules documenting the concepts within the platform – is an equal part of the platform as well as the components [Meyer & Utterback, 1993].

Some definitions of platforms include *norms* and *standards*, i.e. the design rules with which subsystems interact and are built, *constraints*, while respecting that these rules may change over time, [Corso et al., 1996].

Erens [1996] describes a product platform as an *architectural* concept comprising interface definitions and key-components, addressing a market and being a base for deriving different product families.

Some references define how *modular product architectures* serve as efficient "platforms" for leveraging families of products to meet market demands for product variety more quickly and efficiently [Sanchez et al., 1999]. The concept of architectures is often tied together with product platforms.

The above perceptions rest on the concept of some sort of description or model, often using the term *product architecture*. This concept is further discussed in chapter 4.5.2.

Brand platforms

In a discussion on brand platforms, denote the platform as "*a set of shared functionality across multiple products*", i.e. they do not imply physical sharing. They add to the perception the possibility to share functions across multiple brands [Sudjianto & Otto, 2001].

The work of Claesson [2006] also points out the importance of platforms that cross brand borders and give examples from SAAB and GM.

Platforms as an organisational change

Some references note that platform initiatives call for several changes in companies [Simpson et al., 2006c], and raise it to an enterprise wide initiative, and points out that it is not just a planning or product development initiative;

- A corporate culture change in the sense that people and working patterns change and the organisations have to change the way functional and business units are separated in order to ensure sharing and reuse of knowledge across departmental and organisational borders.
- Upper management has to stand by the change process.
- The product development organisation itself has to be cross-functional.
- The platform has to be documented in order to be shared
- Understanding the market and forecasting for trimming and maintaining the product portfolio and thereby the underlying platform
- Platform planning as a corporate strategy: The argument again being that the platform has an impact not only as a product development construct but also in various other life phases and thereby functional areas. Therefore planning the product platform becomes the task of planning the purchasing, fabrication, assembly, distribution etc.

The concept of cross-functional teams corresponds very well with the viewpoint of platform effects in the *meetings* between platforms and different life phases. Cross-functional teams bring together people in various positions representing different life phases, such as manufacturing or distribution.

4.5.2 The product architecture

Several of the above platform perceptions include an understanding of *architectural* definitions or *product architecture* in various ways. The *product architecture* is a concept, which is often reported in relation to product platforms.

The architecture is perceived as both a model and a characteristic

The most frequent interpretations of the term are; a *product characteristic* (such as structure), a *product family characteristic*, a *product model* or a *product family and/or platform model.* The word *architecture* (apart from its apparent use in the construction industry) usually refers to the layout of a system, i.e. a holistic description or perception of the position and interactions of elements within a system. In the US, *product architecture* often refers to the built-up of a single product and the majority of the European design community would probably use the term *product structure* instead. This little detail is sometimes important to bear in mind when comparing the different references within the field.

The following two quotes are both examples of architectures on various levels, as well as examples of two fundamental perceptions of architectures, as either a characteristic or a description of a product of product family;

"The combination of subsystems and interfaces defines the architecture of any single product. Every product has an architecture; the goal is to make that architecture common across many products. Any single product's architecture therefore has the potential to become a product platform architecture if it is designed and then used as the basis for creating several more derivative products." [Meyer et al., 1997].

Note that this perception of an architecture is that of a *characteristic* of a product (or family), and it is close to the *structure* of a product.

"An architecture is a structural description of a product assortment, a product family or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces with the surroundings", [Harlou, 2006].

Note that this perception of an architecture is that of a *description* of a product (or family).

Some of the definitions of product architectures in the following can even be perceived in both ways, in the sense that they contain mapping – as a characteristic – while also including specification. A specification is a description of a desired state of a product, and thereby not a characteristic. Therefore, there is little consensus on how to perceive the nature of a product architecture and how to relate it to platforms.

Mapping and decoupling

Just like the case of the *platform*, the *architecture* is a diverse concept without a common consensus. However, a few general comments can be emphasised;

Product architectures are reported in several forms, of which two characteristics are emphasised, that is, *mapping* and/or *decoupling*. However, it is from many perspectives the same, only a matter of difference in words. The word *mapping*, here refers to *"any prescribed way of assigning to each object in one set a particular object in another (or the same) set"* (adopted from Encyclopaedia Britannica), that is, the process of relating elements in one domain to elements in another domain;

1. *Mapping*
   The architecture is seen as a mapping between domains, mainly of a functional and physical kind respectively, [Ulrich, 1995], [Ulrich & Eppinger, 2000]. Some broaden the perception of mapping to include organs or other functionally separated regions of parts that do not necessarily fit the boundaries of parts, [Erens & Vershulst, 1997], [Andreasen, 2004], [Miller, 2001], others again adding the (manufacturing) processes [Jiao & Tseng, 1999], [Du et al., 2001].

2. *Decoupling and interface specification*
   Some put more emphasis on the decoupling or interdependencies between the various elements in a system rather than mapping between domains [Baldwin & Clark, 1997], [Baldwin & Clark, 2000]. [Gershenson et al, 1999], [Sanchez & Mahoney, 1997].

In the following, the concepts of mapping and decoupling are discussed.

Architecture as a mapping between domains

A seminal piece of work within the field of product architectures is that of Karl Ulrich. With various colleagues - of which Karen Tung and Steven Eppinger are probably the most important - Ulrich has described and refined the perception of a product architecture as a *mapping* of the functional and physical elements of a product [Ulrich, 1995], [Ulrich, 2000];

The product architecture is described as "*the scheme by which the function of a product is allocated to physical components*", and further elaborated as:

"…the architecture of a product is

1. The arrangement of functional elements
2. The mapping from functional elements to physical components
3. The specification of the interfaces among interacting physical components"

The functional elements refer to functions i.e. what an axiomatic designer (such as Suh [1990]) would call functional requirements, and a European designer would call function. The physical components largely correspond to the part domain of the Domain Theory.

A similar perception is that of a product architecture as *"...in its essence, the transformation from product function to product form."* [Stone et al., 2000a].

Fujita [2002] illustrates the mapping from customer needs, via functions to parts;

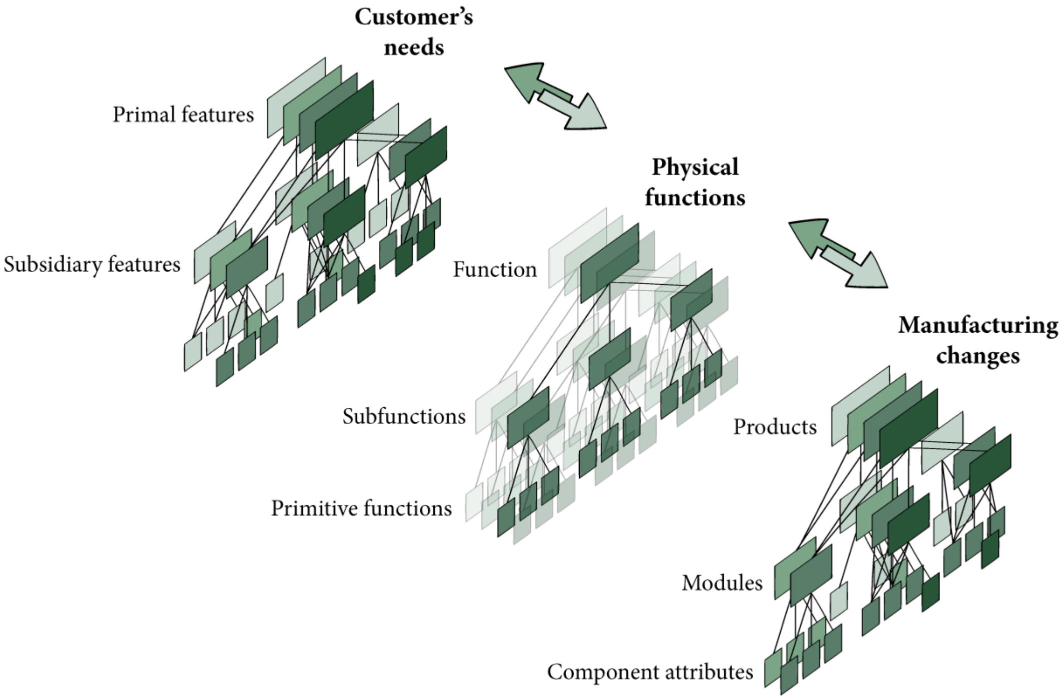


Figure 4.3: The mapping from customer needs to functions to components and attributes. (Figure redrawn from Fujita [2002])

The Theory of Domains is used by Andreasen [Andreasen et al., 2001] and Miller [2001], to describe the mapping between different domains;

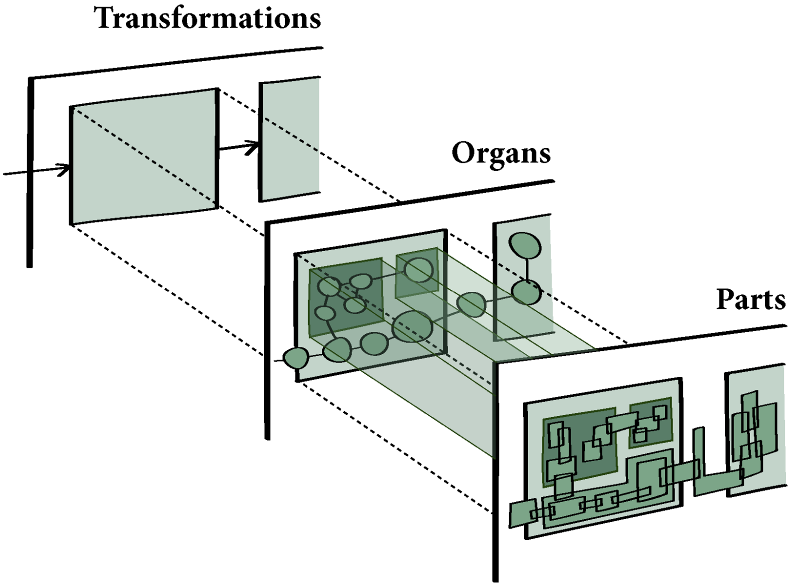


Figure 4.4: Architectures as a mapping between organs, figure redrawn from Miller [2001].

Figure 4.4 depict the phenomenon of a product architecture as a certain mapping between the three fundamental domains (transformation, organ, parts) from the Theory of Domains (See chapter 3.2.2 in Part 3 for a further discussion on the Theory of Domains).

Other authors recognise the aspect of domains, such as in the work of Erens & Verhulst [1997]. Their domains largely correspond to the domains of the Theory of Domains, see figure 4.5

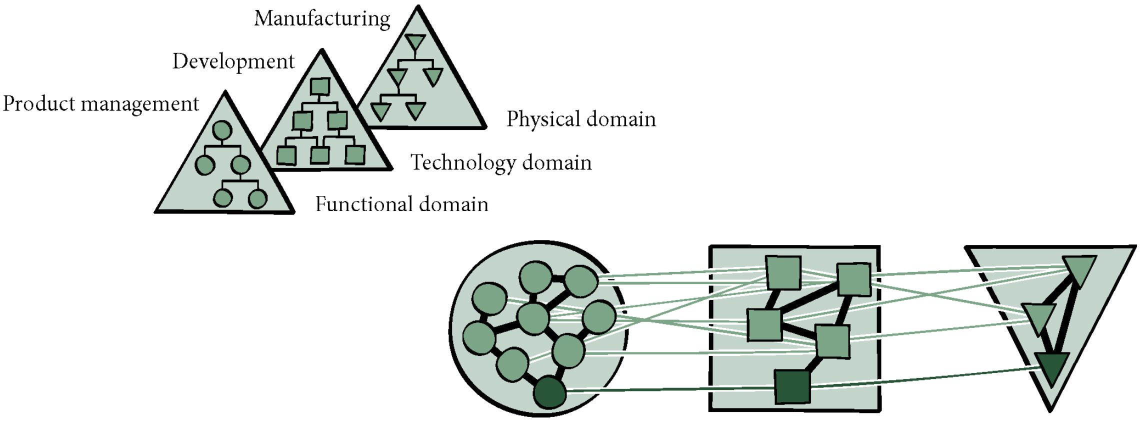


Figure 4.5: The three domains of Erens and Verhulst. Product families are based on coordinated product architectures in the three domains [Erens & Verhulst, 1997].

The Product Family Architecture (PFA) in various works of Michtell Tseng, Jianxin Jiao, and Xuehong Du, [Du et al., 2000], [Jiao & Tseng, 1999], are also a final example of an understanding of product architectures as some kind of mapping between domains. They emphasise the processes in the manufacturing as a part of the architecture, define the PFA like this;

"In essence, a PFA [Product Family Architecture] means the underlying architecture of a firm's product platform, within which various product variants can be derived from basic product designs to satisfy a spectrum of customer needs related to various market niches." [Jiao & Tseng, 1999].

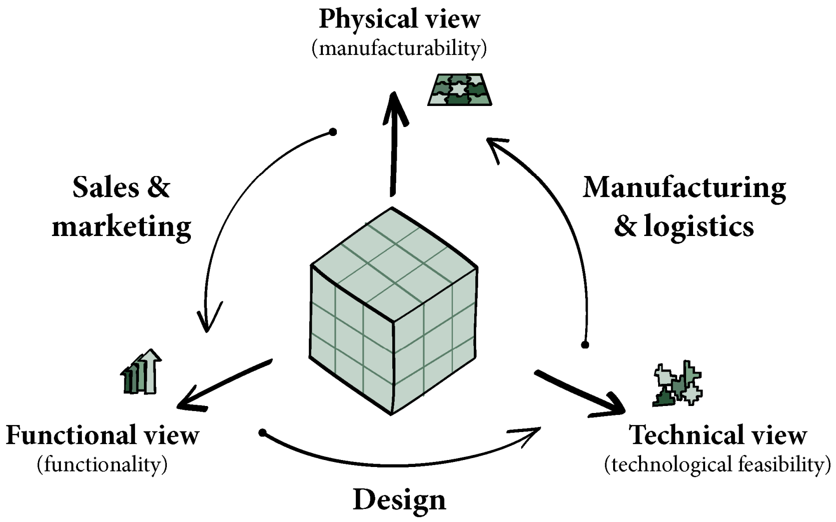


Figure 4.6: The Product Family Architecture has three views; A physical with an emphasis on manufacturing, a functional, with an emphasis on functions, and a technical view with an emphasis on solution principles, [Jiao & Tseng, 1999].

The Product Family Architecture (PFA) in figure 4.6, has three views; A physical with an emphasis on parts and manufacturing. It corresponds largely to the part domain. A functional, with an emphasis on functions, which corresponds to the functions of the Chromosome Model (see Part 3, chapter 3.2.5), and a technical view with an emphasis on solution principles.

Consensus on domains

Except the definition of Karl Ulrich – that only includes parts and function – the above perceptions include some sort of *functional understanding*, some sort of *concept or solution principle understanding* and some sort of *physical parts understanding*. To distinguish between solution principles (organs) and physical parts is important in the discussion on *modularity* and *integrity*, which is provided in chapter 4.5.3.

Sometimes domains, that are not directly related to the product is included. In their discussion on misalignment of product architectures and organizational structure, Sosa et al. [2004] bring into play the organisational fit to the architecture. They provide a method to align the interfaces of the product architecture with organisational interfaces, adding a fit between *module* and team *structure*.

4.5.3 Modularity and encapsulation

In literature, *modularity* is often mentioned as the key characteristic of a product architecture. A product architecture can be more or less *modular*. Karl Ulrich, [Ulrich, 1995], has provided a widely cited definition of a modular architecture;

"A modular architecture includes a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies the decoupled interfaces between components".

..and its opposite – the integral architecture – like this;

"An integral architecture includes a complex (non one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components"

Note the decoupling. This widely used perception builds on a strict distinction between the functional and physical elements of a product (originating from earlier work of Ulrich, [Ulrich & Seering, 1990]).

It is a rather theoretical perception of modularity and it somehow implies that a single function can reside in a single component. Karl Ulrich has 'loosened' the definition a bit in a more recent piece of work, in which modular and integral architectures are defined like this slightly different, [Ulrich & Eppinger, 2000];

"A modular *architecture has the following two 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 functions of the product"...*

... *"An* integral *architecture exhibits one or more of the following properties:*

- *Functional elements of the product are implemented using more than one chunk.*
- *A single chunk implements many functional elements*
- *The interactions between chunks are ill defined and may be incidental to the primary functions of the products."*

The term chunk is a rather loose definition of a subsystem, i.e. a perception that does not need a strict and detailed representation. The functions no longer have to reside in a single physical component. Rather, it is an abstraction of a subdivision of the product, yet a chunk is said to consist of components on a higher level of decomposition. Thus, chunks are *not* organs. The term *functional element* denotes the sub functions of a product. Ulrich's framework does provide a quite intuitive way to distinguish different product architecture types, and he also provides several practical implications of the different types of architectures. The framework is widely adopted in various slightly rephrased versions, in the work of other renown sources, such as the example from Robert Stone and Kristin Wood, [Stone et al., 2000b];

"An integral architecture is defined as a physical structure where the functional elements map to a single or very small number of physical elements"

"Modular architectures, ..., are physical product sub-structures that have a one-to-one correspondence with a subset of a product's functional model."

The example in figure 4.7 gives an indication of a modular versus integral architecture of a product with the same overall function;

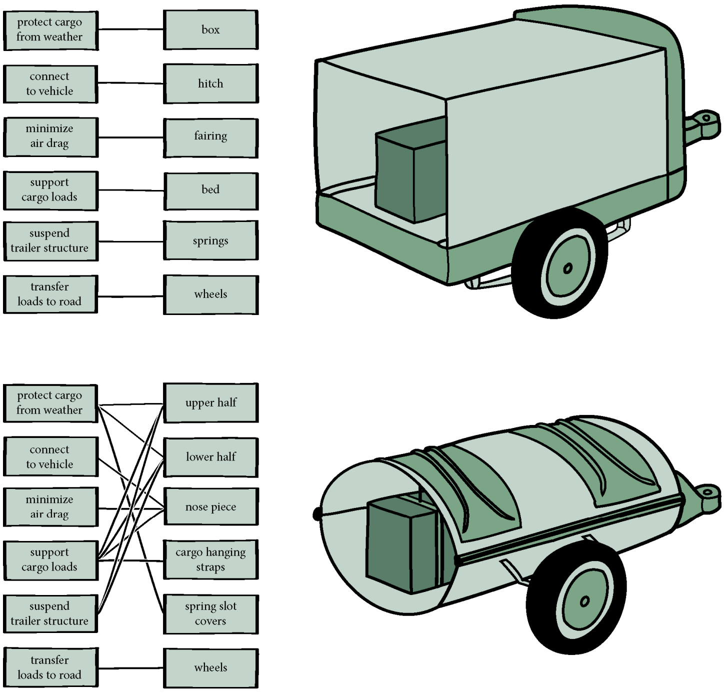


Figure 4.7: An integral and modular architecture of a product serving the same over all function [Ulrich, 1995].

A short comment on the function structure

There is one aspect of Ulrich's approach highlighting a slight difference in perceptions between the US and European engineering design communities. The key difference is the perception of functions and how functions are distributed into a design. The European engineering design school, based on the Theory of Technical Systems and in particular the Theory of Domains, operates with a closer relation between the functions and the physical parts. In the Theory of Domains this relation is instantiated in the *organs*. The practical implication of this, is that one cannot draw a function means tree to a relatively detailed level without knowing the means. Thus, it is hard to operate with a function structure that is independent of the means structure. The reason is that functions are realised by means that in turn demands new sub functions in order to work properly. The key point here to understand is that an organ does not necessarily reside in a single component. An organ (a function carrier) can reside in a part, in a proportion of a part or in several different parts. Several organs can reside in the same part and so on. Ulrich's definition of a modular architecture somehow implies that there is a functional and a physical structure of a product and that the mapping between the two, determines the modularity of the product. From a strict domain theoretical viewpoint the above figures are somewhat problematic in the sense that they do not provide a way to represent the organs. However, this may be a rather theoretical detail, and the concepts and examples from Ulrich have reached wide acknowledgement in the field, and is probably the most cited and widely used perception of product architectures.

Various types of modularity

Modules can be reused in several generations, shared in one generation; modules may share the interface, or have unique interfaces, modules can be combined or scaled. These fundamental options have been addressed by various authors [Ulrich & Tung, 1991], [Miller, 2001], [Salvador et al., 2001].

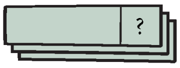
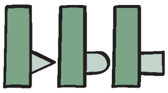
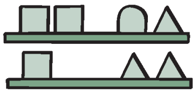
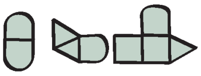
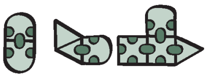
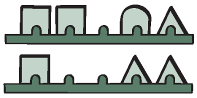
References	**Classification criterion**		**Types of module/modularity**
Pahl & Beitz [1984]	Stability of the function allocated to the component		*Basic and auxiliary modules* implement functions that are common thorughout the product family.
			*Special modules* implement complementary and task-spesific functions that do not need to appear in all the product variants.
			*Adaptive modules* implement functions related to the adaption to other systems and to marginal conditions.
Ulrich & Tung [1991]	How the final product configuration is built		*Component swapping modularity*: product variants are obtained by swapping one or more components on the common product body.
			*Fabricate-to-fit modularity*: product variants are obtained by changing a continuously variable feature within a given component.
			*Bus modularity*: product variants are obtained by matching any selection of components from a set of component types with a component that has two or more interfaces.
			*Sectional modularity*: product variants are obtained by mixing and matching in an abitrary way a set of components as long as they ate connected at their interfaces.
Ulrich [1995]	Nature of the interface between components		*Slot modularity*: interfaces between different components are different.
			*Sectional modularity*: all the components are connected via identical interfaces.
			*Bus modularity*: special case of sectional modularity where there is a single component, the bus, performing the connection function.

Figure 4.8: Modularity typologies, (adapted from Salvador et al., [2001]).

Combinatorial modularity

In addition to the modularity types proposed by Ulrich in various references, Salvador et al, [2001] suggest a new type of modularity, denoted "combinatorial modularity";

"....we can more formally characterize combinatorial modularity as follows.

- *All components making up a product family variant belong to component families, meaning that each component itself is a variant.*
- *Each component family interfaces with a subset of other component families, with the interface being standardized by pairings of component families. The interface refers to a set of rules that constraint how two components are to connect and to interact.*
- *The interface between two component families is dependent upon the specific coupling of component families, but is independent of the specific component variants selected from the two component families that need to be combined."*

For the second bullet they quote [Parnas, 1971], [Baldwin & Clark, 2000]. Especially Baldwin and Clark have raised the issue of interface importance, and see decoupling as the key to success.

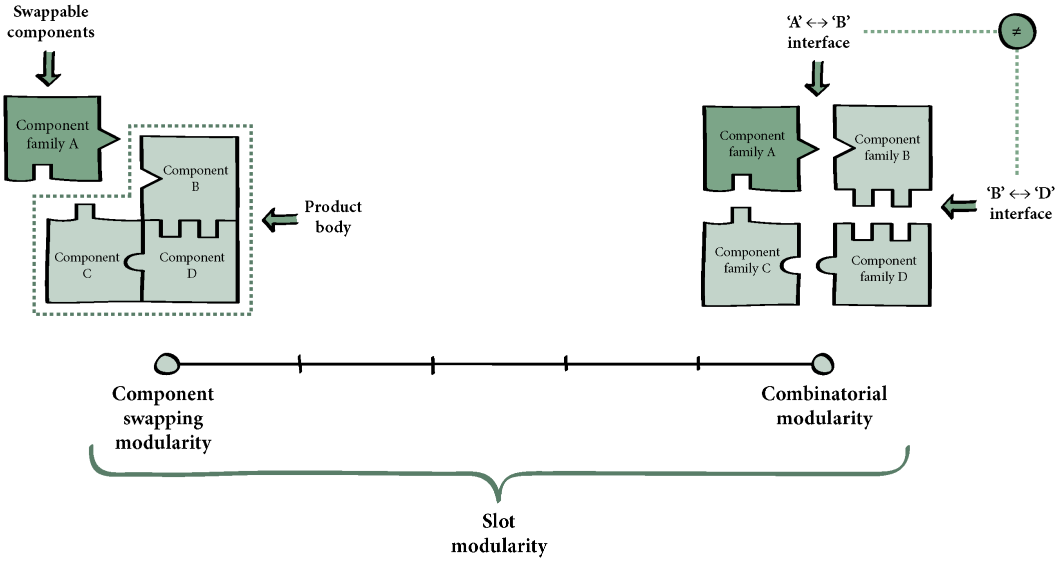


Figure 4.9: The combinatorial modularity as a subset of sot modularity. Figure redrawn from Salvador et al., [2001].

The point of combinatorial modularity versus component swapping modularity in figure 4.9, is basically the degrees of freedom with which components (modules) can be combined. Later in this chapter, the discussion will move towards the cases, in which combinatorial modularity is broken down further, and the degrees of freedom are on a attribute level rather than on a modular level.

Miller [2001] points out that *fabricate to fit is mainly done in fabrication* while the other modularity types from the work of Ulrich are mainly ensured through *assembly*. Miller adds several other types of modularity, of which three types are mainly effective after production/sales [Miller, 2001];

- *Adjustment* – an interface makes it possible to adjust the relation between two modules, e.g. a saddle pole.
- *Adaptation* – a rather special case. The modules adjust to the use within a given range, like a pair of shoes
- *Widening* – the module is flexible within a one-dimensional range, such as the ability for a power supply to take up 110 Volt and 220 Volt.

Adaptation and *widening* and the *fabricate-to-fit* modularity types are characterised by the fact that decoupling takes place outside the parts domains. Within the varying modules, there is a changing and a constant region, but there is no physical interface between these. The aspect of modularity without physical interfaces is discussed in the following sections.

Equivalent perceptions of modularity

Long before the interest in product architectures in the mechanical engineering industry grew, similar initiatives were phrased. Examples are found in the Design for Assembly (DFA) literature. Andreasen et al. [1982] provides various structuring principles, not only for single product DFA but also for product family rationalisation. Here, the integral versus modular architectures are described, yet with a difference in words and examples.

Encapsulation is a prerequisite for modularisation

The fundamental activity in the above *modularisation* is a decoupling and grouping of elements in the physical structure, governed by the desire to decouple and group the functionality of the product. From that perspective the one-to-one of one-to-few mapping in the modular case, is ensured by *encapsulation* or parts by grouping of parts. The decoupling is ensured mainly by the introduction of physical interfaces between *chunks*.

As it is pointed out in the following, the concept of encapsulation can be used outside the part domain, to denote other types of grouping and decoupling that does not require a physical split between *chunks*.

Modularity described using the Theory of Domains

Returning once more to the architectural perception as a mapping [Andreasen, 2001] and [Miller, 2001], modularity can be perceived as a *certain kind of mapping* between the domains of the Domain Theory. Different types of modularity can be defined from this mapping.;

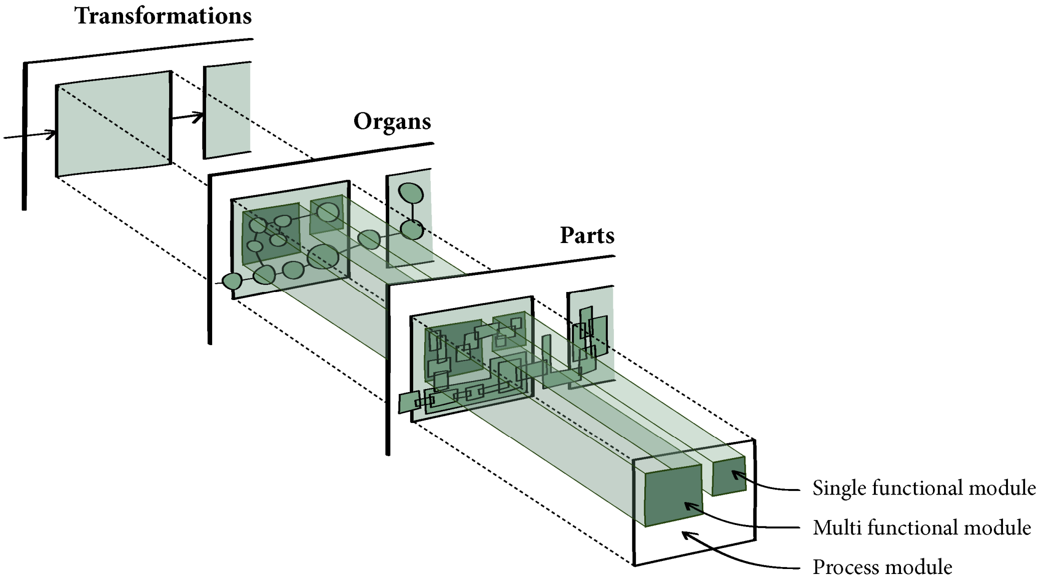


Figure 4.10. Modulariaty depends on the mapping between domains, in particular the organ and part domains,[Miller, 2001].

Miller [2001] operates with several different module descriptions in an attempt to describe modularisation of large scale process installations, such as pharmaceutical plants. The single function module carry a single sub functional on a specific level of decomposition or elaboration. The multi functional module carries a set of functions, while the Process module corresponds to the whole transformation in the transformation domain (sometimes referred to as the process domain).

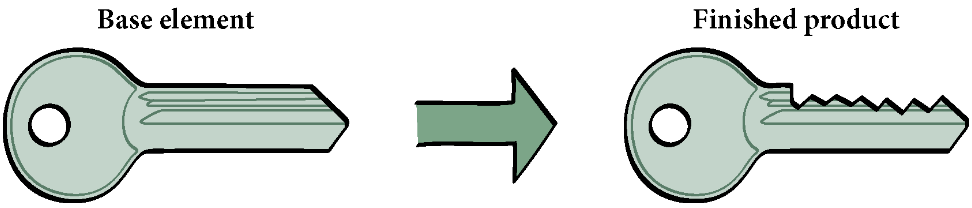
Encapsulation of organs – a certain kind of modularisation?

The above figure implies (figure 4.10) that the mapping continue all the way to "the end" i.e. that the order of organs are reflected in the order of parts, and that *decoupling* has to take place in the parts domain. This is in fact not always the case, and the main reason to be careful with the use of the term *modularisation*, and also why encapsulation is emphasised in this thesis instead.

Consider the following example;

Example

A key manufacturer (such as Ruko / Assa Abloy) uses a rather inflexible and standardised manufacturing process to make a base element – in one piece – from which a near infinity of key variants and corresponding door locks can be made.



From the base element, a milling process is used to make the finished shape of the key:

There are no physical interfaces *within* the key (as it consists of one part) and so many authors would denote the key as a highly integral architecture, (as in the top trailer in figure 4.7). However, the key is made in millions of variants, and is actually part of a highly flexible product family.

In general, the integral - or non modular -architecture is mostly perceived as an inflexible way to orchestrate a product family. In fact many references focus solely on *modularity* in the part domain as the key characteristic of a product family approach, [Dahmus et al., 2001], [Stone et al., 2000], [Zamirowski et al, 1999], [Sudjianto & Otto, 2001], [Gershenson et al., 2003], [Simpson et al. 2006c], [Fixson, 2007]. Thereby, many initiatives tend to address a high focus on component commonality and the reduction of part differences, and thereby a focus on decoupling in the parts domain, standardised interfaces and the importance of assembly [Otto & Hölttä-Otto, 2007].

However, the (somewhat extreme) example above illustrate that there is another dimension than just modularity in the parts domain, and that component commonality and interfaces in the parts domain are not the necessarily the key drivers for a successful platform setup.

Encapsulation of organs

The main aspect here is the way *decoupling* is done. In the key example, the decoupling takes place not in the part domain, but from many perspectives in the organ domain. There is an organ ensuring the right door lock combination, and this organ is primarily made of wirk surfaces on the customised part of the key.

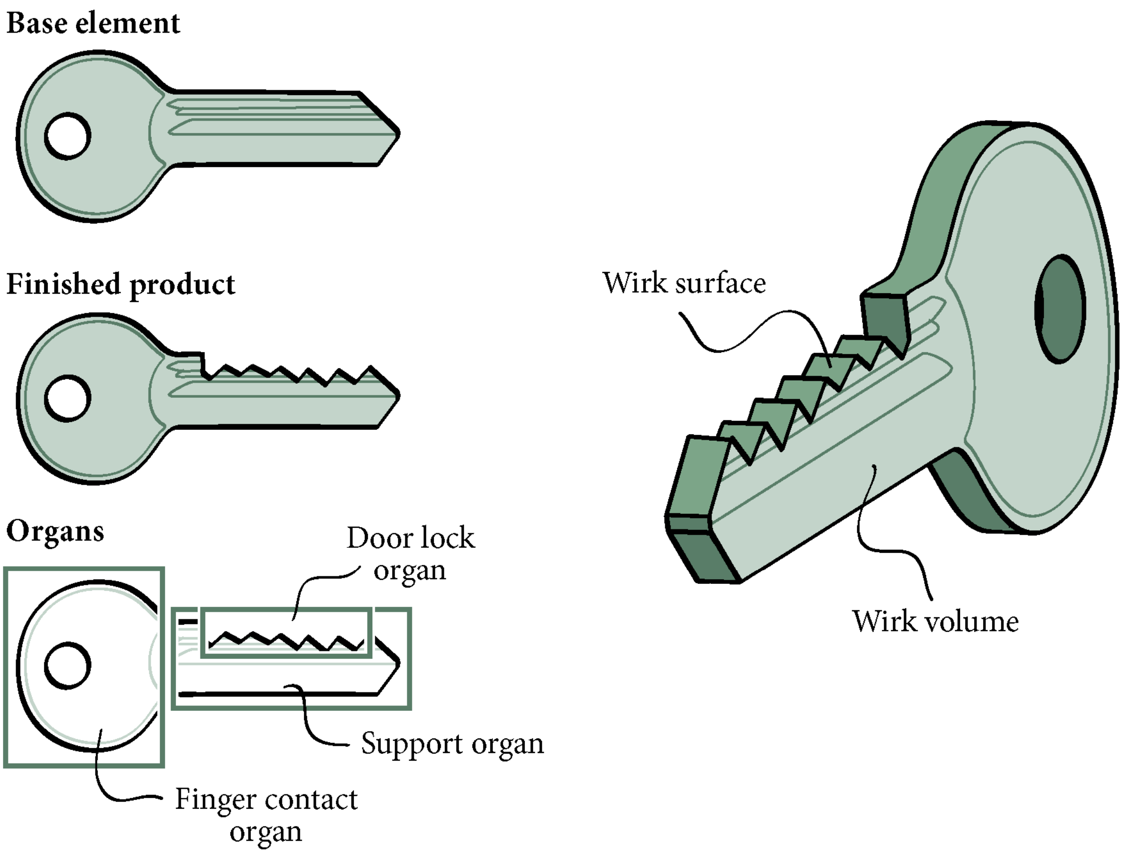


Figure 4.11: Various areas of the key are parts of different organs. Strictly speaking, the finger of the user is part of the finger contact organ, and the pals in the lock are par of the Door lock organ.

Thus, on a certain level of resolution, it is about grouping and decoupling of functional surfaces, i.e. *wirk elements* and the *organs* that they make up. Thus, *organ encapsulation* is in some cases as important as parts encapsulation. The common understanding of modularisation is that it has to with parts encapsulation through carefully designed interfaces. With organ encapsulation, there are not necessarily interfaces in the part domain, and therefore decoupling has to be accomplished with other means.

Encapsulation of parts

The vast majority of perceptions of modules, modularity, and platforms in a product context (not including activities, knowledge etc.) fall within the *parts* domain, and imply physical decoupled subassemblies.

Thus, if the concept of encapsulation and the Theory of Domains is used to explain modularisation in the parts domain, the core of these references can be rephrased to the same fundamental definition;

Modularisation (of products) implies grouping and decoupling and thereby encapsulation in the parts domain

Encapsulation of organs

The main reason to distinguish modularisation from encapsulation is to describe the types of encapsulations that do not happen in the part domain. Sometimes, a subset of a part is varied while the rest of the part is held constant. Decoupling of parts is not a prerequisite to make the attributes vary independently. Instead, it is the organs that are grouped and decoupled;

Encapsulation of organs is different from encapsulation of parts

Encapsulation of organs does not have to match the encapsulation of parts

Fabrication flexibility versus assembly flexibility

The above key example illustrates the need for decoupling in the organ domain. The way to achieve decoupling in the organ domain is essentially *process flexibility.* In the ‘traditional’ modular approach, with decoupling in the parts domain, the assembly process is often the key to achieve variety during fabrication. In the case of organ encapsulation, the key driver is process flexibility.

Decoupling of parts has implications on* assembly *flexibility

Following the above argumentation, modularisation implies a decoupling between parts, i.e. interfaces between parts. Therefore, the effects *in the production* are mainly found in the assembly, because assembly has to do with physical couplings between parts;

Production System Dispositions 1

Part encapsulation (modularisation) has strong dispositional effects in the ***assembly*** *system*

Decoupling of organs has implications on* fabrication *flexibility

This is often the case when companies work with different types of parametric designs. Again, one can talk about decoupling, however in this case the decoupling takes place in the organ domain. The parts do not have to be decoupled. Therefore, the effects lie mainly in the fabrication, because it has to do the fabrication of different variants of parts, rather than assembly processes.

Production System Dispositions 2

Organ encapsulation has strong dispositional effects in the ***fabrication*** *system*

The perception of modularisation as encapsulation of parts into decoupled subassemblies is often coupled with an intention of also encapsulating functions. Therefore many of the present definitions do try to grasp the effects in the organ domain, even though they do not articulate or accept the organ as a phenomenon. Ulrich modularity perception has to do with a certain *mapping from functional elements to physical components* [Ulrich, 1995]. However, Ulrich (and many other authors) does not consider organs as a phenomenon within modularisation. Therefore they miss the opportunity to articulate encapsulation of organs and wirk elements as a system characteristic (of the platform) and thereby describing the relation between the platform and the process flexibility and not just articulate flexibility as a characteristic of the manufacturing system. The key is to understand that the effects take place in meetings, which is why the alignment of the platform and the production system has to be taken into account.

Muffatto [2002] describes coherence between a modular and integral architecture and the corresponding component designs in the platform;

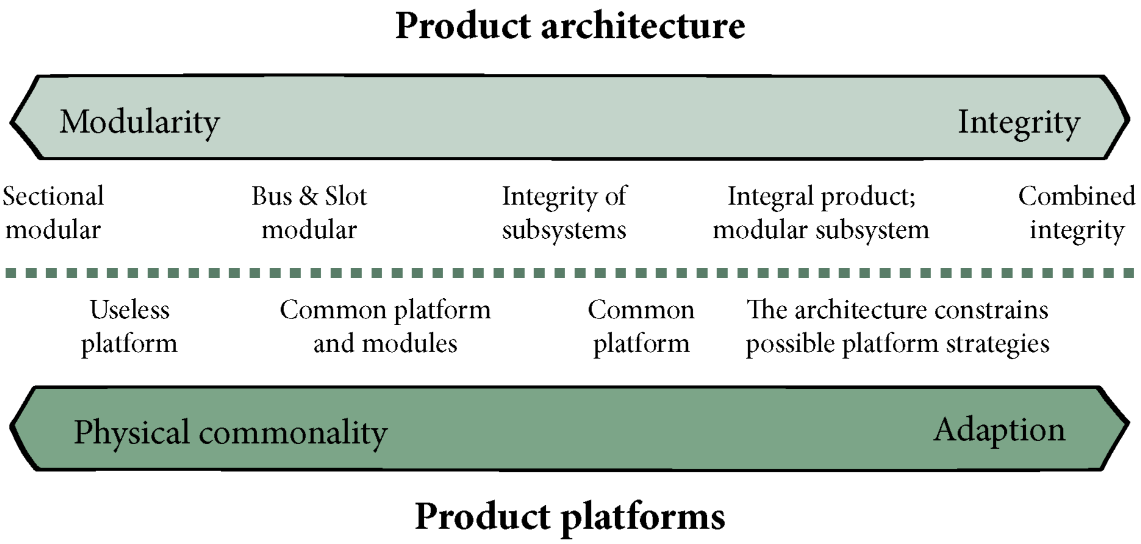
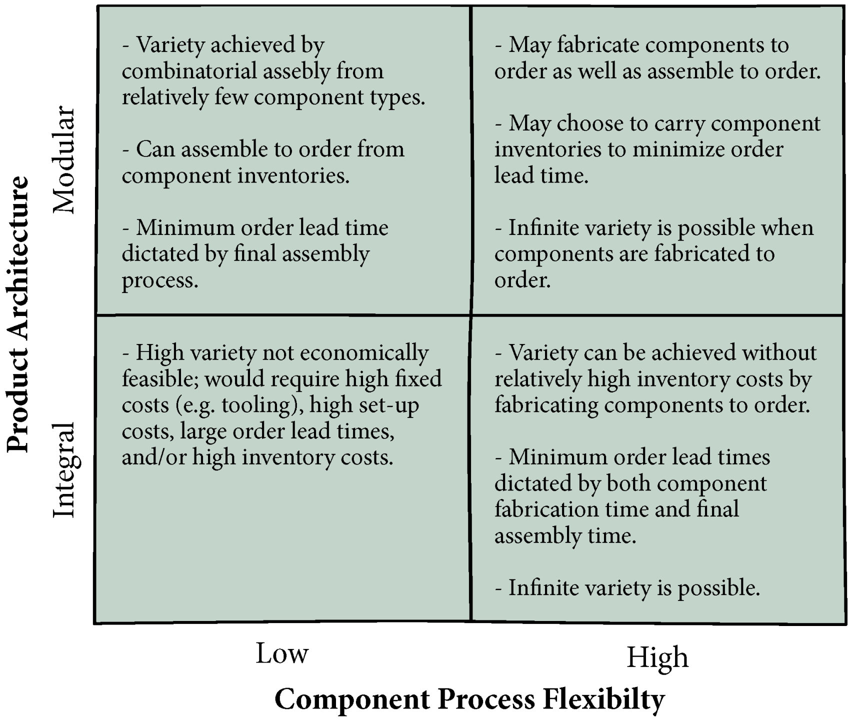


Figure 4.12a: Various modularity types have different implications on the platform strategy. An integrated architecture fits adaptation well – that is adaptation of attributes or parts. On the other hand, a modular architecture fits physical commonality of the modules. Variation comes from combinations of different modules, and not adaptation of the single modules. (Redrawn from Muffatto [2002]).

The point raised by Muffatto is that the degree of modularity has an impact on the process flexibility, just as it was argued above, in the case of organ encapsulation. This fits the notion that part encapsulation have strong dispositions in the assembly system, while encapsulation of organs – without a physical detachment of parts – has to do with adaptation and thereby fabrication flexibility. Fabrication flexibility is denoted *adaptation* by Muffatto, and somewhat fit the fabricate-to-fit modularity of Ulrich [Ulrich & Tung, 1991].

In a recent piece of work, Karl Ulrich, [Ulrich, 2007], returns to the subject of modularity and discuss the relations to process flexibility (see figure 4.12b). The degree of modularity and component process flexibility are mapped as two dimensions. The lower right corner of the space in figure 4.12b is what one could call organ encapsulation without a corresponding part encapsulation;



Product Architecture	Low	High
Modular	- Variety achieved by combinatorial assebly from relatively few component types. - Can assemble to order from component inventories. - Minimum order lead time dictated by final assembly process.	- May fabricate components to order as well as assemble to order. - May choose to carry component inventories to minimize order lead time. - Infinite variety is possible when components are fabricated to order.
Integral	- High variety not economically feasible; would require high fixed costs (e.g. tooling), high set-up costs, large order lead times, and/or high inventory costs.	- Variety can be achieved without relatively high inventory costs by fabricating components to order. - Minimum order lead times dictated by both component fabrication time and final assembly time. - Infinite variety is possible.

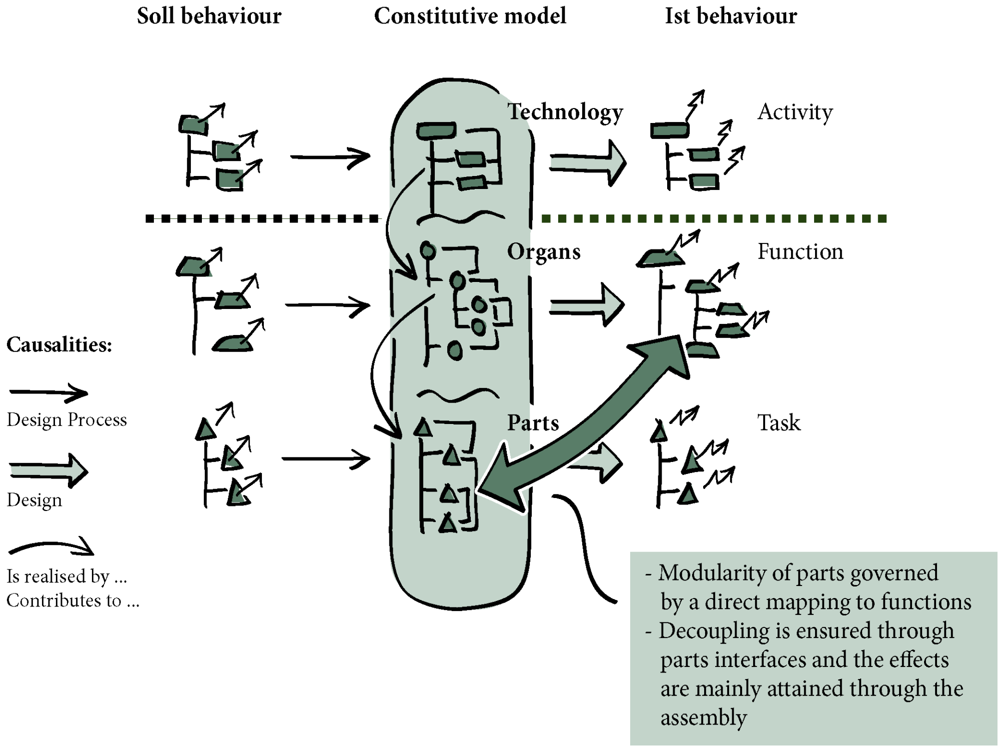
Figure 4.12b:Architectural types based on a two dimensional distinction. (Redrawn from Ulrich [2007]).

Why emphasise encapsulation of organs?

All three industrial cases in this thesis have aspects of organ encapsulation. Some of the models explained in Part 5 particularly deals with the topic of organ encapsulation relative to part encapsulation. Typically, the *organ encapsulation* takes place without a corresponding decoupling in the part domain taking place. The word *modularisation* would be somewhat imprecise to use, because it implies both a mapping and in many cases a physical split, i.e. a decoupling in the parts domain.

Organ encapsulation explained by the chromosome model

The research community has largely adopted Karl Ulrich's perception of modular products architectures as the opposite of integrated product architectures [Ulrich & Eppinger, 2000]. This means that most – if not all – references in the field emphasise the physical split between subsystems, i.e. what would be called part encapsulation following the line of argumentation earlier in this chapter, in which encapsulation in the part domain is introduced. An interesting question is now whether it is possible to describe the phenomenon of encapsulation without the presence of modularity. Ulrich jumps directly from functions to parts. His *functional elements* are not physical function carriers (such as organs), but more functional requirements on a higher level. The Genetic Modelling Design System (GMDS) [Mortensen, 2000], can be helpful in distinguishing functions from organs and organs from parts. Ulrich's concept of modularity can be visualised using the GMDS framework (See chapter 3.2.5 or Mortensen [2000]), see figure 4.13. The grouping of function carriers is done implicitly in the definition of modularity, therefore organs are not taken into account, and thereby the link from functions to parts is direct.



- Modularity of parts governed by a direct mapping to functions
- Decoupling is ensured through parts interfaces and the effects are mainly attained through the assembly

Figure 4.13: Modularity as a direct mapping between functions and parts without using the phenomena of organs. Parts are encapsulated to match functions in a certain pattern. Decoupling is obtained using parts interfaces, and thereby the effects are mainly attained in the assembly.

Figure 4.13 depicts the ‘classic’ perception of modularisation as a direct mapping between functions and parts. This is not supposed to be understood as a one to one mapping from functions to parts. Instead, Ulrich talks about a one to few mapping, i.e. that a single function is realised by few parts. Therefore decoupling has to take place in the parts domain in order for the effects to occur, and therefore a physical interface is needed between modules in the part domain.

The hypothesis is now that encapsulation can take place outside the parts domain, i.e. between organs. It is still feasible to respect Ulrich’s desire to encapsulate functions; however, we can also encapsulate functions in organs without restraining the encapsulation directly to parts. Then the GDMS looks like this;

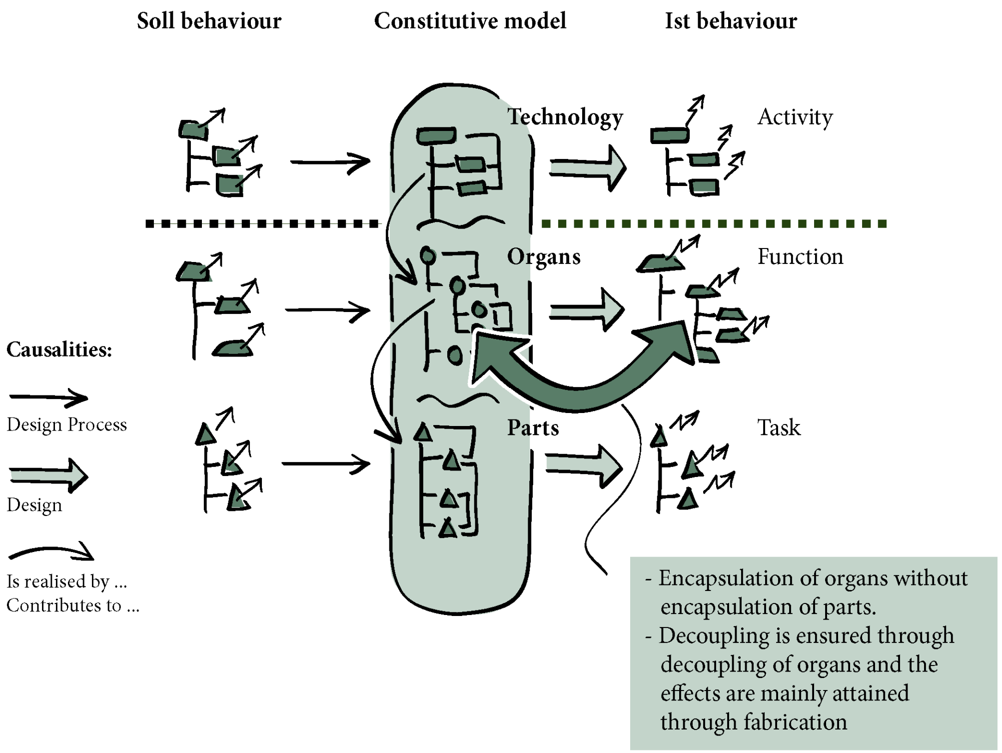


Figure 4.14: Organ encapsulation. Organs are decoupled relatively independently of the part domain. Decoupling is obtained through flexibility in fabrication.

Clearly, organs are defined as function carriers, and so they are by definition mapped to functions. The point is not as much the mapping as it is the decoupling. In figure 4.14 decoupling takes place outside the parts domain. It is possible to change an organ without the changes propagating to other organs relatively independent of the boundaries in the part domain.

Configuration, scaling and combination

The topic of organ encapsulation is described in the above from a viewpoint founded in the Theory of Domains. A topic similar to that of organ encapsulation is accounted for in various references from a slightly different angle. Basically it has to do with the level of resolution, i.e. the level *elaboration* (Remember that elaboration is the opposite of encapsulation – see chapter 4.3 for a discussion on elaboration).

Configuring attributes

A key aspect is the level of elaboration, which somewhat reflects the freedom to choose attributes interdependently. Consider the figure below (figure 4.15);

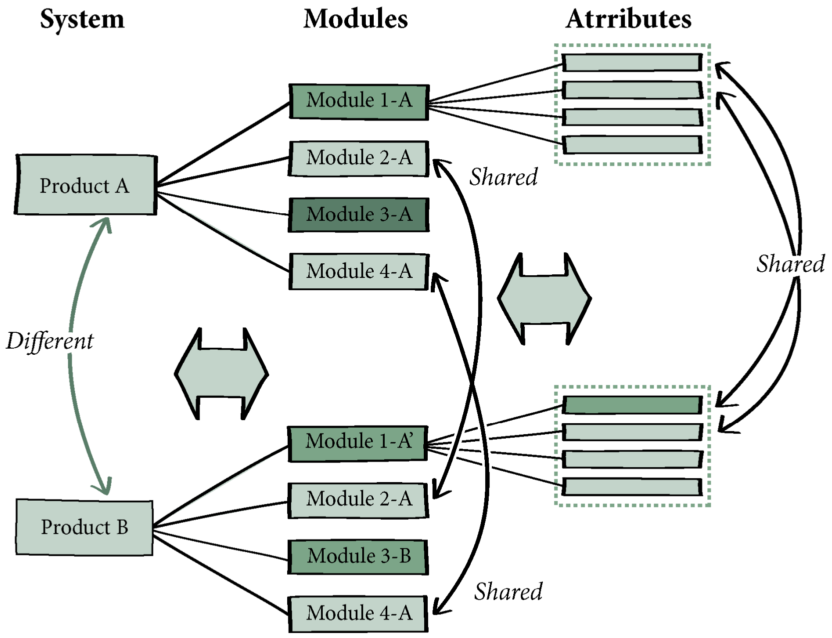


Figure 4.15: Modules are in fact grouped sets of attributes, [Fujita, 2002].The degree of freedom to choose attributes determines the nature of the product architecture. Moving to the right, the system is elaborated and broken down to a low level of decomposition.

In figure 4.15 the systems perspective is somewhat *encapsulated* to the left and *elaborated* to the right.

The *modular product architecture* concept – that is encapsulation of parts - mainly has to do with *grouping and decoupling of attributes* on a certain level of encapsulation, here shown in the middle of the figure. If instead

Selection and quantification

Consequently, some authors, point out two main types of product platforms/architectures, in which attributes are either chosen in *sets*, or varied more *independently*. Fujita [2002] refers to this as *combinatorial selection* and *attribute quantification* respectively;

1. *Attribute Quantification*
   ... to develop modules across multiple products by quantifying attributes under acceptable ranges of specifications, for cost minimizing, etc.
2. *Combinatorial selection*
   ...to develop multiple products by selecting practical combinations of modules from feasible ones.

This distinction is recognised by several other authors, and terms like *configurational/combinatorial* [Muffatto, 2000] exists. Simpson & Mistree [1999] talk about scale factors for a product platform, and divide them into *parametric* and *configurational* factors, and further note that the scale factors can be *discrete* or *continuous.*

Configurable components and autonomous structures

Many – if not all – of the above architectural concepts imply a fixed structure and a set of relatively fixed components. Fujita's point about grouped attributes and an elaboration of the architecture perception to a system level of *attributes,* enable a systems viewpoint even more flexible than the traditional product architecture concept.

The parametric approach to product architectures is taken one step further by Claesson [2006]. Figure 4.16 depicts the general perception of parametric design;

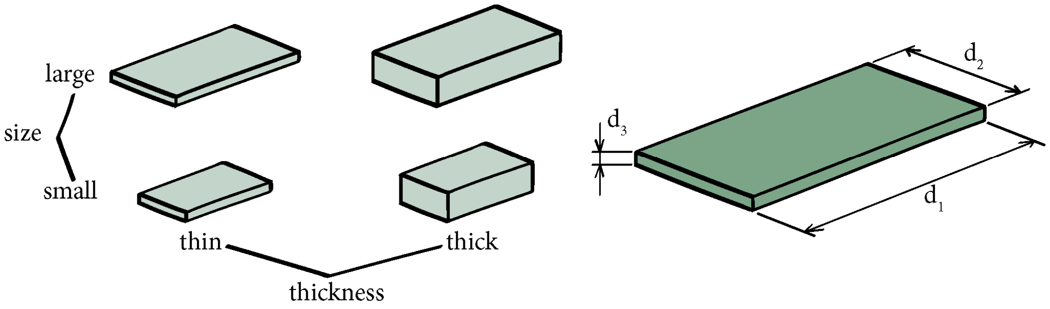


Figure 4.16: Two classes describing four parts, and a corresponding parametric component. It is possible to make all four variants on the basis of changing the parameters of the configurable component.

Parametric and feature based design is well known and has been used in industry for long. However, Claesson introduces the concept of *configurable components*, to denote the fact that more floating specifications of *components* as well as *structures* are feasible in many situations. Figure 4.16 depicts the basic different between discrete components and a configurable component. Claesson take the parametric abilities of modern CAD systems and put it into a framework ensuring the management of bills of materials and component hierarchies.

An important aspect is the loose specification of a predetermined structure in which the components and sub assemblies have to fit. Claesson argue that – with the evolution of IT systems and product data management – there is no need for a fixed architecture in the sense that the overall layout of a system might be unknown before a configuration process begins. Instead, Claesson operates with autonomous system models that serve as configurable subassemblies fitting each other in a super model. The structure/architecture of the super model is not known beforehand – it emerges from the configuration process.

To illustrate the constraints of the architectural structure, Claesson describes the evolution of bill of material handling in various industries (fig. 4.17);

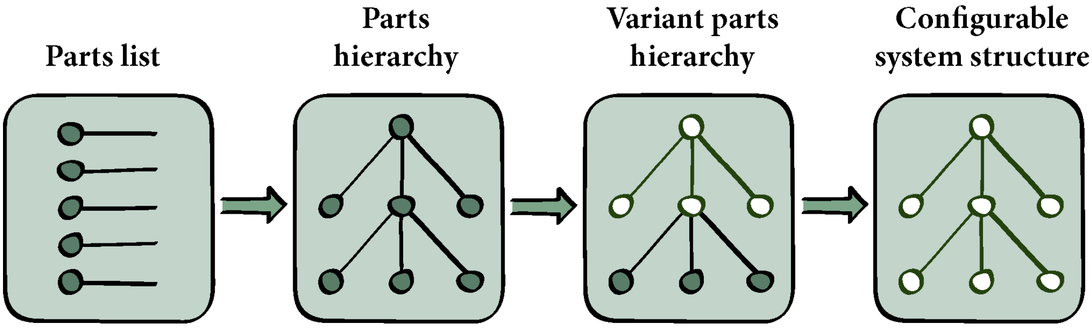


Figure 4.17: The evolution of part structures from; (a) flat BOM, (b) a parts hierarchy, (c) a hierarchy of variable parts, and finally (c) a configurable structure.

The point is that the configurable components framework of Claesson, makes way for a system structure that can vary. Not only modules, but whole subassemblies are able to be configured. Several examples from complex machinery have the characteristic that different subsystems will in turn create different part structures. The Grundfos case and the Aker case in Part 5, are in fact such examples, of a product, where the overall architecture is not known.

4.5.4 Organs and wirk elements are platform elements

Form feature elements

If a mechanical product is broken down to an attribute level, as it is done in figure 4.15, it is possible to group attributes and corresponding parameters into elements which does not necessarily follow the boundaries of parts. Form feature elements are used in feature based CAD design [van Holland & Bronsvoort, 1996] as a design object. In feature based CAD design, parts are made up of features consisting of e.g. surfaces or solid bodies, certain extrusions, chamfers etc.

Form and wirk elements

The concept of wirk elements (see chapter 3.2.3 for an elaboration on wirk elements) share some interesting similarities differences with form feature elements. Form feature elements (such as geometrical surfaces and volumes) are different from wirk elements in the sense that the points of view are different. The form feature element is geometrical while the wirk element has a functional point of view. The following example provides a description of the difference between a form feature element and a wirk element.

The difference between a wirk element and a feature/form element

Consider a male plug with a multiple-spring bunch pins as shown in figure 4.18. Each of the spring pins may be considered as a form element. When the male plug is inserted in the corresponding female plug, several wirk elements are allocated on the spring form element, e.g.:

- *The wirk element of a spring organ*
  Creates a normal power that, together with the reaction force form the inner surface of the female plug, causes a frictional force preventing the plug to be accidentally taken out.
- *The wirk element of a conductor organ*
  For conducting electrical energy between the wires connected to the male and female plug respectively.

The difference between the two types of elements is a consequence of *function integration*. Function integration happens when several functions resides in the same part [Ulrich & Seering, 1990].

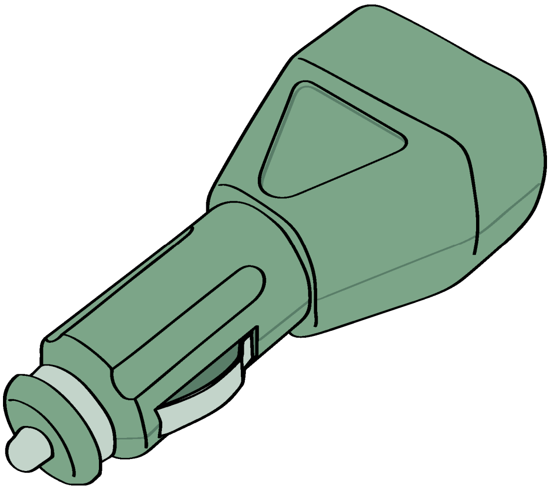


Figure 4.18: A typical male 12 volt plug. The spring on either side (only one is visible) is a single form element. However, is hosts several wirk elements. One wirk element is part of a spring organ, making sure that the plug fits in the female. Another wirk element is part of a conductor organ. The example is adapted from Jensen [1999].

In the theoretical base in Part 3, (chapter 3.2.3), the concept of *skeletons* is introduced. There are skeletons in the organ domain (spatial relations between wirk elements) and skeletons in the part domain (spatial relations between form feature elements). In modern CAD systems, a part skeleton is used as a design constituent in the so-called Top Down Approach. This is further described from a CAD modelling perspective in Part 5, chapter 5.6.

Initiatives like the one from Claesson [2006] (which is described in the end of chapter 4.5.3) bring practical design closer to a way to handle organs as a design object. Instead of seeing the system as a fixed structure in which elements/modules/chunks fit within, one can perceive the product platform as a set of variable and non variable parameters, on a certain level of resolution.

From the above discussion it is now stated that organs and wirk elements can serve the purpose of *constitutive platform elements*, i.e. they can be seen as platform elements, which can be reused and encapsulated. Using the part and organ domains from the Theory of Domains the statement can be elaborated (see chapter 3.2.2 or Andreasen [1980] or Hansen & Andreasen [2002] for more on the Theory of Domains);

Constitutive platform elements in the organ domain

Organs can serve as constitutive platform elements. On a higher level of decomposition, organs can be further elaborated into wirk elements, and wirk elements are also considered to be constitutive platform elements. Organs are related in organ structures, wirk elements in organ skeletons.

Other authors take into account the wirk elements as asset in a product family. van Wie and colleagues [van Wie et al., 2003] have extended Ulrich’s classic definition of an architecture and state the following, which somewhat softens the demands for part domain decoupling of the original architecture definition, and also includes the concept of wirk elements;

"Function to Form mapping…" is "*…The relationship between a set of functions and the physical embodiment that instantiates that functionality*", and when explaining the concept, they state: *"Functionality is correlated with spatial regions of the product. (Similar to the wirk element concept)",* However, the function to wirk element mapping should be a direct consequence of the definition of wirk elements.

Following the line of argumentation from above and in the discussion of part encapsulation in chapter 4.5.3, the Theory of Domains is again useful as a framework for describing the counterpart to organs and wirk elements, from a platform element perspective;

Constitutive platform elements in the part domain

Parts and form features are considered to be constitutive platform elements in the part domain. Parts are related in structures, form features are related in part skeletons.

Feature based design in CAD systems [van Holland & Bronsvoort, 1996] and Top Down Design with skeletons (see chapter 5.6) are practical ways to manipulate form feature elements.

Coinciding form and wirk elements

From certain points of view, form feature elements may coincide with wirk elements - in particular wirk surfaces and wirk volumes since they are based on a relatively geometrical point of view, i.e. nesting in geometries of parts. A wirk media for example, is somewhat more abstract than a wirk surface, at least from a CAD and design perspective, due to the geometrical limitations in a CAD system. Organs are abstractions, but the concept of organs can be brought into a practical design context by the use of form feature elements, which closely resemble wirk elements. Modern CAD systems makes it possible to model and control form features that are not necessarily depending on the boundaries of parts.

Coinciding part and organ skeletons

The concept of skeletons is used in modern CAD systems such as Pro/Engineer [www.ptc.com] to control the spatial relations between form elements in a generic repository. If the form elements resemble the wirk elements, the CAD skeleton (which is in fact a part skeleton following the argumentation above) will resemble the organ skeleton.

If the concept is used in the right way, it is possible to express surfaces from a functional point of view and to relate them to each other in a skeleton. The concept somewhat enable a design engineer to get close to a tool to manipulate the *wirk elements*, rather than parts, and master the distribution of organs into parts, by controlling features that resemble wirk surfaces (while still respecting the theoretical difference between wirk surfaces and form features described in the example above).

The most important implication of the skeleton concept, is the ability to group and decouple design attributes *within the same parts,* i.e. to enable a practical way to make encapsulation of wirk elements in a geometrical system.

The Aker Solutions and Grundfos cases (in Part 5) elaborate on this issue of skeletons in geometrical designs, and the links to the product platform modelling efforts related to Research Question #2.

Software as a unique class

When classifying platform elements into parts and organs, one specific asset has to be addressed with particular care: That is software. Mechanical products are the main examples in this thesis, yet software also have the ability to be reused and encapsulated. In fact, many of the virtues of platform based product development, and the concept of product architectures owe a lot to the software development discipline.

Buur [1990] points to the fact that function carriers (organs) are also supported by software as well as electronics. Electronics is somewhat physical, and thereby covered by the parts domain in the Theory of Domains. Software, however, is a rather special case due to the intangible nature. For the purpose of this thesis, software is regarded as a possible platform element yet in its own class.

4.5.5 Interfaces

In the case of part encapsulation, the *interface* between parts and between subassemblies is a key aspect. Interfaces is a part of many product platform and product architecture definitions (as it is seen in chapters 4.5.1 and 4.5.2), and the interface is an important phenomenon to investigate. In the classic perception of modularisation it is the interface that ensures decoupling, and thereby enables reuse and sharing.

It is stated in chapter 4.5.2 that there are two common perceptions of product architectures; as a *model description/specification* or as a *characteristic*. Similar perceptions seem feasible for the concept of *interfaces*, in the sense that they can also be viewed from several viewpoints;

- Interfaces as a feature of a single part that has to abide to certain rules.
- Interfaces as a common feature of two or more parts, i.e. a property of the relation between the parts.
- Interfaces as a description of one part, i.e. a design rule or functional description
- Interfaces as a description of two parts, i.e. a common design

Thus, in a constitutive and structural perception of a product platform, where does the interface belong?

- From a *systems perspective* it is a problem where to assign the interface and how to perceive it, mainly because an interface involves several elements – and is the interface then a feature on a part or a property of the relation between parts? If the interface is perceived as a feature element of a part in a system, the interface may – from some perspectives - be perceived as a collection of wirk elements. If the wirk elements are coincident with form feature elements, it is possible to model a generic interface in the part skeleton in a CAD system. This is described in chapter 5.6.
- From a *description* or modelling point of view, the interface is more of a design specification that the interacting elements have to accommodate. In a product modelling context, the interface has to belong to a common structure, or some sort of generic placeholder, in order for the interfaces to be inherited to the involved elements.

It is outside the scope of this research to establish a definition of an interface. The point in the above is that the concept of part skeletons makes it possible to model interfaces as a generic feature element, which can be inherited to two or more parts. The part skeleton serves as the placeholder for the interface.

Interface classifications

There are several ways to classify interfaces. Clearly, an interface has to do with the borderline between components or regions of the product.

"Interface: A spatial region where energy and/or material flow between components or between a component and the external environment." [van Wie et al., 2001].

In a study of the nature of "module interfaces" from Michigan Technological University [Bettig & Gershenson, 2006], several interface types are discussed, and of these four are deemed generic;

- *Attachment Interfaces* – an interface in which two or more modules are mechanically connected to restrict relative motion and transmit force
- *Control & power interfaces* – an interface in which two or more modules are connected to convey electrical power and/or signals
- *Transfer interfaces* – an interface intended to transfer energy, material or signal through mechanical means
- *Field interfaces* – an interface that transmits energy, material, or signal as an unintended side-effect of the intended function of the module

However, it does not seem generic to distinguish between control & power and transfer interfaces solely on the basis of whether the signals are electric or mechanic. From a functional point of view, a hydraulic power system share many overall characteristics to that of an electrical power system. That is particularly the case because a control purpose can be realised by means of hydraulics, cables or other mechanical means.

The study also reports other interface classification schemes in the same context, based on the work of Steward [1981]. The four categories are also reported by Pimmler & Eppinger [1994], who add to their perception that an interface need to be documented, i.e. as a design rule;

- *Spatial* – physical relationship between two modules
- *Material* – transfer of materials between two modules
- *Energy* – transfer of power between two modules, including interactions in which force-type quantities react between modules, without energy being exhanced (e.g. force without motion, voltage without current, pressure without velocity)
- *Information* – transfer of information or signal between two modules

From a systems perspective, Hubka's *Function Complex Law* [Hubka & Eder, 1996], [Hansen & Andresen, 2002], can be used to classify interfaces. The law, states that any means in a function-means structure has to have the following subordinate functions in order to work;

- *Control and/or regulate functions* – control and regulation purposes
- *Drive functions* – the energy that the means (subsystem or part) needs in order to work.
- *Connect and/or support functions* – supposing that any need some sort of support and connection to the rest of the system.
- *Auxiliary functions* – are subordinate help functions that the means need in order to work.

Supposing that the elements in a platform also need these functions, the interfaces can be classified accordingly.

Yet another classification of interfaces is given in the work of Sanchez [2000b];

- *Attachment* – the physical attachment between modules
- *Spatial* – the spatial implications from one module on the other, determined by available space. A concave shape may lead to a convex shape in a neighbouring module.

- *Transfer* – transferring physical effects
- *Control and Communications* – transferring control signals
- *User* – the user interface directly between a user and the module
- *Environmental* – one module affecting a neighbouring module or the surroundings, by transmitting sound, vibration, smell etc.

The above interface definitions can be described as either form feature elements or wirk elements. The spatial interface in the classification of Steward and Sanchez respectively are possible to be explained as wirk volume and/or wirk surface.

Looking at interfaces as a wirk element, makes it possible to use the concept of organ skeletons described in chapter 4.5.4 as a generic placeholder for interfaces. In the practical case, interfaces will often be modelled as form feature elements in a CAD system. In chapter 5.7 (in Part 5) it is discussed how the concept of skeletons can be used to control generic interfaces in a product family.

External and internal interfaces

Some hardware interfaces are external in the sense that they serve a purpose in a meeting and are not only to other platform elements. A very common example is the interfaces to the production system, i.e. to the fabrication, assembly, and distribution systems. Reuse of manufacturing interfaces is an important driver for commonality.

Interface evolution

One thing to bear in mind is fact that an interfaces may change throughout the product life phases – especially throughout the production. Some interfaces are physically detachable in the first processes in a production line, and are then permanently or temporarily joined to form a united component (from an operations management point of view). Thereby, interfaces may change and evolve during the different life phases.

Bettig and Gershenson from Michigan Technological University, [Bettig & Gershenson, 2006], provide a hierarchical model of different interface types:

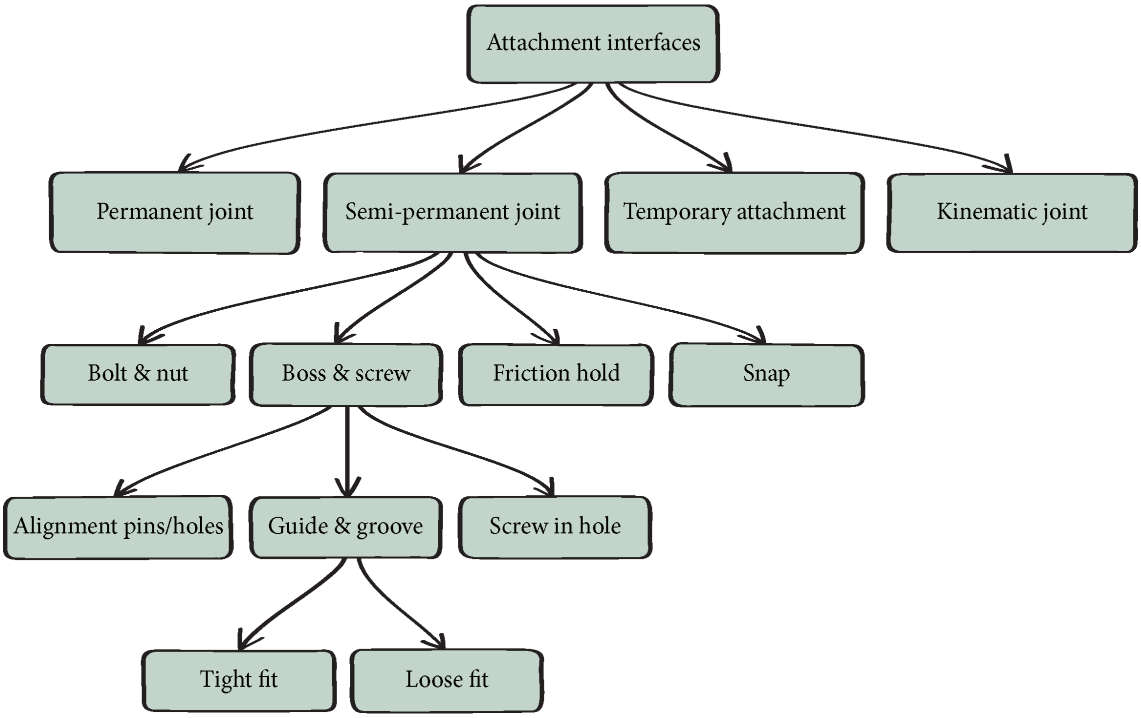


Figure 4.19: A type designation of different attachment interfaces [Bettig & Gershenson, 2006]

Figure 4.19 depicts different interface types. During evolution of interfaces, part relations may change from e.g. temporary to permanent. This interface evolution is sometimes useful to bear in mind when pursuing a postponement strategy. (See chapter 4.6.2 for a discussion of postponement).

Other interface classes

The above discussion of interfaces related mainly to *products* and the viewpoint of a mechanical system. If encapsulation takes place in platform elements that are not related to the products, parts, and components, then the interfaces are of a different kind from what it seen in the discussion above.

From the different perceptions of platforms, which are listed in chapter 4.5.1, it is seen that there are different classes of platform elements. It is stated that *activities* and *knowledge* are also perceived as platform elements. It makes sense to talk about decoupling between activities and thereby probably also to talk about interfaces between activities. However, it is considered to outside the scope of this work to further elaborate on the nature of interfaces between activities and between knowledge elements.

4.5.6 Concluding on the constitutive phenomena

Platform elements

In general, platforms are about reuse and encapsulation of various *platform elements*. From a review of various platform perceptions, the following three fundamental classes of platform elements are identified;

- *Product/artefact/part/component related elements*

This has to do with the products in the product family. In Chapter 4.5.4 it is stated that there are platform elements in the part domain and organ domain (using the terminology of the Theory of Domains [Andreasen, 1980]). In the organ domain, *organs* and *wirk elements* can be reused and encapsulated. In the part domain, *parts* and *form feature elements* can be reused and encapsulated. These are considered to be platform elements.

- *Activity elements*

  Activities and processes are part of several platform perceptions. Therefore, activities are considered to be constitutive platform elements.

- *Knowledge elements*

  Knowledge – in various forms. There are various knowledge elements such as drawings, procedures, design templates etc. [Sanchez, 2000], [Harlou, 2006].

Part 4 has an emphasis on the product related assets – and in particular the concept of encapsulation in the organ and part domain. The activity and knowledge elements are less elaborated, yet still considered to be constitutive platform elements.

- *People and relationships* are also agued as a platform element however it is a somewhat different platform element than the other three above. *People* also have the dual role of being both parts of platform and users of the platform.

Interfaces

The nature of interfaces between platform elements (and in particular between parts) is another aspect of product platforms discussed in chapter 4.5. It is stated that interfaces in mechanical products can be perceived as wirk elements.

Parts and organ encapsulation

As a subset of the discussion of organs and wirk elements, the concept of encapsulation in the organ and part domains is introduced (chapter 4.5.3). Part encapsulation resembles the traditional modularisation and has strong dispositional effects in the assembly system. Encapsulation in the organ domain is different, and does not imply a physical split between parts. Therefore, encapsulation in the organ domain induces strong dispositional effects in the fabrication system.

Software

It is argued that software can also be reused and encapsulated. Software is considered to be a special case due to the intangible nature of software, and therefore software is thought of as a unique class of platform elements.

The product architecture

The concept of *product architectures* has been discussed and related to the topic of product platforms. In literature, *product architecture* is seen in (at least) two different ways;

1. As a certain structural characteristic of a system, mostly combining an aspect of *mapping* between domains, and mainly a mapping between *function* and *form*
2. As a model or specification of a product family or product platform

Out of the various perceptions it is – for the purpose of this thesis - chosen to use the term product architecture as a model of the platform. The term architecture is not used to denote a *characteristic* of the platform, because the definition of the concept is so broad and there are different and sometimes contradicting explanations attached to the term *architecture*. However, many of the virtues, such as function/form mapping, separate views etc. may be handled in a product platform model – which is then called *a product architecture*. In that sense, none of the concepts (like modularity), are 'lost', only perceived as *viewpoints* rather than *characteristics* of the platform.

4.6 Behavioural phenomena – the effects

The following chapter provides an elaboration of various benefits, which decision makers should be aware of while managing a product platform and while manipulating the encapsulation of parts and organs, as it is discussed in the former chapter (in particular chapter 4.5.3). These desired benefits are the prime drivers for pursuing a product platform approach.

Several renowned industrial cases report benefits from component sharing in Toyota, [Nobeoka & Cusumao, 1998], *postponement* (of the creation of variation during production), leading to a more flexible setup, ease of problem diagnosis, and parallel production activities at Hewlett-Packard ([Feitzinger & Lee, 1997], increased innovation and speed to market with the Sony Walkman success, [Sanderson & Uzumeri, 1995], lower material cost, improved quality, and lower stock levels in the Swedish automotive industry, [Erixon et al., 1996], rationalised product development process at General Electric, [Sanchez & Collins, 1999], to name a few. Some authors extend the potential benefits even further to encompass stronger brand advocacy in the sense that sales based on a platform may extend through word of mouth among related customers, [Sawhney, 1998].

This chapter (4.6) is mainly based on a review of existing literature, and it is divided in a series of subordinate chapters. Chapter 4.6 has the following structure;

- *Chapter 4.6.1: Efficiency and effectiveness*

  The fundamental drivers for virtually any platform approach, *efficiency* and *effectiveness* are discussed.

- *Chapter 4.6.2: Commonality and variety*

  Two instruments to achieve efficiency and effectiveness are discussed. These are *commonality* and *variety*. Commonality and variety are considered to be derivatives of reuse and encapsulation, which are discussed in chapter 4.3 and 4.4. On the basis of the discussion of commonality and variety, the concept of alignment is discussed in this chapter. As a subset of this discussion, the concept of *postponement* is illustrated by means of an example. Postponement is one of the potential beneficial effects that may arise from encapsulation of activities, organs and parts and it has profound implications on the setup of production and supply chain in a company.

- *Chapter 4.6.3: General platform benefits*

  This chapter gives a general discussion of the most fundamental benefits reported in literature and tie it to the concepts of reuse and encapsulation.

4.6.1 Efficiency and effectiveness

Product platform benefits are both internal and external. Miller [2001] has made an extensive study on the effects of *modularisation*, and the findings are applicable in any of the platform perceptions listed in the review in chapter 4.5. Miller points to the fact that the fundamental ambition is to *achieve more with* *less*. Ultimately, most companies would use this to create a better profit, however a lot of other benefits arise, and they are not directly related to the turnover or profit.

Achieving more with less has a twofold meaning in the sense that it phrases the *external* benefits (more) and the *internal* benefits (less). To illustrate this point, Miller turns to the work of O´Donnell & Duffy [1999], who deem efficiency and effectiveness in a product development context in the following way. It can be interpreted more or less quantitative;

- *Efficiency*: Is the outcome of an activity relative to the resources spent
  Efficiency = (output-input)/resources
- *Effectiveness:* Is the difference between the goals and the actual outcome
  Effectiveness = goal - output

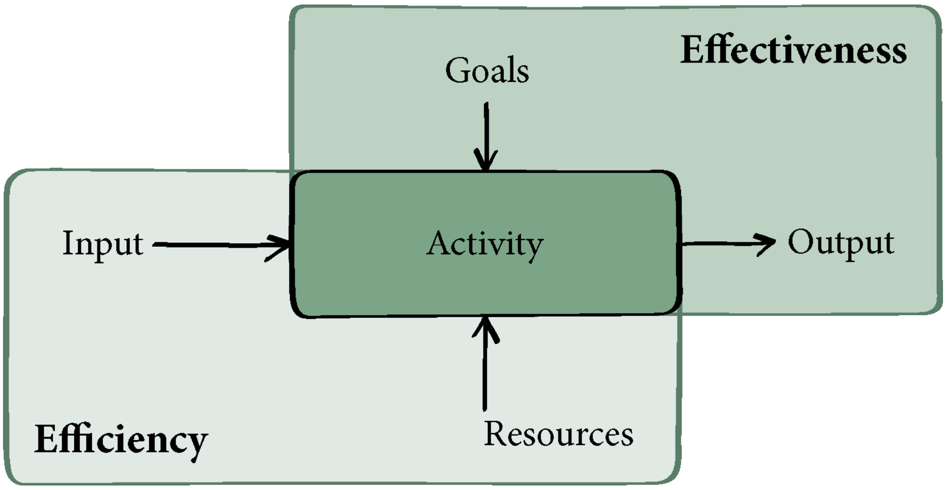


Figure 4.20: Efficiency has to do with internal utilisation of resources. Effectiveness has to do with the match between the intended outcome and the actual outcome. Redrawn from [Miller, 2001, originally from O´Donnel & Duffy, 1999]].

Following the argumentation visualised in figure 4.20, the overall benefit of a platform approach is the ability to be more *efficient* and *effective*. Figure 4.20 can be perceived from a more or less quantitative viewpoint. Meyer et al., [1997] provide quantitative measures as to calculate platform efficiency and effectiveness; The efficiency is calculated as the R&D cost for derivative products relative to the R&D cost for the platform as a whole, while effectiveness is the value of the net sales of a derivative product relative to the development cost of a derivative product. Such quantities measures have one obvious drawback in that they are hard to estimate in the early phases of a project, and thereby hard for decision makers to use in a context of choosing between alternatives when designing the platform. In this thesis the concept of platform efficiency and effectiveness is considered from a relatively qualitative point of view.

Single products versus platforms

Effectiveness and efficiency have different implications whether from a single product or a multiple product viewpoint;

The effectiveness of a single product

The effectiveness of a single product is often measured as a function of its capability to satisfy a specified range of expectations. It is often possible to assign metrics to a single product that tells something about the effectiveness, i.e. to what extend customers expectations are met for that particular product.

The efficiency s of a single product

The efficiency of a single product is the resources spent on that single product relative to the earnings it provides to the company. In fact, economic models focusing on single products often lead to sub optimisation, because the variable costs on a single product will often constitute a counterargument to standardisation and reuse between product variants.

The effectiveness of a product family is related to variety

The viewpoint is slightly different in a product family. That is due to the extra dimension added by the fact that the family consists of multiple designs. Product specifications no longer have to satisfy *set* values, but rather have to reflect different segments of customers through *ranges* of values. Thus, the effectiveness has a lot to do with the ability to "fill" out a customer need space. From a product family point of view effectiveness has a lot to do with *variety*, and variety is a common driver reported in the platform cases in literature (see chapter 4.5.1).

The efficiency of a product family is related to commonality

Looking at the efficiency of product families, again one aspect makes a difference compared to the single product case. That is the aspect of *reuse*. Conscious, planned and intentional reuse is a fundamental difference between single products and product families. Reuse by means of encapsulation gives *commonality*, and commonality is a major driver in achieving the internal benefits leading to efficiency.

Efficiency, effectiveness and the 7 universal virtues

Miller [2001] also provides a useful link to the so-called 7 universal virtues, which are part of the framework in the Theory of Dispositions [Olesen, 1992] – see chapter 3.2.4 for more on the Theory of Dispositions.

Olesen [1992] argues that an activity - such as the activity in the efficiency/effectiveness framework in figure 4.20 - can be measured by seven universal virtues, which describe the state of the system on a fundamental level. Apart from the efficiency/effectiveness aspect, the virtues are *cost*, *quality, time, flexibility, Risk, Environmental effects.* According to Olesen, the performance of a product development activity can be sufficiently and completely described by these virtues. If that is true for product platforms as well, we get at least the following benefits [Miller, 2001]. Note that reuse and encapsulation – in various ways – are fundamental drivers underlying the benefits. Reuse is mentioned directly by Miller, while encapsulation is essentially discussed as either *focus* or *modularisation*;

- *Lower cost* due to *reuse* of resources and learning effects
- *Improved quality* due to *reuse* of known good solutions/better practices
- *Less time consumption* due to *reuse* of solutions, focus of resources, learning effects and by readiness inherent in the modular setup.
- *Increased efficiency* due to learning effects and *reuse* of resources, and focused innovation at a modular level.

- *Increased flexibility* due to focussed readiness and possibility of different configurations of modules, as well as reuse of existing subsystems in new products
- *Decreased risk* due to reuse of known good solutions, and flexibility in addressing different market needs.
- *Improved environmental effects* due to material separation, ease of disassembly, and recycling of modules.

The above list of benefits from Miller [2001] is rather fundamental and similar benefits are reported in various reviews [Gershenson et al., 2003], [Simpson, 2003], [Andreasen et al., 2004], [Fixson, 2007].

Platform performance

In the clarification of the research setup in Part 2, the *platform performance* is included in the argumentation without a thorough explanation. However, with the concepts of efficiency and effectiveness, one can now provide a slight elaboration of the platform performance in figure 2.9, Chapter 2.7.

It reflects the desire to provide great variety towards the market place while at the same time achieving a set of benefits internally. The efficiency corresponds to the internal use of resources. The effectiveness corresponds to the external level of variety. Thus, however rather qualitative, the platform perception can be perceived like this;

The performance of a platform can be expressed by means of the efficiency and effectiveness

This is by no means a research result or fully supported statement. The reader should think of the statement as an explanation to figure 2.9 and thereby as a further elaboration of the chain of arguments from the introduction in Part 1, leading to the research questions in Part 2.

4.6.2 Commonality and variety

If the platform encapsulation is successful, it provides the opportunity to reuse, while at the same time offering a satisfactory level of variety in the market place. The concepts of *commonality* and *variety* have to do with the ability to have variety in the market place without sacrificing internal reuse benefits. Commonality and variety are introduced in Part 1, chapter 1.2.

There are several perceptions of commonality. Many authors see commonality as a quantitative measure calculated on the basis of part commonality, that is, attributes that are common across parts [Jiao & Tseng, 2000b], [Martin & Ishii, 2002], [Thevenot & Simpson, 2007]. However, these measures often fail to take into account the relations to life phases, and because of their quantitative nature, they are also very specific and dependant on the definition of the indices.

Commonality can also be explained in a more qualitative way, in which *viewpoints* are essential. In the case of viewpoints, commonality is best described together with its counterpart, *variety*.

The key to obtain reuse benefits in a product platform is to have commonality from a life phase system point of view and variety from a market point of view [Andreasen, 1998]. Figure 4.21 depicts the concept;

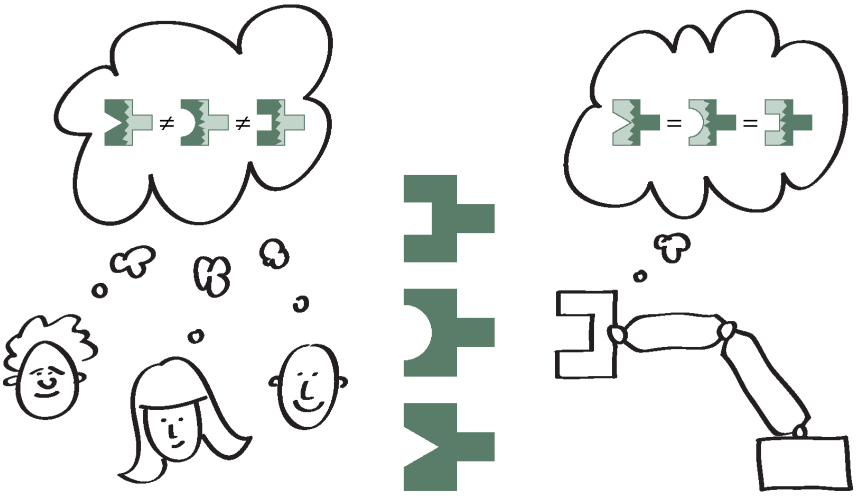


Figure 4.21: Variety to the left: The products are different from a customer viewpoint. Commonality to the right: From a production system viewpoint (or any life phase system), the products are common.

The life phase systems, i.e. the fabrication system, assembly system, distribution system etc. can be designed in interplay with the platform in order to obtain commonality from an operations viewpoint. Grouping and decoupling, i.e. encapsulation, are key concepts in this context.

There is no simple way to perceive commonality. It has to do with 'smart' designing, as in the platform perception of Andreasen [1998];

"A platform is a means for rationalisation of the product development and product realisation seen in relation to the business process, based upon a smart, fitted interrelation between products, knowledge and activities".

Alignment - fitting the platform with the life phase systems

Rationalising product development and product realisation has to do with a certain fit between different life phases and the product. This concept is referred to as *alignment*, [Andreasen, et al. 2001], and has also been coined f-familiarity [Hildre, 1996], see figure 4.22;

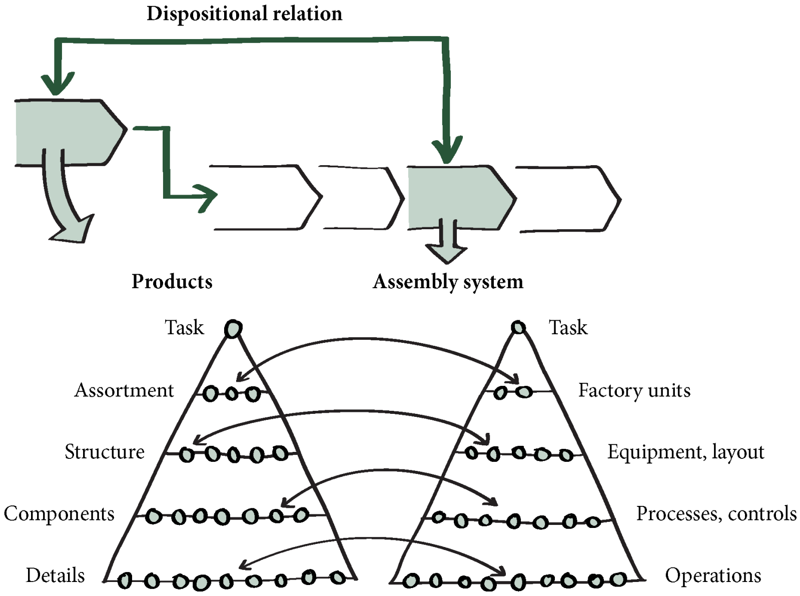


Figure 4.22: The concept of alignment. There is a structural or architectural fit between the product and various life phase systems. In the figure, a possible fit on different levels between the product and the production is shown.[Andreasen et al., 2001].

Alignment is about creating a fit between the product platform and the life phase systems. Different recursive levels can be recognised in a product [Mortensen, 2000], and if they fit the recursive levels of the life phase systems, certain benefits arise. Alignment is essentially about a concurrent design of the product platform and the life phase system, or at least ensuring that they fit each other.

Alignment as mapping

The architecture concept often involves mapping between function and form, or even various other domains. Alignment is a kind of extension of the internal mapping within the product related domains, to also fit the life phase systems.

Mass Customization

The term Mass Customization is often a key aspect in literature on product platforms, product architectures and modularisation. Mass customization is enabled partly by a product platform setup and partly by certain logistical planning concepts during the supply chain. Mass Customization is included here as a subset of the discussion of commonality and variety, because it essentially covers the same desire to balance efficiency and effectiveness.

The term Mass Customization is a contraction of *mass production* and *product customization* and thus denotes a situation in which a company is able to produce customised products at a cost level near that of mass production [Pine, 1993], [Tseng & Jiao, 2001].

A central part of mass customization strategy is postponement, and postponement as a lot to do with commonality.

Postponement

Postponement is a strategy in which variation is deliberately postponed during the internal operations in order to keep variation limited in as many operations as possible. In a case from Hewlett-Packard, postponement is described;

”The key to mass-customizing effectively is postponing the task of differentiating a product for a specific customer until the latest possible point in the supply chain network.” [Feitzinger & Lee, 1997].

Time is not the only dimension of postponement. Postponement can be divided into three typologies [Brun & Zorzini, 2009], [van Hoek, 1998];

- *Time postponement, involving the delaying of those activities not determining forms and function of the products until orders are received.*
- *Place postponement, involving the delaying of moving goods downstream in the chain until orders are received, thus keeping goods centrally and not making them place specific.*
- *Form postponement, involving the delaying of those activities that determine the form and function of products until orders are received.*

Postponement is as much a logistics strategy as is it a product and production strategy [van Hoek, 2000]. Postponement has a lot to do with the *order entry point,* and the *variegation point;*

- *Order entry point/customer order decoupling point [Madsen, 2001], [Michelsen & Pagh, 2002]*
  The point in the operations at which the customer order enters, that is, at which the specification of product and delivery details are settled. Clearly, the order entry point is a floating topic, depending on business and product types, and there may be more order entry points during a specification process (if for example, the product details and delivery details are settled separately).
- *Variegation point [Ramdas, 2003]*
  The variation point is the point at which the product goods are adapted to a specific purpose. Clearly, there are many variegation points throughout a production line. What is essential is to make sure that those processes that really narrow the scope of a good, is postponed.

Ramdas uses the word *variegation* in order to avoid a mix-up with the word *differentiation*. Differentiation is often used to denote how company A’s products are differentiated from company B’s products. Variegation is the task of making one product within a company different from another product within the company, i.e. to create variety. Note that *differentiation* in the Hewlett Packard quote above refers to *variegation* i.e. the point in which the customer specification starts to influence the transformation of raw materials into parts and finished goods.

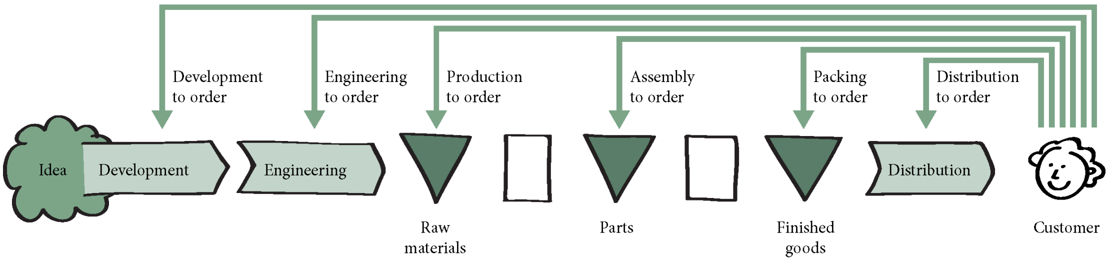


Figure 4.23: Postponement is a strategy in which the lead time after the order entry point and points of variegation are sought minimised. The order entry point can be situation in various operations, making way for different strategies, [Michelsen & Pagh], [Madsen, 2001].

Figure 4.23 shows a typical sequence of activities in a company. The order entry point may enter at any of these activities resulting in different product leverage strategies; Development-to-order, DTO, Engineer-to-order, ETO, Production-to-order, PTO, Assemble-to-order, ATO, Packing-to-order, PTO, Distribution-to-order, DTO. Postponement is really about minimising the lead time after the order entry point, by controlling the various points of variegation and make sure that they are predominantly placed *after* the order entry point rather than before. In the above figure, all the activities are "*to-order*". Nevertheless, all activities before the order entry point will be "*to-stock*", i.e. based on a forecast.

A simple example of different variegation/order entry points:

- If the order entry point is placed after the point of variegation, the variants are made based on a forecast, sometimes referred to as *speculation* [Michelsen & Pagh, 2002].
- If the order entry point is placed before the point of variegation, the variants are based on specific orders

There is a great aspect of risk associated with the relative position of the decoupling and variegation points in a time dimension. In a discussion of order standardisation, Bertegazzi & Verganti [1995] touch the same challenge of planning production and orders. One aspect is the volume of various variations, another aspect the mix of orders, i.e. the expected variation.

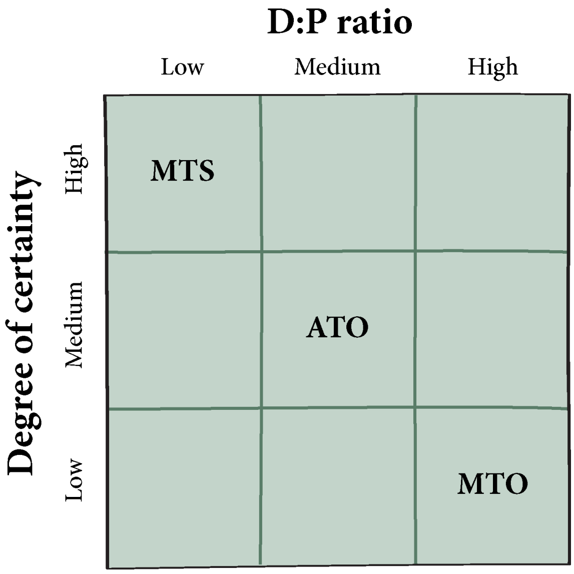


Figure 4.24: The degree of certainty versus the D:P ratio. (MTS Make-to-Stock, ATO, Assemble-to-Order, MTO, Make-to-Order).

Bertagazzi and Verganti propose a framework, in which the relative placement of the order entry point and the point of variegation, is related to the risk associated with forecasting, as depicted in figure 4.24.

The degree of certainty of demand versus the D:P ratio [Bartezzaghi & Verganti, 1995];

- Degree of certainty
  "The level of knowledge of general and technical product characteristics, both in quantitative and qualitative terms, prior to customer orders arriving"..."it determines the possibility to predefine what and how much should be produced. As the degree of customization and the number of product variants increase, the degree of certainty decreases, unless considerable component standardization and product modularisation are achieved"
- D:P ratio
  "The D:P ratio is the delivery lead time. (that is, the length of time a customer waits between placing an order and receiving shipments. P is the total or cumulative lead time for a product"

Thus when the D:P ratio is less than one, some sort of forecasting is necessary, and thus the risk may be high, because the products are produced on speculation rather than real time customer orders.

A postponement example

Company A

Company A is producing jumpers. They can offer 13 variants on the market place. They have three basic sizes, small, medium and large. They have a total of 5 colours, yet not all sizes and colours can be combined freely due to constraints in the factory. Their production setup fundamentally consists of a colouring process and a knitting process. Consider the factory layout below (figure 4.25a);

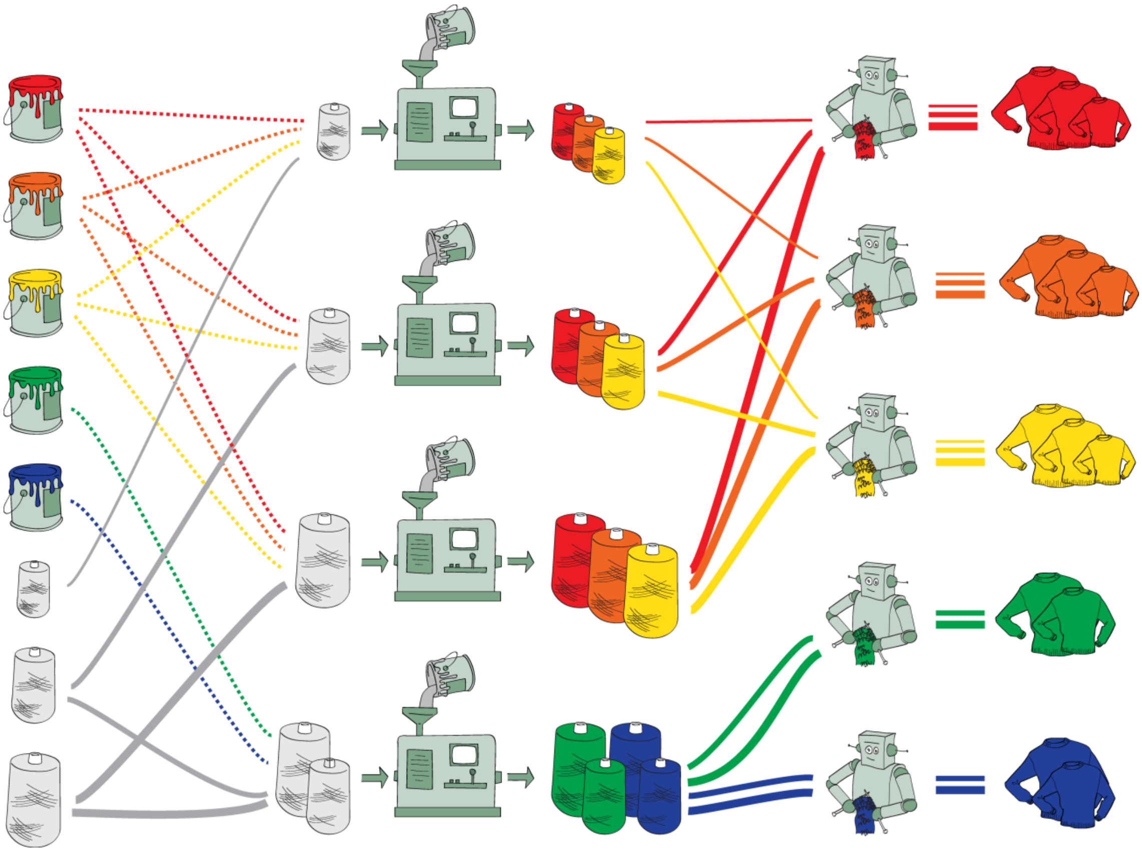


Figure 4.25a: A factory setup for the production of a family of jumpers.

The raw materials

Colours and knitting yarn enter the factory and is kept on a raw material stock. The paint come in five variants and is kept in separate bowls. The yarn has a neutral colour and come in three different sizes, small medium and large which eventually fits the sizes of the jumpers. That gives a total of eight different items in the first stock.

The colouring process

The yarn is coloured in one of four colouring machines:

- The first machine can take the small yarn type
- The second machine can take the medium yarn type
- The third machine can take the large yarn type
- These three machines can handle the colours red, orange and yellow.

It takes a lot of time to clean the machines, when the darker colours green and blue are used. Therefore the first three machines are never used for green and blue, because it would stain the yellow jumpers with green/blue stains, if not the machine is totally cleaned.

- The fourth machine dye with green and blue

This machine was bought recently because the demand for green and blue jumpers has increased over the past years. When the machine was bought, the demands were only for medium and large jumpers, and so the fourth machine was specified to take medium and large yarn types.

- The fourth machine can't take the small yarn type

After the colouring process the coloured yarn is spooled on a drum.

The semi finished goods stock

The yarn drums are placed in a stock. They have to be placed in a stock, because each knitting machine only knits one colour at a time. In the stock there are a total of 13 different yarn drums (red/yellow/orange in all sizes and blue/green in medium and large).

The knitting process

The jumpers are knit on five machines.

- All knitting machines are identical
- They can take all yarn sizes
- They can take all colours

However, every machine only knit one colour at a time. If the colour is changed, the machine has to be totally disassembled and cleaned in order avoid fluffs of wool in the wrong colour.

The product variation

Company A can deliver red, yellow and orange jumpers in sizes small, medium and large, and blue and green jumpers in sizes medium and large.

Competitive problems

Company A has some problems satisfying the demands of the customers and keeping a satisfactory cost level;

- *Cost in purchasing*
  The purchaser has a hard time getting a good bargain on paint and yarn. He has to manage five different paint types, and three different yarn types are bought from three different sub suppliers. The total volume of jumpers is divided between the three yarn types. If he gets above 10 tons of yarn on the same type, he can get a good discount. Sometimes they try to buy 10 tons of each yarn type, but the factory does not have the floor space to accommodate that much yarn and it is expensive to rent an extra warehouse elsewhere.
- *Colour process*
  The colour process is not flexible because each machine can only take one (or two) yarn type(s). It often happens that one or two machines are left useless in a few weeks, while the other machines are used 24 hours a day. Still, the stock capacity is limited. Company has tried to pursue a Make-to-stock strategy, but they failed to estimate the demands of the customers, and had a fatal Christmas sales once, with the wrong amount of coloured yarn produced.
- *The stock*
  The employees at the stock sometimes have difficulties managing the yarn in stock. The small and medium drums look like each other, and it often happens that the wrong yarn type is installed in the wrong knitting machine. Moreover, the quality of the yarn gets bad if it – after being coloured – stay

on the drums for more than eight months. The yarn gets stretched. Sometimes the employees at the stock have to throw away yarn because it has not been used.

- *Knitting process*
  The knitting process is not very flexible because each machine only takes one colour. Sometimes all customers suddenly ask for one colour, and then the factory capacity is highly limited.
- *Overall planning*
  The factory manager has problems planning the whole operations. It is often difficult for him to use all machines at their full capacity, and there are several different bottlenecks regarding jumper size and jumper colour. It is also hard to ensure that all knitting machines are fed with yarn. Sometimes there is too much small yarn and no medium yarn for the knitting machines to work on. The manager has employed two planners to keep track on this, but they are expensive.
- *The greatest challenge*
  The greatest challenge for Company A is the fact that the fashion in the coming season suddenly tend to favour green and blue jumpers in small sizes. But Company A can't make green and blue jumpers in small sizes. And since they are renowned for their unique dye process, they can't just ask someone else to dye a batch of green yarn.

Company A suffer from a rather classical situation characterised by two main challenges;

1. The *variegation points* are placed very *early* in the process chain
   a. The yarn is determined for specific size ranges even before it enters the factory
   b. The yarn is dyed as the very first step resulting in 13 different items in stock
   c. The colours are clearly also determined for a specific variant already when entering the factory
2. There is *little commonality* in the factory
   a. The colour machines 'notice' the difference between yarn types
   b. The knitting machines 'notice' the difference between colour variants

Company B

Across the street is company B. They have a different approach, and they try to compete with company A in the coming season. They have a different factory layout;

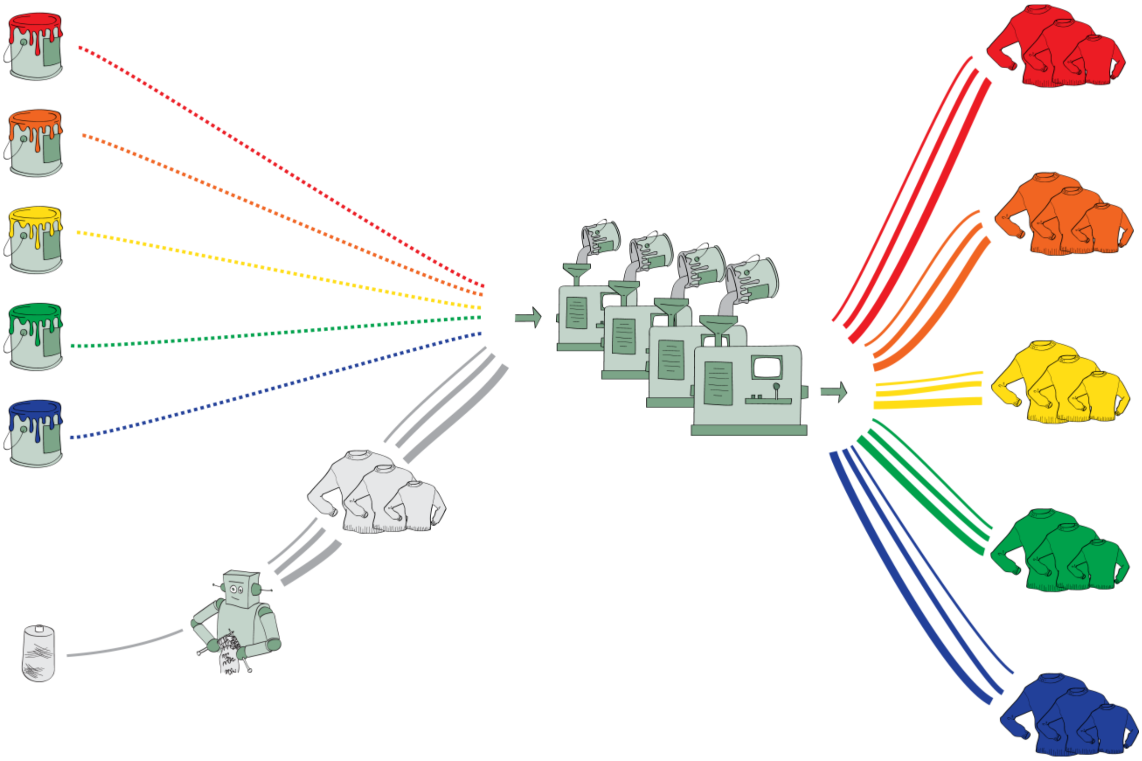


Figure 4.25b: Company B has a different approach from company A. They have much more commonality in the factory and their variegation points are postponed.

Figure 4.25b depicts the factory layout in Company B. There are several major differences from that of company A;

- Colour and knitting processes are swapped
  The colour process and knitting process have swapped places in the operations sequence. Thereby the colour dependency of the knitting machines is removed. Company B has the same type of knitting machines as company A. However, they are colouring machines that can take the knitted jumpers, instead of the yarn. Thus, Company B has only three items in their stock, that is, the three jumpers. Because there are no drums, the stock area is actually roughly the same size as that of Company A. By swapping the two processes the complexity of the in-house stock is reduced by a factor 13:3.
- Weaving is in-house
  The knitting process is coupled directly to a weaving process. This means that Company B can buy one type of yarn – the small type – and then weave the right size by using one, two, or three strains of yarn in their jumpers. Company A get more bargain power at their sub suppliers than does company B. They have a higher volume on only one yarn type. If the knitting process becomes too critical it can be duplicated, meaning that a series of knitting-weaving machines serve the same purpose.
- The colouring process is not an old school dye process but a printing process. This makes it possible for Company B to make different patterns, and make green sleeves and blue torsos. This is impossible for Company A.

- Instead of buying ready-mixed colours, Company B can mix their own colours. If suddenly customers want a lighter blue, Company B can change the tone of their blue by adding a bit of white. Company A will have to buy every single ready-mixed colour, if they want to compete on that ability.
- The number of raw materials is reduced compared to company A's five colour buckets and three yarn drums.
- Company B can do without the two planners in the factory. Their fixed costs are lower than Company A's.

Clearly, this is a simple example with a few important assumptions on investment, total costs etc. in the two companies.

Complexity

The jumper example above is rather simple, yet it gives an idea of the power of postponement, while also stressing that the full force happens when the logistics/operations setup is changed *together* with the product design. The jumpers in Company A & B are not fully identical – the product structuring principles are different.

There are less than ten purchased raw materials and less than twenty finished goods. An average manufacturing company has several thousand purchased goods and an equally diverse variation in the market place. Changing the products and the production setup can have immense power. If the example here is transferred to an average company, it would greatly reduce the cost of stocks and purchasing while making the company much more agile towards changing market demands and fluctuations in sales volume.

Complexity, commonality and postponement

Complexity is a major issue in many companies. Complexity is a cost driver. In the example above, the items in stock were more complex in Company A than in company B.

According to Hitchins [2003], complexity is a subjective thing and has to do with three aspects;

- Variety
- Connectedness
- Disorder

From a fundamental viewpoint, variety and connectedness have to do with viewpoints, i.e. the equivalent to variety and commonality. Disorder has to do with *structure* and essentially *encapsulation*. Think of the hard drive in a regular personal computer. It contains thousands of files, yet the average user is still able to navigate through the files, due to the classification in the folder structure. Classification is a kind of grouping and the folder structure resembles decoupling, thus encapsulation.

Miller [2001] further points out that decoupling in general lead to the reduction both structural and perceived complexity internally in the factory.

Complexity reduction is a platform effect

Encapsulation reduces the apparent complexity of a system. And as seen in the postponement example, a delay of the variegation point will reduced variety and potentially increases commonality, all of which helps to reduce complexity. Thus, complexity reduction is a key effect of a platform approach.

Encapsulation and reuse are prerequisites for postponement

Postponement – as in the jumper example above - is not just a change of planning and a change of production processes. It is also a change in the product. The final jumpers where changed so that they always consist of the small yarn type and the yarn types can then be combined in order to build medium or large jumpers. That is an example of encapsulation in the parts domain. The encapsulation makes it possible to reuse the same yarn type.

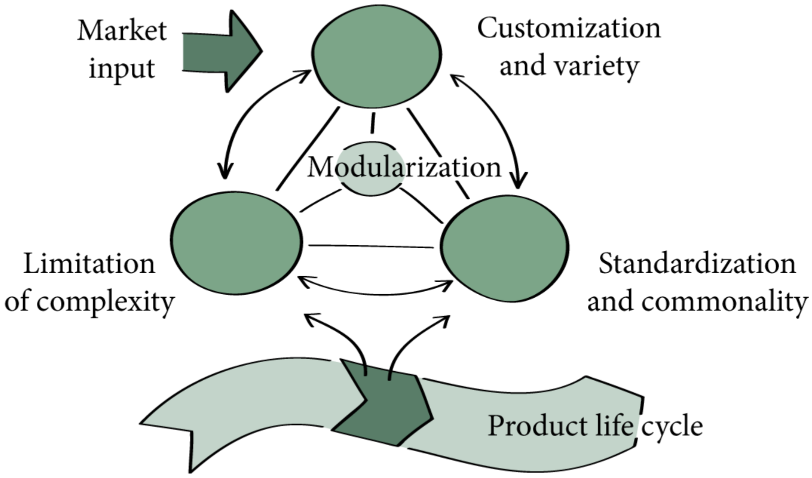
The colour variants were made from a highly flexible production process. From a constitutive product point of view the colour flexibility has to do with decoupling of organs, yet the example does not illustrate organ encapsulation very well.

4.6.3 General platform benefits

Encapsulation and reuse that enable commonality and variety gives a series of different derivative benefits, of which reduced complexity internally, increased lead time and increased flexibility are fundamental. Some of the most frequently reported benefits, such as increased flexibility and reduced lead time and cost have been commented during the above discussions and examples, and are found in several reviews [Andresen et al, 2004], [Gershenson, 2003], [Simpson, 2003], [Fixson, 2007].

Miller [2001] has proposed a general model of modularisation effects that largely cover the fundamental benefits of a product platform approach (figure 4.26). From a fundamental viewpoint, encapsulation and reuse are sufficient dimensions to explain the means to achieve the benefits below;

- *Resource leverage*
  All of the points raised by Miller are essentially about reuse
- *Limitation of complexity*
  All the points raised are essentially about encapsulation
- *Variety*
  Variety – with the presence of commonality – is a key issue. From a fundamental viewpoint, variety is a characteristic of all product ranges. The trick is to have variety AND commonality. Miller's so-called "not-wanted" types of variety are reduced by means of reuse and encapsulation.



Resource leverage	***Limitation of complexity***	***Variety***
Reuse resources gain rationalization benefits	*Decouple tasks and increase overview*	*Provide customers a well-fitted product*
• 'Avoid work' – not inventing the wheel over again • Working faster and better by learning effects and supporting tools • Reduce risks by using well-known solutions • Reducing internal variety, as it generates costs, but adds no value to the customer	• Break down in independent units • Work in parallel • Distribute tasks • Better planning • Better and easier perceived by humans • By encapsulation and creation of structures, humans can more easily grasp, understand and manipulate	• Provide useful external variety – the customer wanted variety created by combination of modules *The following types are not wanted:* • Useless external variety – choices the customer is not interested in • Internal variety – variation in processes, materials and solutions, which generate costs, but adds no value to the customer

Figure 4.26: The fundamental effects of reuse and encapsulation. Redrawn from Miller [2001].

4.7 Activity phenomena

Activity phenomena. This is the *how* question. How are reuse and encapsulation manipulated in platforms, in order to ensure the desired benefits? Activities are also defined as platform elements in Chapter 4.5. However, the focus in this chapter is specifically on the subset of activities that have to do with the conceptualisation and design of product platforms. Depending on the viewpoint on platforms, there is an overlap between the activities *within* the platform and activities *leading to* the platform. Consequently, parts of the following discussion could have been provided in chapter 4.5, while seeing activities as a constitutive *part of* the platform. However, the development activities are sometimes not regarded as a part of the platform, and moreover, the development context is a rather self-contained and important topic. Therefore, the *development of the platform* (preparation) and the *development of the derivative products* based on the platform (execution) are the topics of this chapter.

These two different tasks form the division of the chapter, into the following chapters;

- *Chapter 4.7.1: The preparation & execution split*

  This chapter gives a discussion on the split between preparation and execution activities. The development of a product platform is characterised by activity encapsulation in the sense that preparation and execution activities are grouped into separate sequences and decoupled from each one another.
- *Chapter 4.7.2: Preparing and executing the platform*

  This chapter provides a review of various product platform methodologies and seek to provide an overview of the general patterns. The reason to include such as review here is to provide the context in which the phenomena related to reuse and encapsulation have to fit. It is also a basis for the modelling discussions in Part 5.
- *Chapter 4.7.3: Conclusion*

  Some general conclusions on the development activities are given.

4.7.1 The preparation and execution split

The platform development process has one major difference from that of traditional product development and engineering design. The first one is a consequence of the nature of product platforms;

Product families rather than single products

The platform serves as a basis for several products among which a substantial amount of reuse takes place – i.e. a product family.

This difference has two main implications;

1) The platform is a preparation of design

The platform development is a design preparation upon which a stream of product variants is designed.

2) The development process has two main characteristics

The platform development process is characterised by preparation and execution.

The split between preparation and execution may be more or less explicit but it will always be an aspect of product platform development, in the sense that the platform is a preparation for something to come. *It is meant for reuse.*

The fundamental concept of preparation and execution split is depicted in figure 4.27;

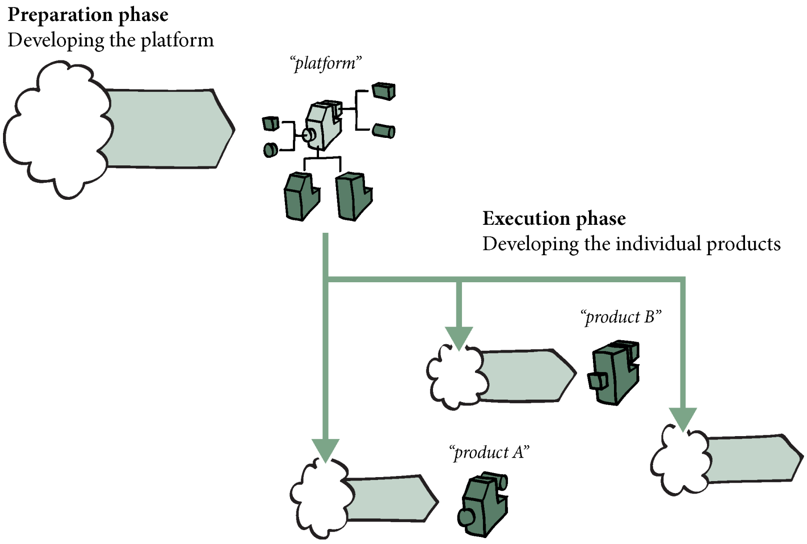


Figure 4.27: The platform serves as a preparation for the design of several products. This makes the development planning and development task different from the case of single product development.

In figure 4.27 the platform development process is shown in the top left. It is in this phase, the preparation of the platform takes place. On the basis of the platform, several development projects can be launched. Depending on company size and product type these *derivative* product projects [Meyer, 1997], may range from small scale projects with minor engineering design tasks, to major projects involving advanced R&D efforts. During the development of derivative projects, the platform preparation is constantly challenged and in some cases, the company may choose to incorporate new functionalities in to the platform, thereby expanding the platform.

These activities constitute a complex trade-off between multitudes of different challenges for the company. The following chapter will elaborate on the different challenges faced by decision makers in a product platform development context.

4.7.2 Preparing and executing the platform

From a design point of view, platform development is about designing the opportunities and limits for several different product variants that has to accommodate a common set of characteristics, and yet still be distinctive.

In industrial practice and reported in literature, there is great diversity in different approaches. Some have a rather strategic approach and seek to compose the product portfolio based on market trends [Meyer & Lehnerd, 1997], [Anderson & Pine, 1997], some include structured approaches to optimise internal factors, such as manufacturing and outsourcing capabilities [Ericsson & Erixon, 1999], and yet others have a relatively quantitative and product related focus, based mainly on an optimisation of existing designs [Hölttä & Otto, 2004].

Top-down and bottom up

Product platform projects can generally be divided in two major groups, not necessarily changing the nature of the project, but rather the starting point [Farrel & Simpson, 2003]:

- A *Top-Down approach* in which the company virtually start 'from scratch' and choose to design and develop a product family based on a platform.
- A *Bottom-Up approach* in which the initiatives are based on an existing product family. Consequently, the specifications are based on the existing product line.

Platform development projects may be of either kind or as a combination of both. The Danfoss case, reported in Part 5, was a redesign of a whole product family, and may - in the terminology of Farrel & Simpson above - be perceived as a bottom up approach. However, it proved impossible to just copy the existing specifications because they where the results of several decades of distinct and different product development projects. Instead, it was necessary to 'clean up' the specifications in order to distil a platform design that would have commonality and variety in a cost efficient way. Simply bringing all existing designs into the platform was not possible, because the tradeoffs would be too many and the side effects too large. Moreover, there were some processes and details within the product and production designs, which were changed substantially. In that respect, the Danfoss approach in product platform development is a mix of a top down and bottom up approach.

In fact, a complete top down approach is relatively seldom, as most companies have a history to base their decisions on, and an installed base to have in mind. However, cases like the Sony Walkman [Sanderson & Uzumeri, 1995] are examples of product family design that is initiated without a strong product history.

General patterns in platform development

Despite the many different approaches to product platform development, a few fundamental characteristics, apart from the split in execution and preparation, are noteworthy. The following list, gives a general overview of some fundamental challenges and decisions in a product platform project, all of which are found in various methodologies;

Platform preparation

- Scoping the platform
    - Often as a trade-off between customer needs and design capabilities
- Designing the platform
    - Grouping and decoupling of reused and variable attributes in the platform
    - Inducing the highest possible variety in the product family
    - Inducing the highest possible commonality in various life phase systems

Platform execution

- Creating derivative products from the platform based on customer requests

Maintenance

- Apart from the strict preparation/execution, the platform also have to be maintained and upgraded

There are many challenges associated with the development of product platforms, and the above is by far not an exhaustive list. However, the list reflects some of the important and fundamental decisions, which various decision makers have to address while making and managing platforms. Decision making – and modelling of the platform – is a challenge in all steps, ranging from the scarce details in the beginning to the very concrete and detailed designs in the end. A model of the platform has different roles and purposes during the course of the project.

Scoping the platform

Scoping the platform is a very important part of product platform development [Meyer & lehnerd, 1997]. During the case studies and particular in the Danfoss case, that particular challenge turned out to be an immense task to master. Some products were discontinued while others were changed slightly or substantially. The large installed base was probably the greatest challenge in the scoping discussion, thereby making compatibility with older products a potential obstacle and *platform initiative killer*.

Scoping the platform has to do with choosing which of the market segments and customers to satisfy. Any product platform project – should the knowledge not already be present in the company - ought to start with a carefully managed process of gathering market data and input, in order to clarify which of the product variants to keep inside and outside of the platform scope.

The Power Tower below, depicts that challenge, and work with two fundamental differentiations in the market place, that is, different customer segments with various demands, and the value added in each segment, i.e. whether to denote the segment *economy, deluxe* or somewhere in between [Meyer & Lehnerd, 1997] (figure 4.28);

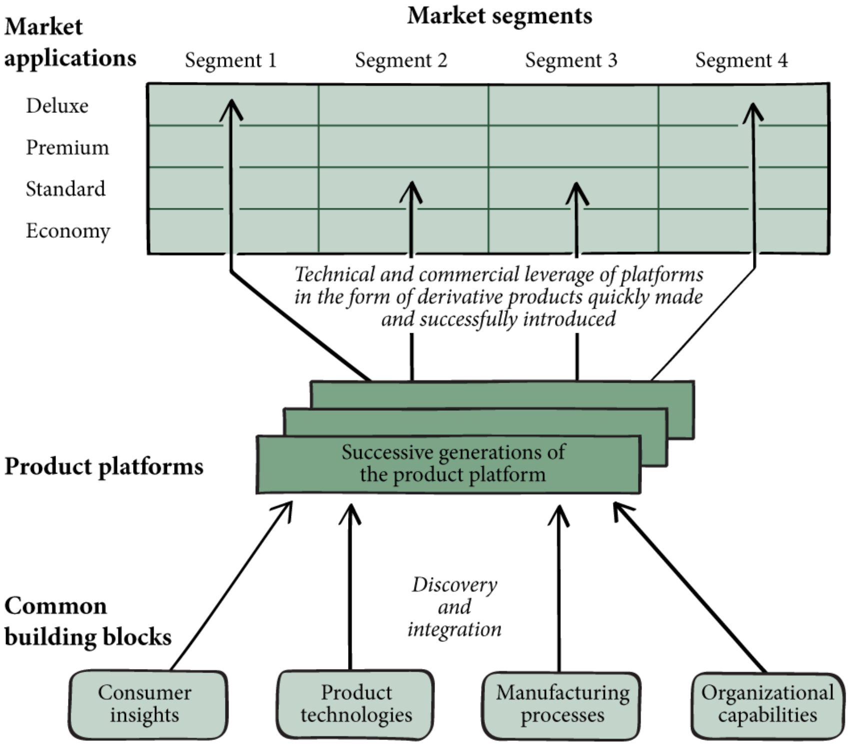


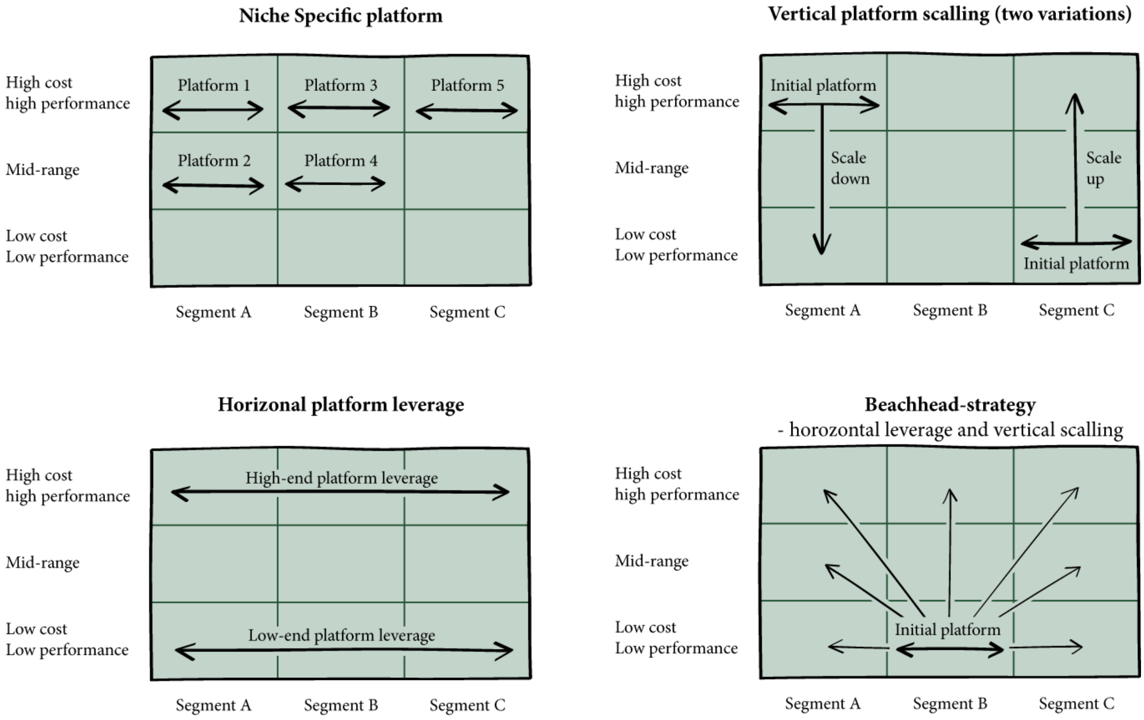
Figure 4.28: The Power Tower, adding a map of the platform and how it fits various customer segments, (Redrawn from Meyer & Lehnerd [1997]).

In the Power Tower, Meyer and Lehnerd distinguish four different strategies for how to cover and expand a market place with a product platform;

- *Vertical platform scaling*
  The platform operates within a certain customer segment on several performance levels. There is scale-up and scale-down depending on the initial platform.

- *Horizontal platform leverage*
  The platform operates across customer segments on the same performance/cost level
- *Niche specific platforms*
  Each market niche has its own specific platform
- *Beachhead strategy*
  This strategy has a starting point in a low cost/low performance niche and is subsequently scaled to other performance levels and other customer segments.

The four strategies are shown in figure 4.29;



Niche Specific platform

Vertical platform scalling (two variations)

Horizonal platform leverage

Beachhead-strategy
- horozontal leverage and vertical scalling

Figure 4.29: Four strategies for a platform approach in a market place [Meyer & Lehnerd, 1997]

Sometimes, the existing products are a good basis to gather the required information. Consequently, some approaches has an initial step in which existing product families are mapped in order to clarify which segments and niches that are to be addressed by the platform, [Meyer & Utterback, 1993].

The platform extend

The outcomes of the scoping of the platform are some sort of overview of the platform contents or *extend* from a customer perspective, [Simpson et. al., 2006], [de Weck, 2006].

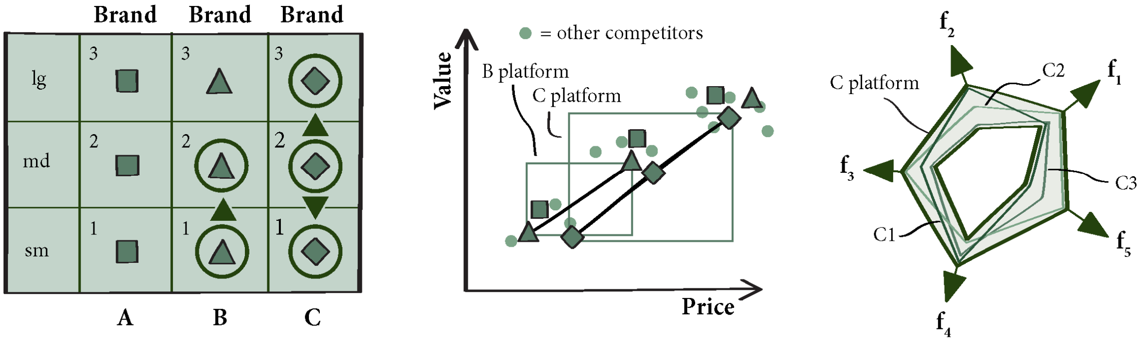


Figure 4.30: The platform extend for three different products (large, lg; medium, md; small, sm) visualised in three different dimensions; (a) In an market segmentation grid, (b) mapped as performance in a value and price space, (c) and as functional performance, [Redrawn from de Weck, 2006].

Figure 4.30 depicts three different ways to perceive the platform extend of three competing platforms in a hypothetical example [de Weck, 2006]. The platform extend is a subjective and diverse topic depending on viewpoint. However, key performance indicators (to the far right in the figure) of the derivative products are often a good indicator of the *extend* of the platform.

The market segmentation grid is also used to map various market demands within the same target group, [Farrel & Simpson, 2003] (figure 4.31);

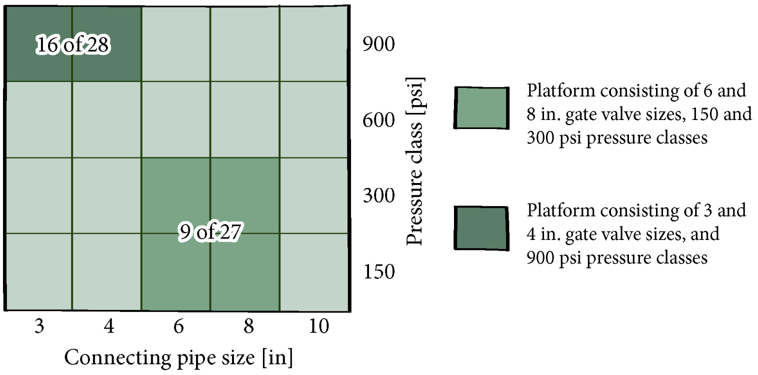


Figure 4.31: A market segmentation grid depicting two distinct platforms in a two dimensional function space [Figure redrawn from Farrel & Simpson, 2003].

Sawhney [1998] points to the fact that the *core* (i.e. the platform candidate(s)) is not necessarily the same from a customer perspective and from an internal operations perspective. There is a danger that companies will form their platforms based on internal technology reasons and not characteristics of the market place. Others add to this, that platforms need to integrate the internal competences in the company with the needs of the market [Yang & Jiang, 2006]. An initial analysis of the actual customer needs, along with an estimation of future trends, will greatly help reduce the risk of a technology driven platform, which is pushed to the market place without sufficient customer pull in the end.

Including the customer

Product platform development has long been viewed as the way to achieve success with Mass Customization in the mechanical engineering industries. Some trends indicate that future research should point towards improvements in the closeness to customers, i.e. understanding of differentiating factors and the whole buying experience (pointing towards configuration systems), manufacturing and logistics, performance measures in order to measure the performance in various dimensions and then – important in this thesis – the design of products that suit a Mass Customization strategy [Jiao et al, 2004].

Designing the platform

There are various top down and bottom up approaches to product platform design [Simpson et al., 2003]. A fair share of these approaches is based on function modelling and the desire to essentially map function to form in a desirable way in order to achieve certain benefits [Ulrich & Eppinger, 2000].

Function based methods

Stone et al [2000a + 2000b] propose a method based on so-called *function heuristics* following a rather quantitative approach including function vectors, i.e. vectors that express the functions as the dimensions and the customer needs rankings the magnitude of that vector, much like the spider visualisation in the figure above. The fundamental concept is to derive a future state functional layout of the product based on customer input, and from that basis design the physical products. The flow of decisions and activities are shown in the figure below;

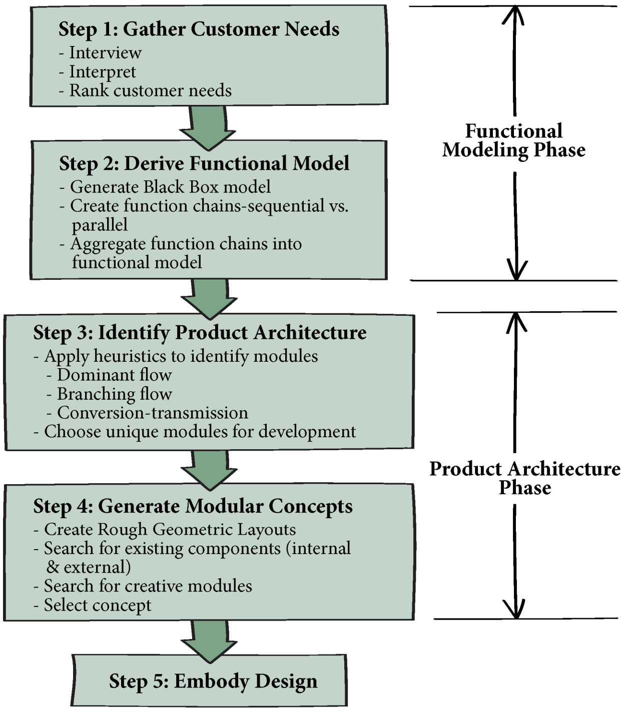


Figure 4.32: A platform design methodology based on function heuristics (Redrawn figure [Stone et al., 2000a+b]).

A *heuristic* is an indication on a possible solution not based on solid evidence but rather as a best guess based on readily available data. The basic idea of the heuristic approach is that encapsulation (modularisation) candidates may evolve from an analysis of the required functions on a certain level of decomposition (Step 2) and then define dominant flows, branching flows, and conversion-transmission pairs (Step 3);

- *"Dominant Flow Proposition:* the set of sub-functions which a flow passes through, from entry or initiation of the flow in the system to exit from the system or conversion of the flow within the system, define a module.
- *Branching Flow Proposition:* parallel function chains associated with a flow that branches constitute modules. Each of the modules interfaces with the remainder of the product through the flow at the branch location.
- *Convert–Transmit Proposition:* a conversion sub-function or a conversion–transmission pair or proper chain of sub-functions constitutes a module [Stone et al., 2000b]".

From analysing these flows, *functional module* candidates emerge and thereafter the rough geometrical layout (much like the quantified structures of Tjavle [1979]) can be designed (Step 4). Finally, the embodiment design may take place.

Including the Bill-of-Material

The function basis is also used in the "Bill of Material Platform identification methodology, (BOM-PIM)" and the "Function-Based Platform Identification Methodology (FCN-PIM)", [Simpson et. al 2006]. Both methodologies are used to dissect the products and then cluster components in a reengineering attempt, on the basis of the present design, i.e. a kind of bottom up approach using the Top-Down/Bottom-Up terminology to distinguish the platform approach [Simpson & Farrell, 2003]. The BOM-PIM use relations between components as a clustering parameter. The FCN-PIM use functional relations as a clustering parameter. However, all functions (and all relations) have to do with the use of the product, and the related sub-functions, and does not consider module drivers that are not directly related to the use phase. Production processes for example, can be mapped to the components thereby giving the opportunity to cluster components based on the same processes. How to redesign with new components in order to create new effects is not covered by the methodologies. One worry might be that the methodology will lead to incremental rather than radical improvements to the design. Moreover, the concept of meetings in several life phases is not incorporated.

Schematics

Ulrich & Eppinger [2000] use the term *schematic* to denote a sketch of the "constituents" of the product. The schematic is used as a first step (provided that knowledge on the markets and desired segments are at hand). The elements in the schematic may be formulated as *designs* and *concepts* ranging to less concrete *ideas* on how to solve the sup problem to fully abstract formulations of *functions* without any implications on the physical design solution. As the project progresses, the functions become concepts and the concepts become designs. Following the work on a schematic, Ulrich & Eppinger propose the phases of *element clustering*, which is essentially the mapping from function to form, as in the product architecture earlier defined by Ulrich [1995]. Different clustering drivers such as *function sharing*, *geometric integration*, *capabilities of vendors*, *localisation of change* etc. are mentioned to govern the clustering process. After the schematic and clustering, Ulrich & Eppinger propose two more phases, resulting in a step by step procedure encompassing a total four steps:

1. *Create a schematic of the product*
   Which is essentially a process of assigning functions and design solutions to the design problem
2. *Cluster the elements of the schematic*
   Which is essentially to group the elements (not necessarily thinking of how to decouple the elements)
3. *Create a rough geometric layout*
   Resembles the quantified structures of Tjavle [1979].
4. *Identify the fundamental and incidental interactions*
   These are essentially the desired (interactions) as well as those interactions that happen due to physical principles, such as heating, vibrations etc. (incidental).

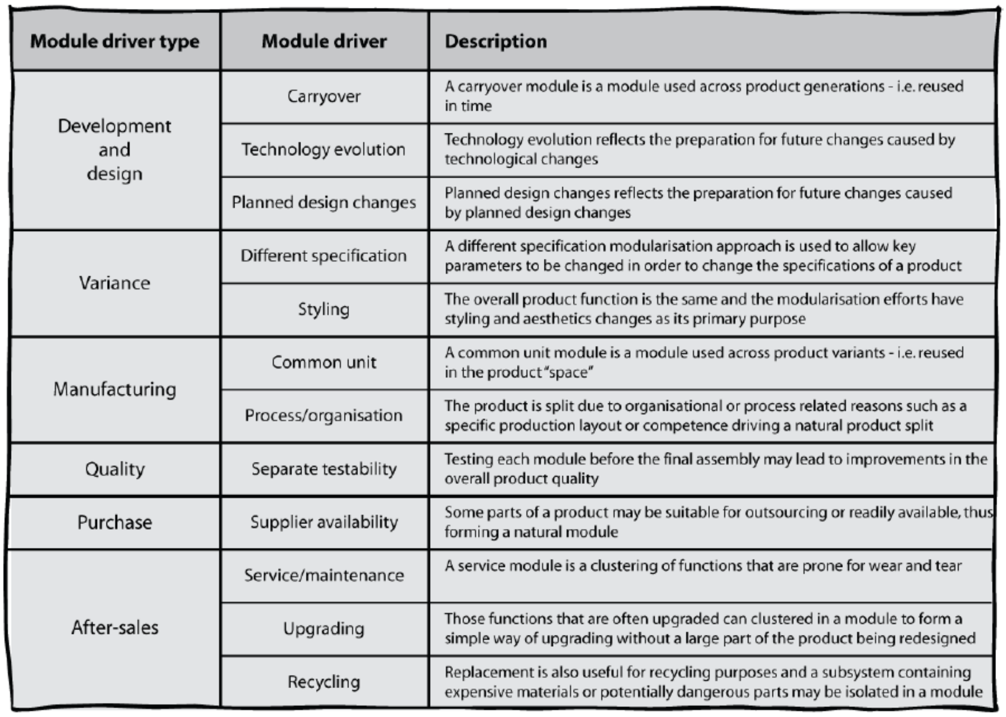
The method is based on the idea of *chunks* i.e. physical subassemblies that become modules, once the clustering and interface designs are made. Thus, there is an emphasis on physical decoupling in the parts domain.

Modular Function Deployment

The clustering drivers from Ulrich & Eppinger [2000] are somewhat similar to the module drivers in the *Modular Function Deployment* (MFD) framework proposed by Gunnar Erixon [Erixon, 1998] and later expanded [Ericsson & Erixon, 1999] even though MFD seem much more substantial and elaborated.

The fundamental basis of the Modular Function Deployment are the *so-called* module drivers. They govern the design of the products and they reflect the desired benefits and effects.

The module drivers are shown in figure 4.33;



Module driver type	Module driver	Description
Development and design	Carryover	A carryover module is a module used across product generations - i.e. reused in time
	Technology evolution	Technology evolution reflects the preparation for future changes caused by technological changes
	Planned design changes	Planned design changes reflects the preparation for future changes caused by planned design changes
Variance	Different specification	A different specification modularisation approach is used to allow key parameters to be changed in order to change the specifications of a product
	Styling	The overall product function is the same and the modularisation efforts have styling and aesthetics changes as its primary purpose
Manufacturing	Common unit	A common unit module is a module used across product variants - i.e. reused in the product "space"
	Process/organisation	The product is split due to organisational or process related reasons such as a specific production layout or competence driving a natural product split
Quality	Separate testability	Testing each module before the final assembly may lead to improvements in the overall product quality
Purchase	Supplier availability	Some parts of a product may be suitable for outsourcing or readily available, thus forming a natural module
After-sales	Service/maintenance	A service module is a clustering of functions that are prone for wear and tear
	Upgrading	Those functions that are often upgraded can clustered in a module to form a simple way of upgrading without a large part of the product being redesigned
	Recycling	Replacement is also useful for recycling purposes and a subsystem containing expensive materials or potentially dangerous parts may be isolated in a module

Figure 4.33: The 12 module drivers [Ericsson & Erixon, 1999].

The module drivers in figure 4.33 are used as evaluation criteria in a series of activities that form the Modular Function Deployment framework. The fundamentals steps are to establish an overview of customer needs through the use of a slightly changed Quality Function Deployment (QFD) methodology. (The QFD methodology is not further described here, as it is considered to be a relatively well known concept. The reader is encouraged to see an introductory Harvard Business Review paper [Hauser & Clausing, 1988] for more details on QFD if necessary). The QFD gives an indication of customer needs and the weighting of these needs. They are mapped to desired functions, and technical solutions are found to these functions. The solutions are then mapped to the module drivers in a Modular Indication Matrix (MIM), in which the solutions are clustered based on the various module drivers. The result of that analysis is a list of module candidates, i.e. possible ways to perform grouping of technical solutions. This is somewhat equivalent to the clustering activity in the above mentioned methods. The strength of the MFD approach lies mainly in the structured assignment of module drivers to various functionalities, forcing the designers to think of various ways to group functions into the product. The module drivers are not only based on the functional layout and expected flow and interactions *within* the product, but much more on relational properties concerning various life phases. Thus, the MFD framework somewhat take meetings into account and acknowledge that effects occur in meetings and not just by partitioning the product in a certain way. Figure 4.34 depicts the iterative sequence suggested in the MFD framework;

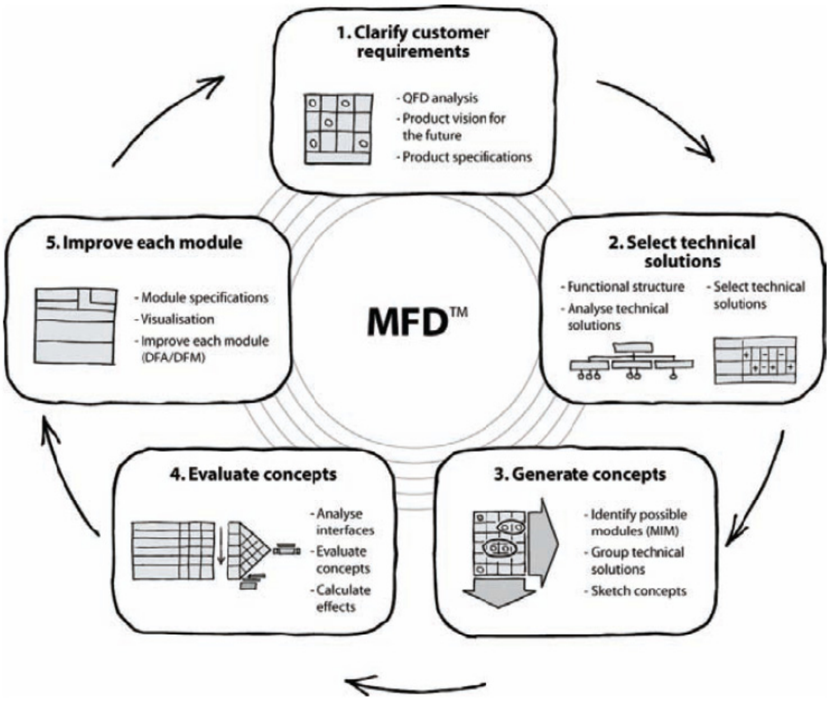


Figure 4.34: The MFD framework. 1) Customer needs are clarified, weighted and 2) translated into functions. Technical solutions to the functions are established and these solutions are then 3) mapped to the module drivers and grouped accordingly. Concepts are sketched and 4) evaluated. Interfaces are analysed and effects calculated. Finally the modules are designed and design for assembly/design for manufacture is accounted for.

The module drivers are also used in the *Product Architecture Design* methodology, PAD, [Lanner & Malmqvist, 1996]. PAD incorporates cost issues as a design parameter along with interactions between *organs*. Note that Lanner & Malmqvist use organs instead of design solutions, pointing towards a limited mapping to the parts domain. *Organ structures* – as an abstract structure of design principles - are coupled with the module drivers of the MFD framework [Erixon, 1996], [Ericsson & Erixon, 1999], and then assigned to a cost analysis.

Quantitative and analytical methods

The Product Platform Concept Exploration Method [Simpson & Mistree, 1999], [Farrel & Simpson, 2003] is a methodology in which product platform concepts can be generated. A key issue is the distinction between *parametric* and *configurational* platforms, the difference being whether component attributes are changed (scaled) or components are interchanged.

The steps of the methodology are shown in figure 4.35;

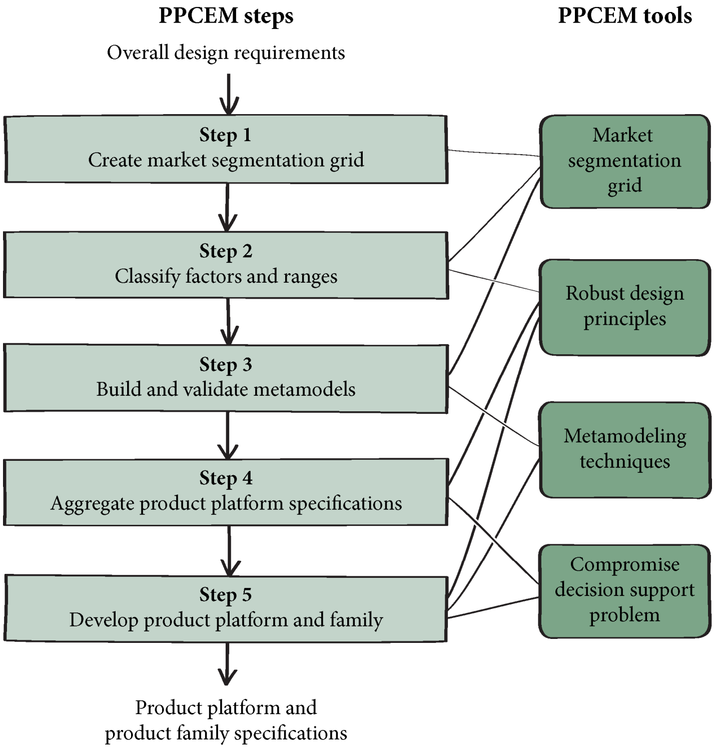


Figure 4.35: The Product Platform Concept Exploration Method. Market needs are gradually transformed into a product platform [Farrell & Simpson, 2003].

1. *Create a Market Segmentation Grid* (described in the former section, and in figure 4.30(a))
   The basic purpose is to get an overview of the markets that the platform has to cover, as it is pointed out by Meyer & Lehnerd [1997], in their horizontal, vertical and beachhead platform strategies respectively (see figure 4.29)
2. *Classify factors and ranges*
   This step includes a mapping of the overall design requirements and the market segmentation grid into appropriate factors and then assign ranges for these factors. It means that key parameters are

chosen and that these key parameters are then subject to scaling, i.e. they determine the variation of the platform.

3. *Build and validate metamodels*
   A metamodel is a statistical tool that enable relatively complicated models to become simpler and solveble by means of inexpensive computer tools. The purposes of the metamodels are to have a model that relates customer requirements with the scalable factors. Metamodels are extensively used in the various works of Timothy Simpson [Simpson et. al., 2001].
4. *Aggregate product family and product platform specifications*
   A formulation of the design of the platform and the derivate products in the sense that the solution space is made on the basis of the market segmentation grid and the factors and ranges from the statistical analysis in the metamodel.
5. *Develop the product platform and the product family*
   This step is basically turning the specifications from step 4 into a physical design.

In this approach, statistics and the formulation of factors (the varying parameters) play a vital role, and in that respect the methodology is rather quantitative. How to include manufacturing and assembly issues, and thereby taking various life phase steps into consideration in step 4, is somewhat unaccounted for. It is, however, outside the scope of this research to judge the usefulness of the methodology. The key issue to bring forward is the fundamental sequence of activities, in the sense that the customer's requirements are established, the platform coverage is established and thereafter the actual design starts.

Metrics and matrices

A large body of research, mainly from the US, reports on the use of various indices and metrics as a (mainly reengineering) approach to various design optimisation problems. The drivers of these studies vary, from ensuring an optimum commonality among components, component sharing between products, mapping variety across generations in order to design accordingly, mapping component sharing among product variants, mapping couplings between components or mapping process commonality, [Fisher et al, 1999], [Hölttä & Otto, 2004], [Jiao & Tseng, 2000b], [Siddique & Rosen, 1998], [Martin & Ishii, 2002]. Some of these quantitative trends expand the calculation efforts to optimise life phase aspects such as customer needs and manufacturing cost, [Williams et al, 2007], [Fixson, 2004], or deriving function structures based on the variations in customer needs and from there cluster components into modules [Zamirowski & Otto, 1999]. Others have a slightly more analytical approach and seek to derive generally applicable equations as representations of design tradeoffs from which optimum designs can be achieved [Fischer, et al., 2004], [Jiao & Tseng, 2000a]. Some report on the use of rather intangible criteria such as customer satisfaction, after-sale, and organization when screening for platform concepts [Hölltä-Otto & Otto, 2007], thereby not only focusing on the internal properties of the product structure but also the relations to more strategic drivers for modularisation. Likewise, brands are mapped against functionality, in similar approaches, [Sudjianto & Otto, 2001].

Modularisation Implementation Profile

Another initiative is the Modularisation Implementation Profile MIP, [Riitahuhta et al, 1998], that rely on stakeholder analysis, by gathering input from key personnel in an organisation. The attempt is thereby rather qualitative in its measures and metrics, making it somewhat less vulnerable to wrong assumptions than the more mathematically oriented approaches.

The MIP framework incorporates rather intangible yet highly important modularisation effects such as growth, profitability and knowledge potential.

Dynamic Modularisation, DYMO

Riitahuhta also points to the fact that a continuous approach is necessary once the platform is implemented and has to be upgraded. This is accounted for in the so-called DYMO framework of Dynamic Modularisation, which is described in the following way [Riitahuhta & Andreasen, 1998b], [Lehtonen et al., 2003];

"Dynamic Modularisation is the novel Modularisation process, which allows bringing in a dynamic way new, technologically or in another way more merited modules to the system and leaving out old ones. This process is based on the definition of the encapsulation, similarities and the description of interfaces as well as Modular Management System. All different stakeholders' views should be taken into account; other dimensions will be very similar to those defined Modularisation."

One ambition has been to extend the framework into a Virtual Reality type of design tool in which organs, rather than physical parts can be manipulated [Riitahuhta, 2001] much like the qualified structures in the design work of Eskild Tjalve [Tjalve, 1979] (see Part 3, chapter 3.3.1 for more information on Tjavle's problem solving model), and the rough geometric layout of Ulrich & Eppinger [2000]. The challenge of assigning a three dimensional geometrical layout of the products is equivalent to the single product case (i.e. normal product development and engineering design methods). However, in the platform case, the trade-offs are mode complex due to variation and the fact, that the same quantified structure has to accommodate varying needs.

The challenges of continuous platform development are accounted for in a thesis by Nielsen [2009].

Using visual models during design

Emphasising *visual modelling* and *establishing* an *overview,* the following design sequence is the result of one of the case studies from this thesis (The Danfoss case reported in Part 5). It had a focus on visualising the meetings in the *production* (that is fabrication and assembly), and the customer needs. (The steps below are slightly adopted from Pedersen et al [2005a+b] and Mortensen et al. [2008a] for the purpose in this thesis);

- *Step 1*
  Establish an overview of customer needs.
- *Step 2*
  Establish an overview of product functions and means (organs) necessary to support a product platform design and prioritise the properties according to business opportunities.
- *Step 3*
  Create a graphical overview of the generic organ and parts structure of the platform
- *Step 4*
  Find alternative solutions –of encapsulation in the part and organ domain - to serve the identified functions/organs and model the space of solutions to give a graphical overview of the possibilities.
- *Step 5*
  Identify and model the manufacturing processes to give a graphical overview of the possibilities.
- *Step 6*
  Combine the different solutions using the generic structure of products in the architecture.
- *Step 7*
  Combine the different processes that support the solutions chosen, so as to generate a draft production layout.

- *Step 8*
  Visualise and evaluate concepts.

The approach given above is somewhat different from many of the reported methods in literature, in the sense that it rely heavily on visual modelling and conceptual work rather than quantitative metrics and analytic relations. This is done on the basis of the assumption that decision makers have to see the platform in order to manage it – the same assumption that is used when phrasing Research Question 2 in this thesis. The figure below depicts a part of the modelling environment, in which a generic organ skeleton serves as the basic placeholder for alternative solutions to design problems. The alternative design problems are added as puzzles in a jig saw puzzle (figure 4.36). Thereby, the design engineers can visualise various concepts based on the same generic organ structure.

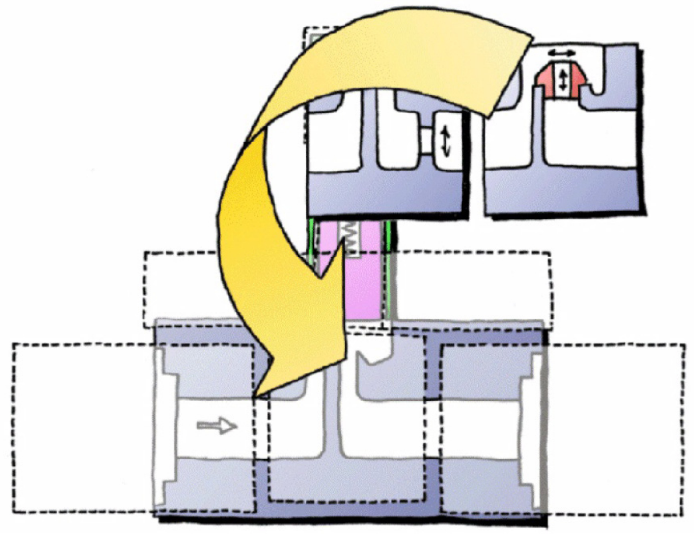


Figure 4.36: The basis of the method is to make a model of a generic organ structure (organ skeleton) of a solenoid valve. Alternative organs (principle design solutions) are added to the structure as puzzles in a puzzle piece.

The puzzle approach is also used to generate alternative production sequences with various manufacturing and assembly processes put in sequence. That allowed the design engineers to evaluate the degree of postponement in various design alternatives, and thereby (qualitatively) estimate the effect of *meetings* between the products and the production.

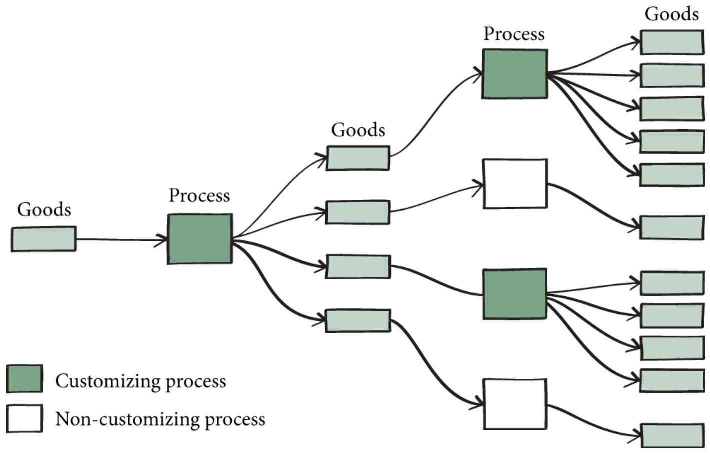


Figure 4.37: Forming a production layout based on puzzle pieces depicting customising and non-customising processes, enabled the design engineers to evaluate the degree of postponement for various design alternatives.

The design methodology has been published in the International Journal of Mass Customization [Mortensen et al., 2008a], and also further elaborated – from a modelling perspective – in the Danfoss case in Part 5. However, the intention in this thesis is not to prescribe a methodology but to point to various modelling aspects. Therefore the sequence of the model and the strength of this approach as a design synthesis approach are not tested in the thesis. Focus is on the models, and how they serve as a decision base for design engineers and other stakeholders involved in platform development.

Here, it is sufficient to note the sequence of decisions, i.e. first start with an overview of customer needs, a scoping of these needs and then a conceptual phase in which the trade-offs between commonality and variety are accounted for by means of encapsulation of attributes – in this case in both product platform and production.

4.7.3 Conclusion

The various platform development methods all share the fact that the platform serves as a basis for several products and that the methods has the purpose to ensure commonality and variety by means of encapsulation of design units. It is also evident that a split in one or more preparation and execution phase(s), is a general approach, in the sense that a generic layout is designed and then final products are made on the basis of that layout (the platform).

It is not the intention of this thesis to prescribe a certain methodology. The platform elements are described in order to understand the activities and decisions that a product platform development project involves. Some of these activities are themselves subject to reuse and/or encapsulation and thereby as such elements of the platform. Reuse of design methods, design rules and design knowledge – especially in the execution case - is a key factor.

The general pattern in the development of a platform calls for various demands on a platform model. In the beginning of a project, the designs are on a very conceptual level. Later, it becomes more detailed and more concrete. However, due to the nature of platforms – and the fact that multiple products are designed in one go – some products may be well established while others may be just on the starting point in a conceptual phase. This was a great challenge in the Danfoss project, in the sense that some products were tested and near finished (with CAD drawings, various certificates etc.) while other products were merely and intention, and the design work had not begun yet. All of these products still had to be managed as a whole.

This chapter has focused on the typical sequence of decisions in a product platform development project. The modelling challenges are further described in Part 5.

4.8 Phenomenological framework

4.8.1 Introduction

Providing a literal answer to Research Question 1 could very well result in a long yet incomplete list of phenomena related to reuse and encapsulation. The concepts of reuse and encapsulation in the organ and part domains are introduced and discussed in the former chapters. However, these are rather fundamental phenomena and they do not span all the different platform definitions. If the generic dimensions in the different definitions can be identified, it will be possible to describe different platform perceptions from the same basis. Therefore, the following section will provide a framework for companies to derive their own perception of a product platform based on the different dimensions in various platform definitions, which are evident from the current state of literature and practice. The ambition is to make a widely applicable yet very concrete way to define a product platform in various applications.

The structure of chapter 4.8

The question is then to find out what life phases and what platform elements that are included in figure 4.39. The following chapters will discuss the life phases, the platform elements and the meetings between these;

- *Chapter 4.8.2: Decision making*

  On the basis of the decision node and decision map (Chapter 3.4, [Hansen & Andreasen, 2004]), a few general points of view on decision making is discussed. It is stated that decisions – from a fundamental point of view – have to do with deciding on the meetings between platform elements and life phase systems. This discussion is elaborated in the following chapters.

- *Chapter 4.8.3: The platform elements*

  On the basis of the discussions throughout Part 4, a classification of platform elements is provided.

- *Chapter 4.8.4: The life phases*

  Various life phase systems inspired by the Theory of Dispositions is discussed.

- *Chapter 4.8.5: A space of meetings*

  The platform elements and the life phase systems span a space of meetings in which different reuse and encapsulation effects occur. This space of meetings constitutes a framework in which various phenomena can be identified.

- *Chapter 4.8.6: Concluding on the framework*

  A general conclusion about the space of meetings

4.8.2 Decision making

The fundamental driver for Research Question 1 is to provide a better decision base for decision makers in companies pursuing a platform approach. From the review above it is clear that there exist very fundamental aspects to decide upon, of which some is listed below:

- What effects are desirable and where are they possible to obtain?
- What elements are included in the platform?
- How is the platform designed?
- How is the platform produced – what is the postponement strategy?
- What other life phases (apart from production) are important?

The decision node

In the engineering design decision making theory [Hansen & Andreasen, 2000], the following five design objects are included:

- The product
- The life phase systems
- The meetings between the products and life phase systems
- The business
- The design process

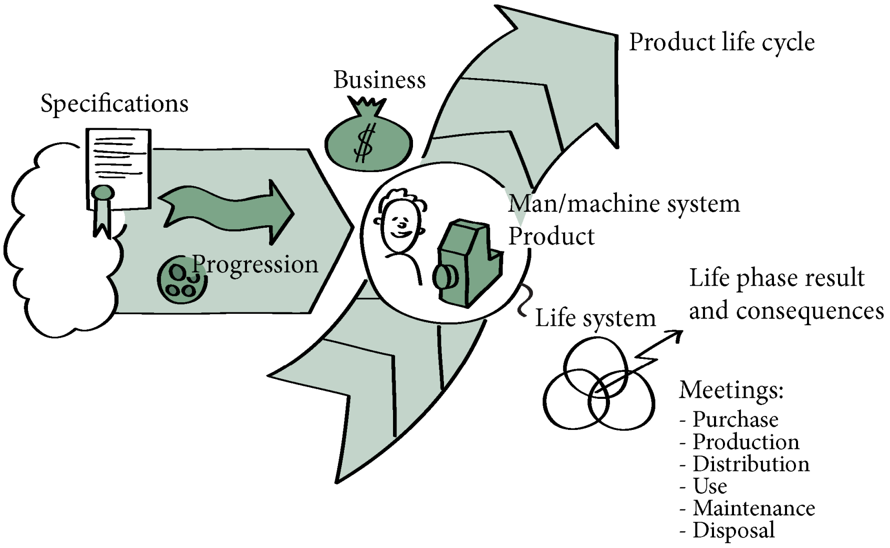


Figure 4.38: The product and the life phase systems result in meetings. Decision makers have to know about the meetings in order to decide upon the business, [figure from Hansen & Andreasen, 2000].

Based on the reviews in the former chapters, two of the five decision objects are considered to be fundamental:

1. The product
2. The life phase systems

The other three are somewhat derivatives of the product and the life phase systems. If the *product* is replaced by the *platform elements*, and the design process is thought of as a process in a certain life phase system (the design system), the platform elements, and the life phase systems will span all decision objects in the decision map in figure 4.38. The meetings are derivatives of the various platform elements and the life phase systems, and the business is a derivative of the meetings.

In order to make the decisions, the decision maker has to have knowledge. And if knowledge is split into *know-how*, *know-what*, and *know-why* (which is done in the argumentation for Research Question 1 in Part 1 chapter 1.3.3, and Part 2, chapter 2.2.2) and reuse and encapsulation are accepted as the fundamental design degrees of freedom of a platform manager to change, the following generic sequence of questions emerges;

Product platform decision making:
"A decision maker has to know
HOW, WHAT and WHY,
...it is possible / desirable to
REUSE and ENCAPSULATE
...different
PLATFORM ELEMENTS
...in different
LIFE PHASES
...in order to achieve the right
PLATFORM EFFECTS"

In fact, this question is relevant in every single *meeting* between various platform elements and various life phases. And if platform elements and platform life phase systems are accepted as two fundamental dimensions, a meeting space is can be spanned from the two;

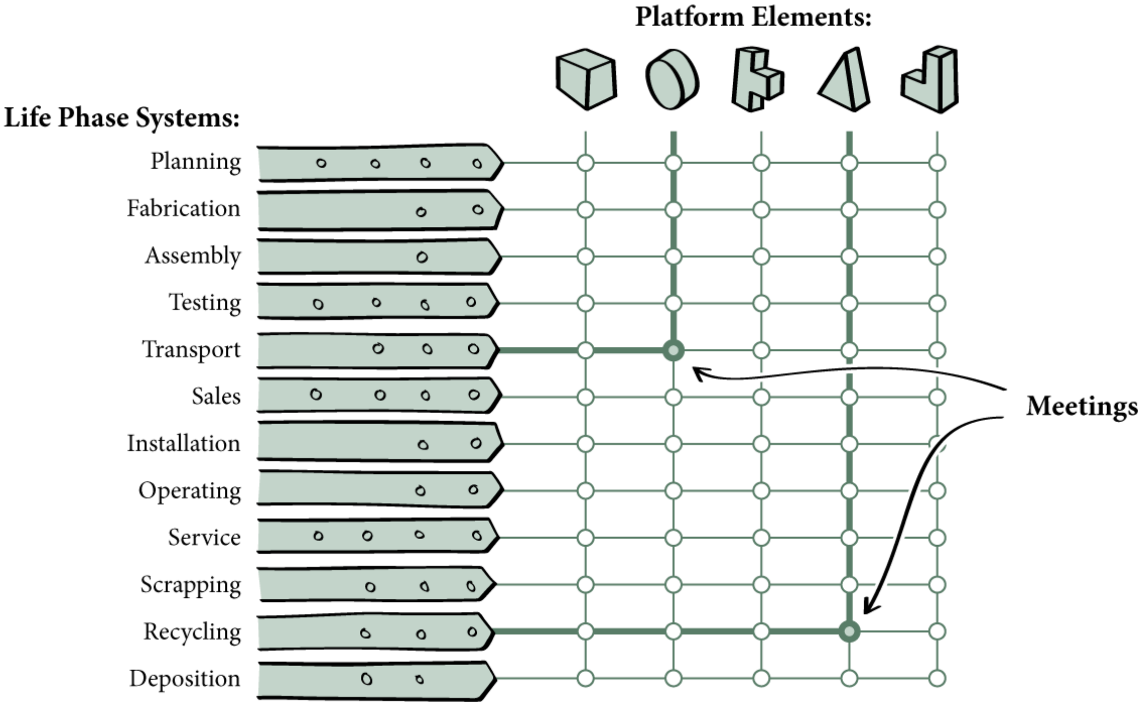


Figure 4.39: Various life phases and platform elements span a solution space for meetings, in which platform effects occur, and in which various platform related phenomena also occur.

4.8.3 The platform elements

In order to get closer to an understanding of all of these various perceptions, and look for common denominators, it seems feasible to distinguish the platform elements by their *type* or *kind,* i.e. to classify the platform elements. There are many different elements to reuse in an industrial project. Is a drawing a platform element? Is a person a platform element? Is a process or service a platform element? And what do these elements have in common and how are they related?

This section will discuss a classification of platform elements based on the review in chapter 4.5.

Explaining the platform element classes

Several references report that a platform is not only about sharing physical components or features of components. As it is pointed out in the conclusion on the review of platform elements (chapter 4.5.6), *product/hardware/artefact* related, *knowledge* related and *activity* related elements seem to be distinct classes of elements. These elements are all subject to reuse and/or encapsulation.

- *Product related constitutive elements*
  The product related elements can be constitutively explained by means of a part domain viewpoint and an organ domain viewpoint. Functions are not taken into account, because they happen in *meetings*, i.e. they are relational and not constitutive.
- *Activities*
  From a product platform viewpoint, activities are constitutive in the sense that they are subject to reuse and encapsulation. Activities are sequences of actions carried out by human beings or machines

(production equipment, computers etc), or a combination hereof. Activities should not be confused with the effects of the sequences. The effects are relational, whereas the activity itself is constitutive.

- *Knowledge*
  Knowledge is understood as the knowledge in the minds of people and the knowledge documented in some form in the company [Miller, 2001]. Thus, the constitutive knowledge elements are understood as the documented knowledge. Clearly, knowledge is viewer dependant, and has to do with pre-established knowledge and the ability of the users to comprehend knowledge documented in various forms.

And of a slightly different nature than the above three element classes;

- *People & relationships*
  People & relationships are both platform elements and platform users. Robertson & Ulrich [1998] and Kristjanson and colleagues [Kristjansson, et al. 2004] include people and relationships to their perception of common/shared assets. People are different from the other elements (besided being human beings) due to the fact that people are both objects of the platform, and users of a platform model, i.e. a product architecture.

Even though not stressed in many mechanical engineering definitions of product platforms and product architectures, software is an obvious platform element. In fact, many of the virtues of standardised designs and interfaces arise from the programming and software industry, and the modularity work of Baldwin & Clark [1997 + 2000], is founded in a software and computer industry context. The concept of architecture as a function to form mapping, is also widely used in the software and programming industry. In that sense, the mechanical engineering industry has adopted lately what the software industry has done almost from the very beginning.

Buur [1990] points to the fact that function carriers (organs) are also supported by software as well as electronics. Electronics is somewhat physical, and is thereby in this thesis perceived to be covered by the parts domain in the Theory of Domains. Software, however, is a rather special case due to the intangible nature of software. For the purpose of this thesis, software is regarded as a possible platform element class, different in nature from the other classes.

This gives the following platform element classes;

Platform element classes

All of which are subject to reuse and encapsulation

Parts

Parts are subject to reuse and encapsulation and make up the products.

Organs

Organs are – like parts – subject to reuse and encapsulation. Organs are made of wirk elements. Organs also make up the products, yet from a more abstract viewpoint that the case of parts.

Software

Organs may reside in software, and software is included as a unique class of platform elements due to the intangible nature of software. CAD programs are software, yet CAD drawings and models are considered to be knowledge.

Activities

Activities are sequences of actions carried out by human beings or machines (production equipment, computers etc), or a combination hereof. Certain production steps, or design sequences are considered activities.

Knowledge

Knowledge refers to the knowledge – tacit as well as tangible – that has to be present in order to excel in a specific life phase. Knowledge is also an object of reuse and encapsulation. Drawings, CAD models, product models etc. are considered as knowledge.

People & relationships

People & relationships cover the organisational aspects of the business. The people in the organisation play a vital role in the platform, and are considered as platform elements (however somewhat different from the other element classes) while also being the users of the platform and the platform model.

4.8.4 The life phases

In the life phases, the *meetings* occur and the *alignment* takes place between the platform and various life phase systems. An extensive list of life phases for (single) products is provided in the Theory of Dispositions [Olesen, 1992] (see Part 3, chapter 3.2.4).

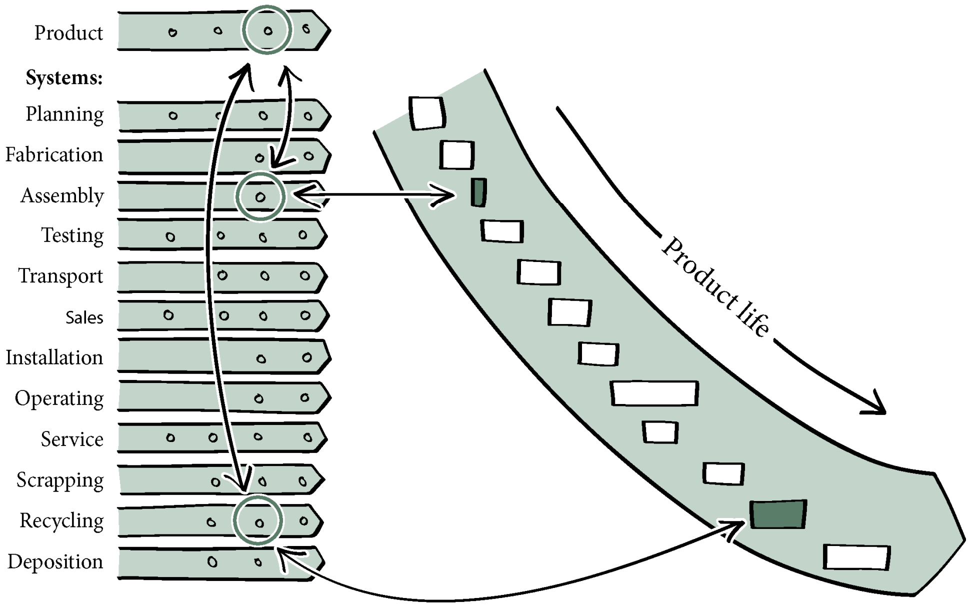


Figure 4.40: Various life phase systems of a product [Olesen, 1992].

A life phase systems is the system that the products meet, i.e. the systems that the products have to interface with during various life phases. A platform also engages in meetings in similar life phases, and the platform also has interfaces to life phase systems.

On the basis of the review of platform definitions and platform development methods in the former chapters, it seems feasible to add the design process, as a meeting – and to distinguish the execution design phase from the preparation phase.

Purchasing turned out to be a major challenge in three cases. From the postponement example in chapter 4.6.2, (and literature on postponement in general [Brun & Zorzini, 2009] it is also evident that purchasing is an important carrier of platform effects. Thus, purchasing is added to Olesen's list.

Olesen's planning refer mainly to scheduling in the production activities. But planning is an equally important task in the preparation of the platform and in the two fabrication steps (and of course as an implicit part of virtually all activities). However, in this case, planning is emphasised in the preparation of the platform and in the production life phase systems (fabrication + assembly).

Explaining the life phase systems

Platform preparation, platform execution, and purchasing are added to Olesen's list of life phases for the purpose of this thesis. Transport, installation, and deposition are not included in the list, as they are considered to be outside the scope of the case companies. Nevertheless, in other contexts these omitted life phases are relevant and can be included in the list of life phases.

The remaining life phase systems are;

Platform Planning & Preparation

This is the initial development phases of a product platform project. In this phase the product platform is designed. The layout and limits of the platform is determined. The life phase “system” is the set of design tools, designers and decision makers the platform has to interface with.

Platform Execution

These are the ongoing activities that occur once the platform is gradually launched and being used as a *design template*. Design engineers accommodate customer requests on the basis of the design limits provided by the platform.

Purchasing

Purchasing is a strategic as well as a day to day activity. Strategic purchasing activities determine price deals and long term relations to suppliers. Day to day ordering and purchasing activities execute the strategic purchasing on a short term basis.

Fabrication (& planning)

In the fabrication system, goods are changed from one state to another state. In mechanical engineering businesses it is often different kinds of mass reducing (cutting, milling, grinding etc.) and mass preserving (annealing, heat treating, hot stamping, die casting etc.) processes.

Assembly (& planning)

In the assembly system several components or goods are joined together into an assembly. There are several subgroups to assembly. There are several assembly processes such as mechanical (screwing, snap fitting etc), chemical (welding, soldering etc), and combinations hereof. From the discussion on interfaces in chapter 4.5.5, it is seen that assembly and joining may be permanent, semi-permanent or temporary.

Testing

Quality Control is a discipline covering several of the above phases. This life phase refer to the final testing or testing taking place late in the value creation. Some reports on modular product platforms report separate testing as a major advantage. One of the Module Drivers in the Modular Function Deployment framework [Ericsson & Erixon, 1999] is called *separate testability*.

Sales

The sales process is important. Here knowledge about the product may be a physical product, and a sales person meets the customer. The products do not necessarily “meet” the sales person, but the knowledge about products is vital in order for the sales person to perform well. Encapsulation of knowledge and sales tools such as a configuration system may make it simpler for the sales person to maintain an overview of the product range.

Operating

In the traditional single product case, this is the meeting between the single product and its use phase. From a platform perspective this phase is not as much about products being used by the end users. This is the meeting between the *totality* of the platform and the *totality* of the market demands i.e. the platform *extend* [de Weck, 2006]. Operating the platform determines the demands for variety and price, along with other product specifications.

Service

Service may benefit from reuse and encapsulation. Xerox (www.xerox.com) is renowned for the ability to replace modules on site making way for a quick service [Chesbrough & Rosenbloom, 2002].

Recycling

In the disposal phase, the product is scrapped and/or reused. Disposal is often synonymous with some kind of disassembly and reuse, which has dispositional relations back to the fabrication and assembly phases.

4.8.5 A space of meetings

The *elements* of the platform and the *life phases* combined result in the *meetings*. The meetings are important because they drive the *platform effects* – the drivers of any platform approach. Within each platform element class, different meetings can take place depending on the life phase systems the platform elements that are confronted with each other.

Mapping the life phases and the object classes gives the following *space of meetings*;

	Platform Elements					
Life Phase Systems	Parts	Organs	Software	Activities	Knowledge	People
Platform preparation						
Platform execution						
Purchasing						
Fabrication						
Assembly						
Testing						
Transport						
Sales						
Operating						
Service						
Recycling						

Figure 4.41: Meetings may occur between different platform elements in different life phases. The different meetings create different effects, and platform designers have to be well aware of their intentions when designing the meetings.

The table in figure 4.41 provides a framework or *space of meetings* for listing different meetings between platform elements and life phases. Each square corresponds to different meetings. Clearly, there are more life phases and it is also possible to expand the number of platform element classes. However, the figure gives some 66 different types of meetings and thereby a concrete way to exemplify different platform elements. In these *meetings* various platform phenomena occur.

Know-how, know-what and know-why

The space of meetings provides an overview of the sites of *reuse* and *encapsulation*.

According to the introduction in Part 1 and later discussed in Part 2, decision makers need to posses know-how, know-why, and know-what in order to have a strong decision base. Therefore these three questions can systematically be asked to each meeting.

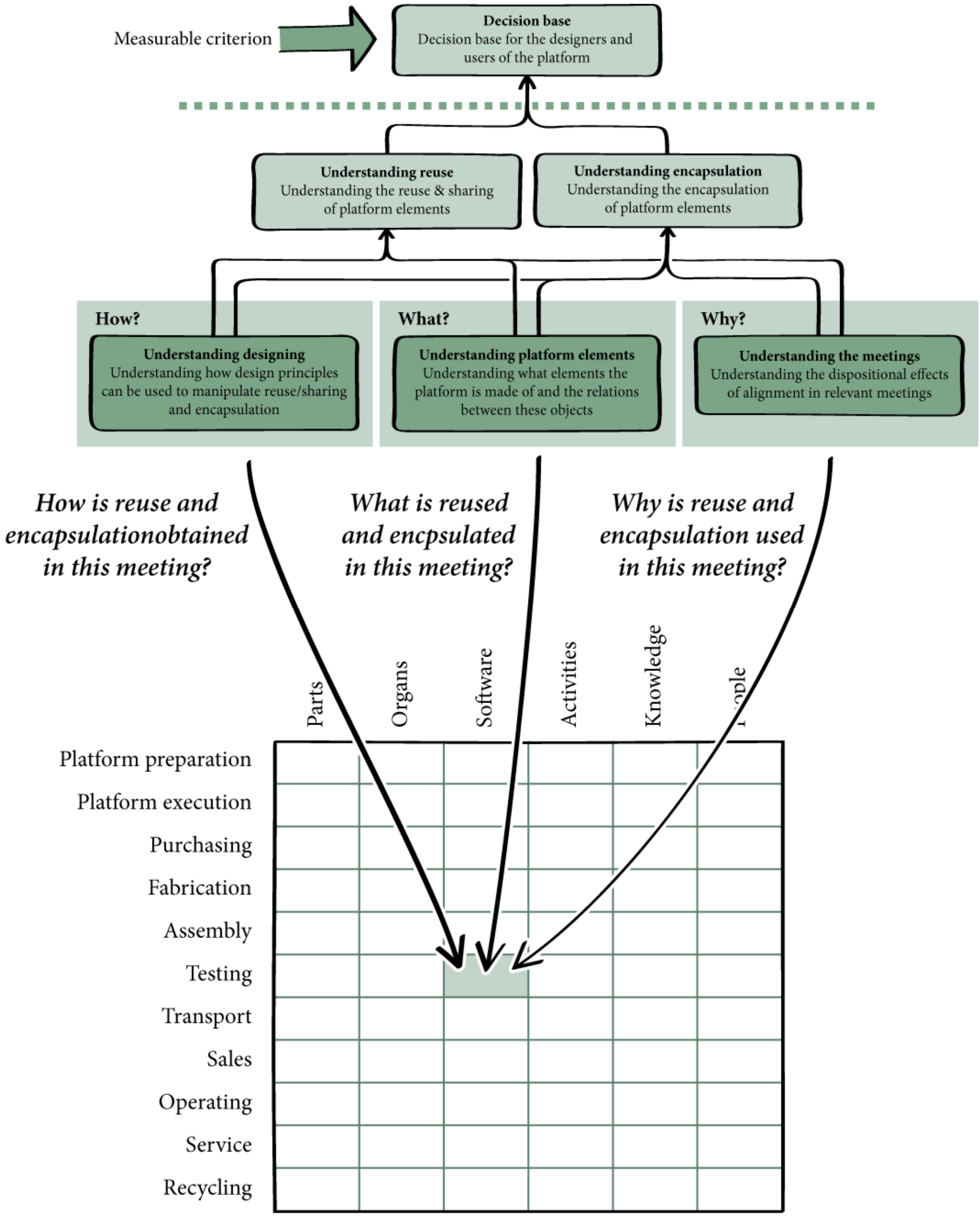


Figure 4.42: For each meeting, the following three questions can be asked: How is reuse and encapsulation obtained in this meeting, what is reused and encapsulated, and why is reuse and encapsulation pursued?

Figure 4.42 depicts a *phenomenological framework*. This means that a company can navigate through the framework, pick relevant meetings and – for each of the selected meetings – ask the three fundamental questions of how, what and why, reuse and encapsulation takes place in the meetings, in order to derive their own list of relevant phenomena to include in the modelling efforts within the company.

Knowledge

As of now, knowledge as a *platform element class* and knowledge as in the HOW, WHAT WHY questions have been discussed. What is the difference? Here, knowledge within the platform and knowledge about the platform is distinguished. The knowledge in the platform element classes refer to the instantiated knowledge, i.e. knowledge that is documented. The framework as a whole point out what a platform model has to document, and what decision makers have to think of. Clearly, there will be an overlap in some dimensions, and from a certain perspective, the platform model itself, will become an instantiated piece of knowledge and thereby a platform element.

The point is that documented knowledge is a potential *part of* the platform, but the decision makers still have to know *how* and *why* that knowledge is reused and encapsulated, *what* the knowledge is about. And this how-why-what-knowledge is also about the other platform elements that do not have to do with knowledge.

4.8.6 Concluding on the framework

A framework or space of meetings is proposed in chapter 4.8. It provides a systematic way to go through some 66 different types of meetings and derive the elements of reuse and encapsulation from that. More life phases can be added and more platform element classes are also feasible. The framework is shown in figure 4.42.

Regardless of the elements and life phases chosen, the concept of the framework is able to span most platform definitions, whether they are focused on products, subassemblies, hardware, knowledge, working patterns, manufacturing procedures and processes etc. The fundamental concept is to map life phases and platform element classes, and in the resulting meetings identify different concrete platform elements and ask *how*, *what* and *why* reuse and encapsulation takes place.

4.9 Concluding on Part 4

Research Question 1 is about identifying platform phenomena from a constitutive, behavioural and activity point of view.

4.9.1 Research contributions

In the search for answers to Research Question 1, Part 4 has provided an explanation to the concepts of encapsulation and reuse;

Encapsulation

Encapsulation is seen as the fundamental activity of *grouping* and *decoupling* elements in a system. It is argued that grouping and decoupling are fundamental activities in a product platform approach.

Reuse

Reuse is what makes product platform development different from single product development. Reuse is what makes groups of products become product families. Variety is often stressed as a key aspect of product platforms; however, variety is only interesting if it comes with a certain degree of reuse. As a consequence, commonality and variety are discussed as important effects of product platforms.

Constitutive phenomena

A review of platform perceptions, and a discussion on what a *platform is made of,* i.e. different *platform elements* is provided in Part 4. It is argued that constitutive platform elements may be divided into the following classes; parts, organs, software, activities, knowledge and people.

Wirk elements and skeletons

It is further noteworthy that within the part and organ domains, one may manipulate wirk elements and form feature elements respectively. These detailed elements are related in organ and part skeletons.

Product architectures

The concept of product architectures is discussed, and it is pointed out that an architectural understanding mainly has to do with mapping from function to form. Modularity and integrity are discussed. From a perspective of the Theory of Domains, a modular architecture is a mapping between transformation, organ and parts domains, i.e. a decoupling of grouped elements in all three domains. It is argued that there is a need for another architectural understanding, in which decoupling in the organ domain can take place without a corresponding decoupling in the part domain. Decoupling of organs and wirk elements can take place as a consequence of process flexibility, whereas decoupling in the part domain mainly has to do with assembly flexibility.

Behavioural phenomena

The behavioural phenomena are understood as the effects of a platform, i.e. what happens when the platform meets a life phase system. The fundamental effects of platforms lie within increased efficiency and effectiveness in the organisation, i.e. doing more with less. Complexity reduction, reduced lead time in production and development, *postponement* and increased flexibility are a few of the most important effects of product platforms.

A major driver for product platforms, are the phenomena of variety and commonality as a viewpoint dependent characteristics of platforms.

Activity phenomena

Finally, the activities in a platform project are accounted for, and typical sequences of decision making in product platform development projects are discussed. It is argued that any platform project has preparation and execution characteristics, due to the nature of platform serving as a fundamental preparation of a *family of products*, and not just a single product.

A framework for deriving phenomena

On the basis of the three studies above, it is argued that product platform definitions are either based on what platforms *are made of*, *what they do* (the effects) or *how they are developed*, or a combination hereof. A fundamental constitutive definition is hard to phrase in a single sentence. Therefore a *space of meetings* is proposed as a function of platform element classes and platform life phase systems. From this framework some 60+ meetings can be identified, and in each meeting, the phenomena and platform elements can be derived, in concrete cases. Thus, virtually any of the contemporary platform perceptions will fit in the framework.

4.9.2 Verification and validation

The work on Research Question 1 is of a rather theoretical nature, and has not as such been validated. On the bases of Olesens [1992] five characteristics of validation, one can state the following about the findings in Part 4. The most important proposal in Part 4 is the concept of reuse and encapsulation in the organ domain. That proposal is discussed from a validation point of view in the following (see Olesen's original list in chapter 2.5.1)

- *Internal logic*
  Hopefully – yet out of the hands of the author to judge – there is an internal logic in the way the different phenomena are reviewed, discussed and proposed.
- *Truth*
  It is a fundamental point of view in this thesis that the concept of encapsulation in the organ domain is seen in practical applications, and is therefore a "true" observation. The cases in Part 5 show various applications of the concept.
- *Acceptance*
  The concept of encapsulation has not been peer reviewed or tested out – apart from the indirect tests in the models in Part 5.
- *Applicability*
  This thesis will claim the applicability of the concept, based on the use of the models in Part 5.
- *Novelty value*
  From the reviews in Part 4 (and 5) is seems fair to claim that no existing systems descriptions or references on the topic or product families and product platforms, talk about encapsulation (or modularisation) in the organ domain, and stress the nature of wirk element encapsulation and the importance of skeletons. Few – if any – authors have dealt with the skeleton concept in a product family context. The concept is used in two of the three cases in Part 5 to control variable and generic attributes in a product family by means of a part skeleton in a hierarchy of CAD files.

Generally, most of the findings in Part 4 are proposals, which have not been tested. The final judgement is left to the reader.

5

Visual platform modelling

In this Part of the thesis the challenges of visualising product platform phenomena and information about the platform are discussed. Various existing attempts to product and platform modelling are reviewed and discussed in the context of visual modelling. Thereafter, three industrial cases are used to illustrate how various platform elements have been visualised in different models. These modelling attempts cover phenomena that are covered by the framework proposed in Part 4, in which meetings between platform elements and life phase systems play a vital role when identifying the elements within the model. The different models in Part 5 are used from the early conceptual phases of a platform project to the final implementation and use of the platform.

5.1 Introduction

This part of the thesis (Part 5) is about visualising the phenomena discussed in Part 4. The power of visualisation and modelling in product development and conceptual design has long been acknowledged by industrial practitioners and in academia [Tjalve, 1976], [McKim, 1980], [Andreasen & Hein, 1987], [Henderson, 1998], [Ulrich & Eppinger, 2000]. The challenge of modelling a product platform is somewhat different from modelling single product concepts and designs for a number of different reasons. As pointed out in Part 4, there are some fundamental phenomena intrinsic to the topic of product platforms, of which some impose great challenges on the task of modelling a platform;

- The platform is a design template for several products – not a single product
- The platform is both a concept and a design template – thus the design template has to be designed (preparation) and thereafter derivate products are designed (execution)
- The platform has limits – either in combinatorial sets or in ranges of parameters
- The platform may consist of various intangible elements such as activities or organs
- There are many complicated tradeoffs to account for in a platform project
- Some elements in a platform are generic while other others may vary

- There are profound implications on product complexity and efficiency in the links to the life phases, and in particular to the production setup.

These are but a few of the many modelling challenges tied to the topic of product platforms. There are different demands for modelling in the conceptual phases of platform development, where the platform is designed, and the execution phases where the derivative products are designed on the basis of the platform.

5.1.1 The structure of Part 5

Part 5 provides a discussion on *visual platform modelling*. Visual is understood as a graphical, simple, and intuitive representation of a phenomena or information. Many existing models are rather detailed models with a relatively complicated syntax – however, this is a subjective characteristic, as the interpretation of syntax and language is depending on the knowledge and mindset of the spectator (see chapter 5.4.2).

On the basis of the phenomena identified in Part 4, present modelling methods for product families, product architectures and product platforms is discussed, and thereafter the framework from Part 4 is used to identify relevant modelling elements in three different platform projects in industry. Finally the usefulness of the framework and the models in the three projects are discussed.

Apart from this introduction, Part 5 includes the following chapters:

Chapter 5.2: Modelling platforms

This chapter includes a general discussion on the demands for modelling product platforms, and a discussion on the interplay between visual models on paper and computer models. It is an elaboration of the introduction and it relates to all of the three cases.

Chapter 5.3: Existing modelling attempts

This chapter provides a review of the current state of modelling approaches. During the review different demands are discussed. In particular it is explored to what extent existing models are visual, to what extent they incorporate; the ability to model generic and variable attributes; the ability to model a product family rather than just a single product; and the ability to represent the products, i.e. as a visual model of the product, rather than a schematic representation. It is concluded from the review, that encapsulation in the organ domain – which is one of the proposed phenomena in Part 4 – is not directly included or sufficiently provided in any existing modelling approach.

Chapter 5.4: Introducing the cases

This chapter gives a general introduction to the choice of case companies. The role of mindset transfer is also discussed. The author engaged in education activities in the companies in which a certain mindset was transferred to the employees of the company. This somewhat bias the findings of the cases, yet it is considered to be a necessary prerequisite in order to induce a change in the companies – and the change was in fact the research object, i.e. studying how the employees experience of the decision base might change.

Chapter 5.5: Danfoss Automatic Controls

In Danfoss, a product platform project is described. The author has participated in a platform project from the beginning in the first conceptual phase, until the platform was gradually implemented. Different visual models are presented in the case. On the basis of a visual modelling tool different concepts were generated with different degrees of encapsulation in the parts and organ domains. The platform ended up as a mainly combinatorial platform, i.e. in which standardised components and interfaces are combined to form products (a classic modularisation example). A game is also introduced in this chapter (chapter 5.5.8). The game was used as a model of activities and as a teaching session.

Chapter 5.6: Using Top Down Design in CAD

The concepts organ and part skeletons are discussed in Part 4. In this chapter, the use of skeleton modelling in CAD systems is discussed. The chapter is included here, because skeleton modelling is used in the following two cases, (Aker and Grundfos). Skeleton modelling is emphasised in the two cases as a readily available and very strong way to control generic and variable attributes in a product family, and thereby as a design strategy for product platforms. The use of skeletons in CAD systems also gives a practical dimension to theoretical discussion of organ skeletons and wirk elements in Part 4.

Chapter 5.7: Aker Solutions

The Aker Solutions case is characterised by a high degree of modelling in the CAD system, meaning that most the platform model is kept in the CAD system. The design information on the platform was embedded in a series of CAD models. The models were made using a skeleton resembling the spatial relations between form feature elements. By having a functional viewpoint on the form feature elements, the skeleton models came very close to being organ skeletons. The skeletons serve as generic placeholders for various form elements, such as surfaces and axis, from which the attributes of different parts are inherited.

Chapter 5.8: Grundfos Technology Center

The Grundfos case reports a practical application of the concept of wirk surface encapsulation. Another finding from the case is that various sets of standardised activities, software packages and knowledge elements can serve as constitutive parts of a platform. These different assets are visually modelled mainly using a Product Family Master Plan [Harlou, 2006]. The platform consists of various standardised work flows, and models in ERP, PDM and CAD systems. Skeletons are also used to model representations of wirk elements in a CAD system.

Chapter 5.9: Mapping the cases

This chapter gives a comparison of the three rather different projects in the above cases. Using the framework from Part 4, the *meetings* of the three cases are visualised, giving an impression of the different effects and phenomena in the cases.

Chapter 5.10: Concluding the cases

This chapter includes a discussion on the validation and confidence in usefulness of the models, and concludes on the three cases and the discipline of modelling product platforms.

5.2 Modelling platforms

Management of platforms and the difficult trade-offs is a challenge in industry, and there are still several opportunities for academia to support industry in the efforts to excel in decision making [Simpson et al., 2006c]. One of the major assumptions in this thesis is that a visual modelling approach can help decision makers navigate through the various trade-offs [Dahl et al., 2001], [Shooter et al, 2005], [Mortensen et al., 2008a + 2008b].

However, the vast majority of present research within product and product platform modelling falls into one of the following two categories;

3. Computer modelling efforts with an intention to build software computer models, such as those supported by PLM systems or configuration systems.
4. Phenomenon models describing the concept of platforms or product architectures from a relatively theoretical standpoint.

Somewhere in between these two modelling classes one can envision models that hold more detailed and concrete information than the theoretical phenomenon model, and are more visual and intuitive to understand than the strict modelling syntax often needed in a computer model. This is the core of Research Question 2, i.e. to build upon the findings in Part 4 and seek ways to model the discussed phenomena in an industrial context – a step beyond the various phenomenon models that have been discussed in Part 4.

There is a rather shallow body of research on the topic of *visual product platform models*. Hopefully, the following chapters will contribute to this body of research.

Interfacing with a computer context

In the introduction of the thesis in Part 1, it is discussed how visual models may be kept somewhat outside computer systems, in order for the platform model not to depend on a specific computer system, but rather serve as a directory for the information in various different computer systems. Moreover, printed posters have the advantage that large print outs can be made, providing a better overview, and a more interactive modelling media than most wide screens can provide.

Virtually any company today, build and maintain various product models in computer systems. CAD systems are often the primary design and documentation tool in many situations. ERP systems keep track on components and processes, and contain bills of material and keep track on product-assembly hierarchies. Some companies use PDM systems to keep track on different types of documents. Therefore, an important aspect of a platform model, which is not itself a computer model, is to interface with the tools and techniques already present in the company and turn these into an asset in the model, depicted in figure 5.1. Another important point is the fact that these computer systems are likely to hold valuable information and still hold various product models even with a platform model as a supplement. Thus, the two halves of figure 5.1 are supplementary rather than mutually exclusive;

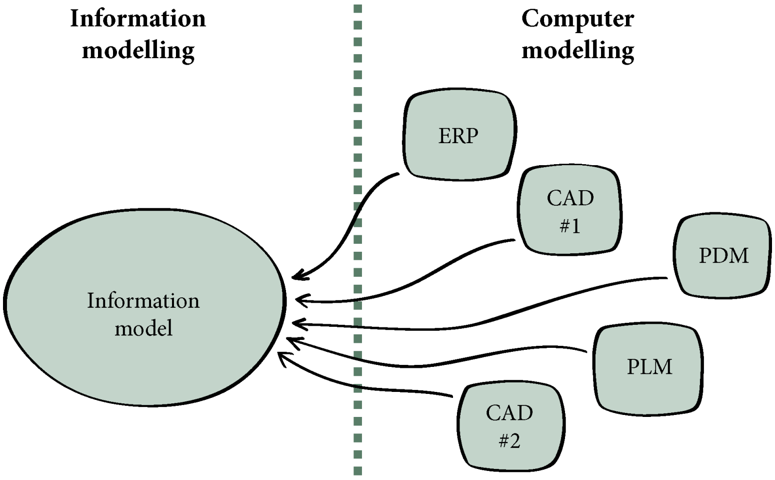


Figure 5.1: A platform model has to interface with the existing modelling tools. Many of these will be computer tools such as commercial CAD and ERP systems. In these tools, various product models are already found. Thus, the information model does not tell the full story about the platform and some of the information is stored in the computer models.

Despite the fact that many tools are computer based today, many other tools are available. Pen and paper are important tools for conceptual work, and in all three of the case companies, a whiteboard was used much more for collaborative team work than a computer. In the three case companies, computers are clearly a single person tool, used when people work on their own. It seems fair to claim, that this is a general characteristic of many companies today.

5.2.1 How many models?

When modelling such a diversified and widespread topic as a product platform, one modelling scheme seems insufficient. From a general systems perspective, there are as many models and representations as there are viewpoints. Product platform decision makers may have various mindsets depending on their position in the company.

The following viewpoint (which is also used as an argument in the introduction in chapter 1.3.5) represents quite well the challenges a platform modelling approach has to help overcome [Tseng et al., 2003, p. 814];

"It has been common practice that different departments in a company have different understandings of product families from their individual perspectives. Such incoherence in semantics and subsequent deployment of information embodies a formidable hindrance in engineering data management systems. It is necessary to maintain different perspectives of product family representation in a single context".

That context might be a model outside the computer domain, in order to avoid the *formidable hindrance* in the data management systems. In all of the case companies reported later in Part 5, the data management was (and is still) a great challenge. Simple things like inconsistent names, spelling mistakes, etc, proved to be a *formidable hindrance* for a successful utilisation of data, and clearly a hindrance for obtaining an overview.

Tseng and colleagues also stress the need for a coherent modelling environment capable of holding various types of information [Tseng et al., 2003, p. 812];

"The main challenge for design methodologies is to support these multiple viewpoints to accommodate different modelling paradigms within a single, coherent and integrated framework."

Tseng and collagues consider these *viewpoints* to be aspects like functionality, cost, schedule, reliability, manufacturability, marketability, and serviceability.

In their work on knowledge as an asset in platforms, Sanchez & Mahoney stress the importance of information within product architectures;

"…The information structure of a modular product architecture thus provides the "glue" of embedded coordination that allows a loosely coupled development organization to achieve synthesis." [Sanchez & Mahoney, 1996].

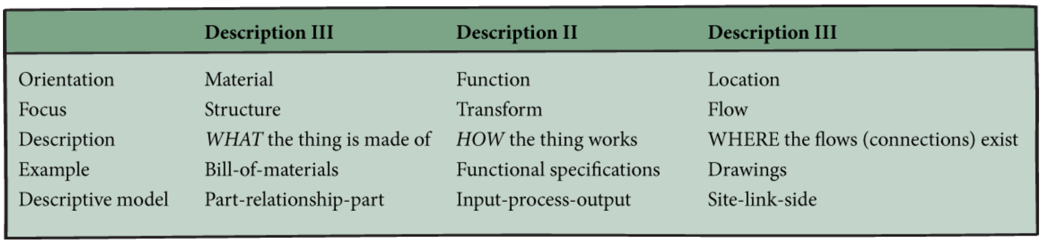
Thus, there is a general consensus about the need for various models encompassing complex and diverse information, while at the same time serving as a unifying model in which decision makers can seek support.

Zachman is renowned for his contributions to the systems architecting principles at IBM in the late 1980'ies. Zachman has phrased the above dilemma of multiple viewpoints and modelling demands [Zachman, 1999, p. 469] like this;

"There is not ***an*** *information systems architecture, but a set of them! Architecting is relative. What you think architecture is depends on what you are doing….* ***a set*** *of architectural representations exists, instead of a single architecture. One is not right and another wrong. The architectures are different….There are reasons for electing to expend the resources for developing each architectural representation. And there are risks associated with not developing any one of the architectural representations".*

In Zachman's perception, the task of architecting is the task of systems information modelling and designing from various viewpoints. Although phrased in a software systems background the work applies to all systems architecting activities ranging from civil engineering to engineering design and – it is assumed here – to product platform modelling.

Zachman discuss three different perspectives of models. These are the viewpoints of *material*, *function* and *location* respectively;



	Description III	Description II	Description III
Orientation	Material	Function	Location
Focus	Structure	Transform	Flow
Description	*WHAT* the thing is made of	*HOW* the thing works	WHERE the flows (connections) exist
Example	Bill-of-materials	Functional specifications	Drawings
Descriptive model	Part-relationship-part	Input-process-output	Site-link-side

Figure 5.2: System models may be viewed from a material, function or location point of view [Redrawn from Zachman, 1999].

All of the models reviewed and discussed in the following somewhat represent either of these viewpoints, or a combination, yet they rarely go beyond more than one viewpoint. The traditional viewpoint in engineering design representation is probably that of *location*, i.e. drawings determining the spatial and geometrical layout of products, and *material*, i.e. bills of material and a structural view point on modelling. Function, however, is still an aspect with which many companies struggle in their models. Zachman further speculates on an extension on the WHAT, HOW, WHERE in the box in figure 5.2 and gives the following descriptions (fig 5.3);

	Description IV	Description V	Description VI
Orientation	People	Time	Purpose
Focus	Responsibility	Dynamics	Motivation
Description	*WHO* is doing what	*WHEN* the events take place	WHY choices are made
Example	Organization chart	Production schedule	Objectives hierarchy
Descriptive model	Organisation-reporting-organisation	Event-cycle-event	Objective-precedent-objective

Figure 5.3: A further elaboration of the architecting framework [Redrawn from Zachman, 1999].

Figure 5.3 depicts an elaboration of the architecting framework in figure 5.2. Notice that there is now HOW, WHAT WHY, which are relatively equivalent to the three basic questions in the framework in Part 4, and the argumentation of the research questions in Part 2. The WHEN and WHERE are somewhat accounted for in the Framework in Part 4 in the sense that the life phase systems bear a time dimension and a location dimension. As example, the production scheduling - which is an example from *Description V* in figure 5.3 - is accounted for in the meeting between ACTIVITIES and FABRICATION/ASSEMBLY in the framework.

Organ modelling

The concept of a product architecture is often seen as a *mapping* between *function* and *form*, or mapping between domains, as it is accounted for in Part 4, chapter 4.5.2. In the framework in figure 5.2, that would imply a mapping between *material*, *function* and *location*, in whatever form these domains then have. However, very few modelling techniques truly hold the ability to visualise *mappings.*

In Part 4 it is argued that organ encapsulation is a central part of product platform design. Organ encapsulation is the process of grouping and decoupling organs (and wirk elements) in order to gain certain benefits. The key is that organ encapsulation does not necessarily have to be accompanied by parts encapsulation, i.e. that physical interfaces between components are not prerequisites for gaining reuse effects. Therefore, modelling organs and wirk elements, may solve parts of the challenge of visualising the function to form mapping, because an organ is itself an instantiation of a functional viewpoint – as a function carrier – and thereby partly represents the function to form mapping. Organ modelling is therefore discussed throughout the following chapters and in the three cases.

Several models in one model

During the cases, which are reported in the Part 5, it turned out to be useful with several models in one model, i.e. models that where different in contents and form, depending on the purpose of the model. Having a single modelling viewpoint was clearly insufficient.

5.2.2 A potential drawback of the visual approach

If the visual approach implies some sort of representation of the product, there is a danger, that the model actually restrains the creativity of the designers involved. This is a potential danger in the three cases, and in particular it is a challenge in the puzzle model described in the Danfoss case in chapter 5.5.5. Each time a sketch or drawing is made of a product, some information and assumptions on the design are made explicit.

From a radical innovation point of view, this might be a restraining factor in the sense that a predetermined design used as a visual representation of the design possibilities in the early stages of a platform design process, will guide the designers in certain directions and keep them away from other directions. However, in some cases – and that was the situation in Danfoss - the design problem is already restrained, and the redesign efforts were more of an optimisation problem regarding alternatives to reuse and encapsulation, rather than a radical innovation problem.

Once the platform is designed and installed, it is very feasible to visualise it using design representations, i.e. drawings or other model types that actually look like the products or platform parts, in order for the users to easily recognise what the objects of the platform are. In the Grundfos case, a physical mockup of the platform was made (as an SLS model). An important challenge is to communicate what parameters are changeable and in particular what parameters which are fixed. An assumption here is that this message is best communicated in a media close to that of the design engineer's toolbox (i.e. the existing drawing, sketching and CAD habits of every day designers).

5.3 Existing modelling approaches

Product modelling and product platform modelling are dealt with by various authors. Often these models are related to a development methodology or a certain approach, and there is a strong correlation between the models and the nature of the development methodology. Many of the methods that are reported in the reviews of Part 4 have related models, some of which are accounted for the in the following.

As discussed above, and depicted in figure 5.2, many product models have either a structural or a functional starting point.

5.3.1 Functional modelling

Modelling functions is the often the first step of representing products, if on a relatively abstract level. Formulating functions gives a hint on the design solutions. Mani functional models are simple input-output models depicting the functional layout of the product [Otto & Wood, 2001].The following example is used in a heuristic modular architecture design method [Stone et al., 2000b] (fig 5.4);

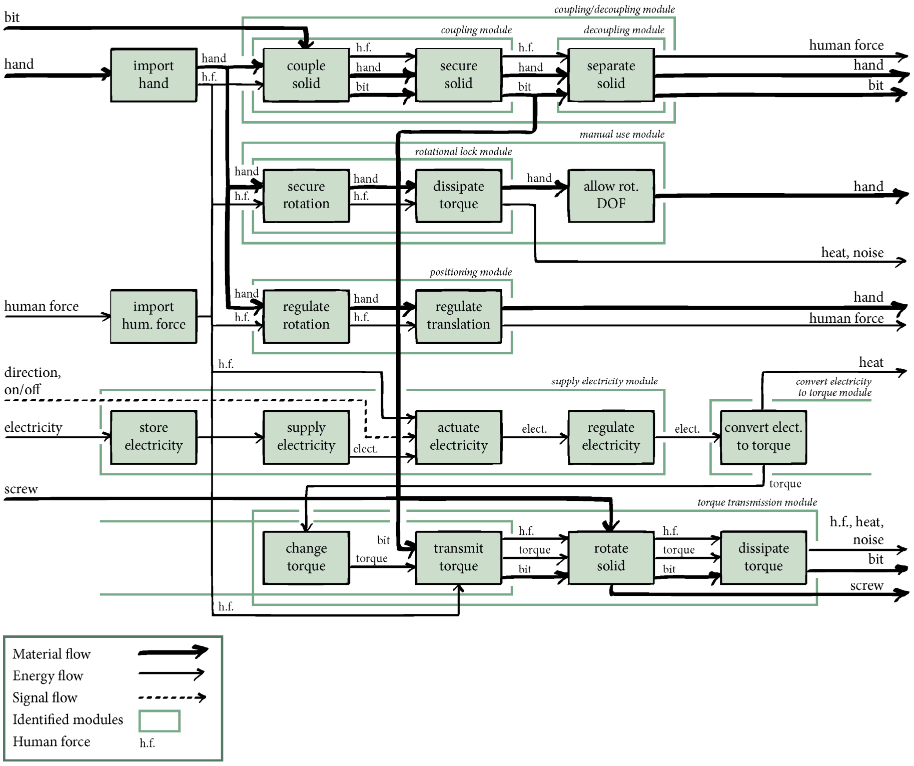


Figure 5.4: A functional model of a electrified handheld drilling machine. The model is used in a function heuristics approach in which module candidates are identified based on a grouping of functions and an analysis of the flow [Stone et al., 2000b].

A similar approach found in the generic organ diagram [Harlou, 2006]. In the generic organ diagram the viewpoint of organs from the Theory of Domains is used instead of functions. Organs are mapped, and not only input, output and flow is emphasised but also interfaces between organs (figure 5.5);

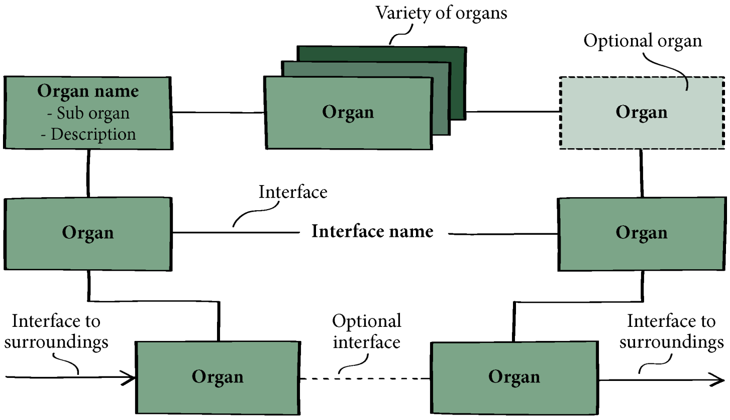


Figure 5.5: The principles of a generic organ diagram [Harlou, 2006]

Whether to use organs or functions may become quite close. The US heuristic school of function formulation comes very close to the concept of an organ in the sense the functions often imply certain physical design principles due to the way they are formulated. This is a basic dilemma when making function structures, and some even argue that there are in fact no such phenomenon as a *function structure* - hence the revised theory of domains, in which the function domain is left out. Instead, function are seen as the effects by organs, as depicted in the Genetic Design Modelling System and the revised Chromosome Model [Mortensen, 2000] (See Part 3 for a discussion on the Theory of Domains (chapter 3.2.2) and the Chromosome Model (3.2.5)). The organ diagram is particularly powerful when screening existing product families for a complexity reduction potential. Various generic organ diagrams can be put on top of each other to highlight variable and generic attributes of the systems, thereby pointing the attention to possible standardisations.

In their Product Family Architecture framework, Jiao & Tseng [1999] provide a model of a modular power supply;

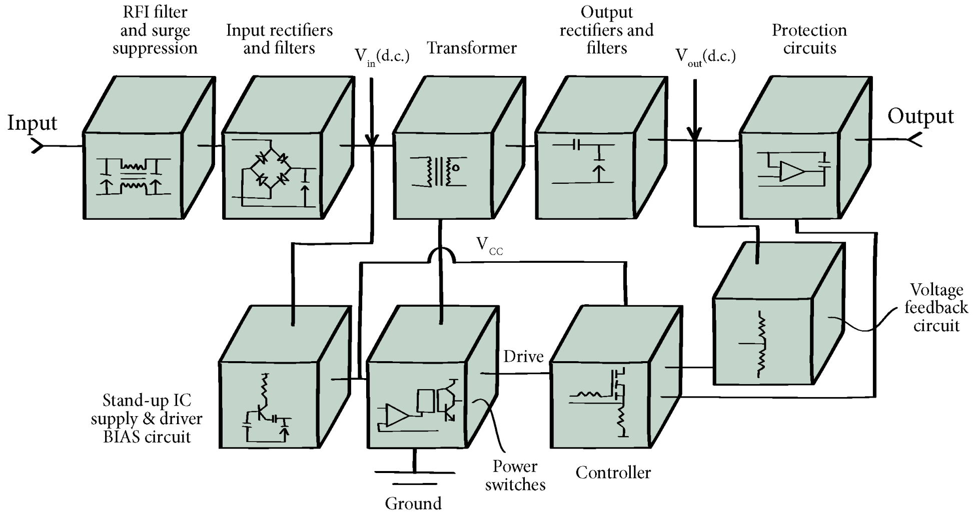


Figure 5.6: A model of a modular power supply. Note the added symbols for easier recognition by domain experts.[Figure adopted from Jiao & Tseng, 1999].

The model in figure 5.6 is an example of the use of simple symbols, greatly improving the readability for those involved in the project. However, the symbols are meant for domain experts with an insight in the engineering notation. The spatial look of the figure adds no further information.

Incorporating more design knowledge

Some authors extend the functional modelling approach and seek to incorporate more detailed knowledge on the design process and rationale. Sahin and colleagues propose a graphical modelling for product platforms and product families, based on a stencil template in Microsoft Visio [Sahin et al., 2006]. Figure below depicts the principles of the modelling environment. The model is extended (from the simple function modelling case) with various module drivers inspired by the Modular Function Deployment framework [Ericsson & Erixon, 1999], (see chapter 4.7.2 in Part 4 for more on the MFD framework, and a list of module drivers (fig. 4.33)).

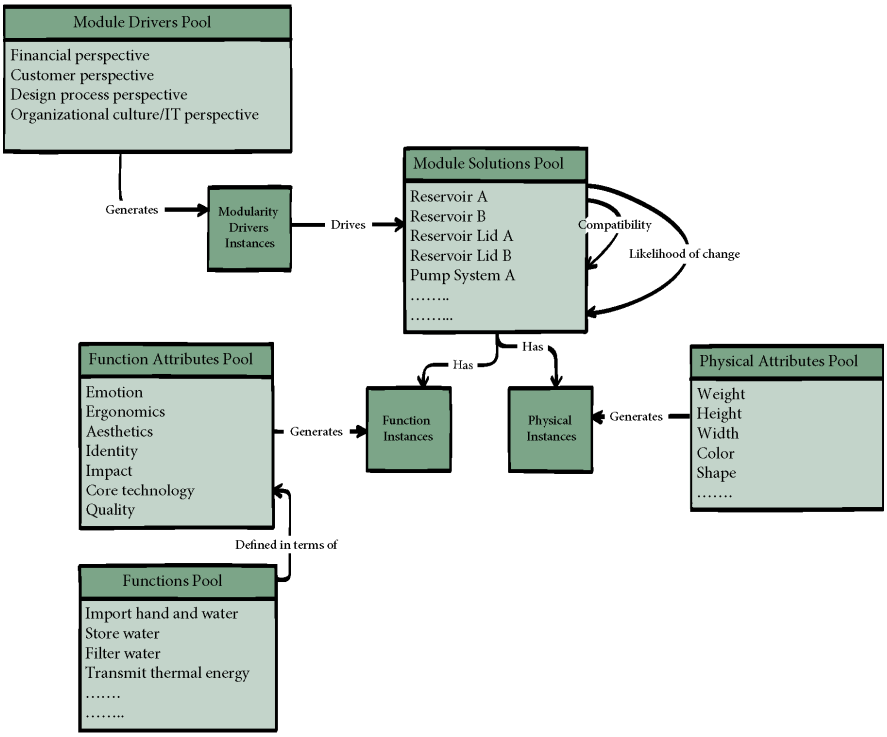


Figure 5.7: The principles of the graphical modelling environment for Microsoft Visio [Sahin et al., 2006].

An example of the modelling approach is shown below. The product is a coffee machine;

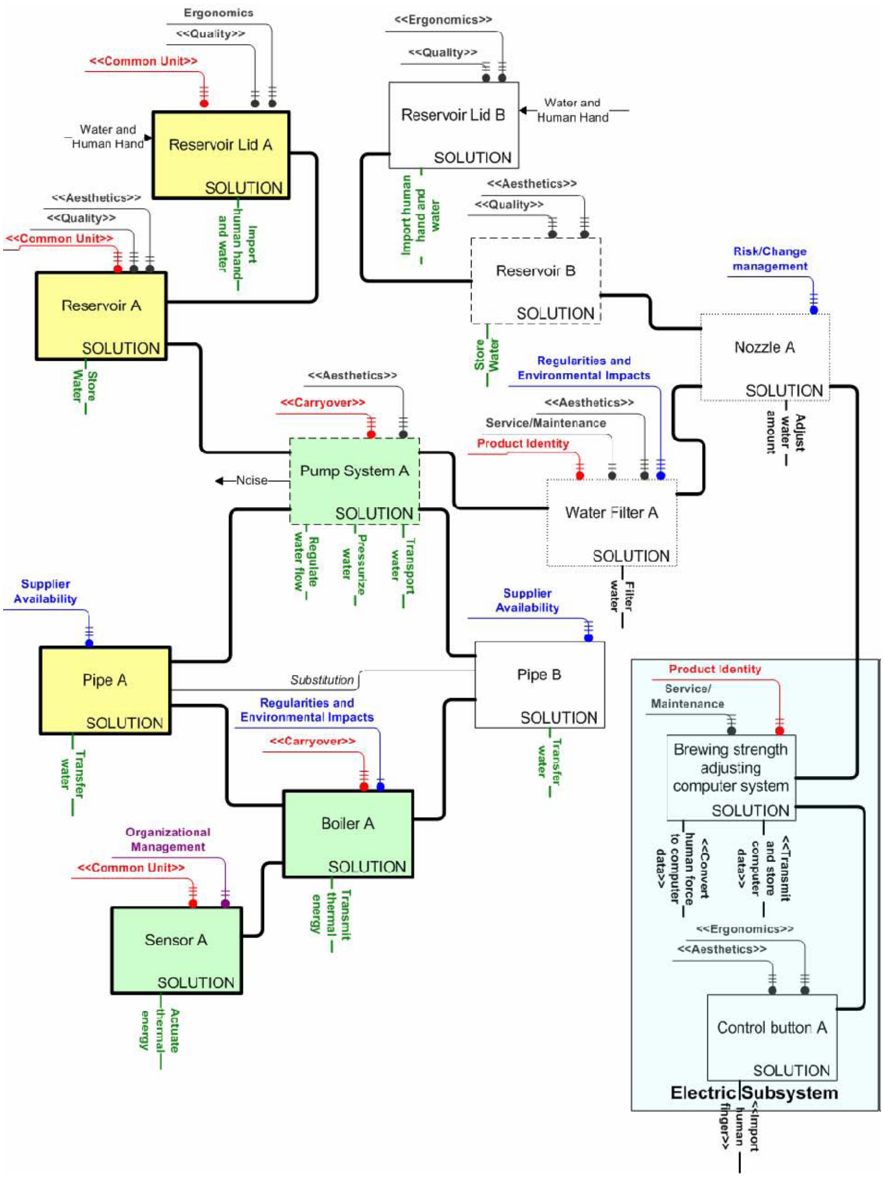


Figure 5.8: The graphical modelling environment exemplified by means of a coffee machine (the water subsystem) [Sahin et al., 2006].

In figure 5.8 the modelling environment is used to depict the water subsystem of a coffee machine. The Various module drivers are attached to different design solutions, which largely corresponds to the organs of the generic organ diagram.

Adding pictures and structure

Other authors work with Microsoft Visio in order to make generally applicable modelling environments [Terpenny & Mathews, 2004], [Shooter et al., 2005].

The work reported by Shooter and colleagues, has three main purposes;

1. *"The development of a generalised information management infrastructure, with particular emphasis on capturing information regarding component-sharing and reuse within a family of products.*
2. *Creation of a corresponding graphical modelling environment.*
5. *Formulation of a software agent-based synthesis framework for product family planning and customisation."*

The work is an example of models moving away from the classical black box diagrams and input-output diagrams, adding slightly more graphical details. The software system reported in the work mainly has the purpose to combine information from various systems as a viewer (fig. 5.9);

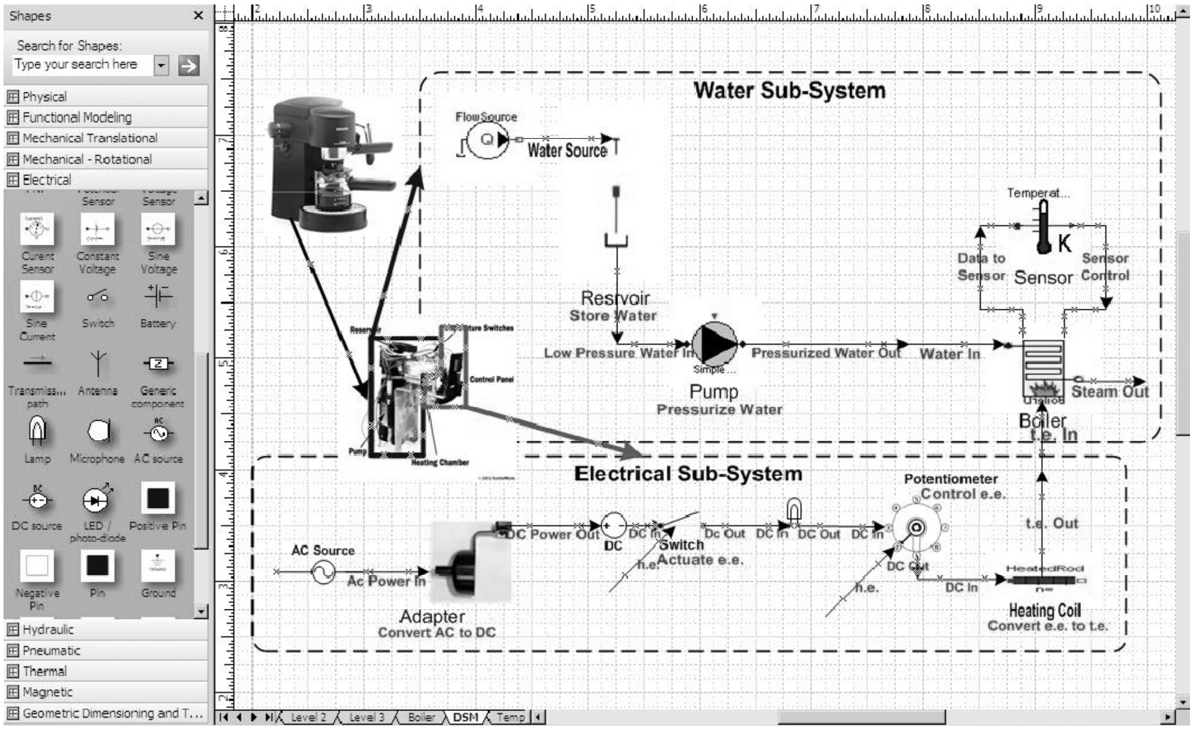


Figure 5.9: A visual function structure with means (design solutions) included [Shooter et al., 2005]

Figure 5.9 depicts a screen shot from the Microsoft Visio modelling environment. Like in figure 5.8 the product is a coffee machine. There is a picture of a coffee machine, pictures of some of the subsystems, thus making the various parts of the model more recognisable than the case of the approach in figure 5.8. Adding pictures and other illustrations greatly helps to interpret the message of the model.

Shooter and colleagues point out that they strive for a series of advantages to be fulfilled by the use of the modelling environment;

1. Intelligent search
2. Collaboration
3. Coordination and negotiation
4. Understanding and learning.

When working on the model and using the model, it has to support an intelligent search in order for the users to quickly find relevant information; serve as a base for collaboration between various employees; serve as a base for coordination and negotiation (and thereby decision making); and finally to support learning and understanding about the product family.

Qualitative function modelling

Some attempts try to distinguish qualitative from quantitative models [van Wie et al, 2005]. The basic concept is to represent quantitative and yet unknown details, by less concrete and more qualitative representations by "*incorporating higher level representations, using a graphical implementation, and using an agent based approach*" [van Wie et al., 2005, pp. 312]. The authors work with four levels of abstraction, depicted in figure 5.10;

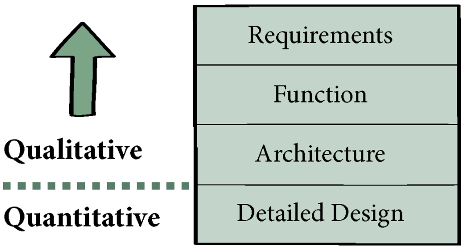


Figure 5.10: Four levels of design data representation and an attempt to distinguish them as qualitative and quantitative respectively, according to van Wie et al, [2005].

The four levels of abstraction somewhat represent the idea of different domains from various authors [Andreasen, 1980], [Suh, 1990], [Erens & Verhulst, 1999]. On the basis of qualitative representations of the product, the following graphical representation is made (see figure 5.11);

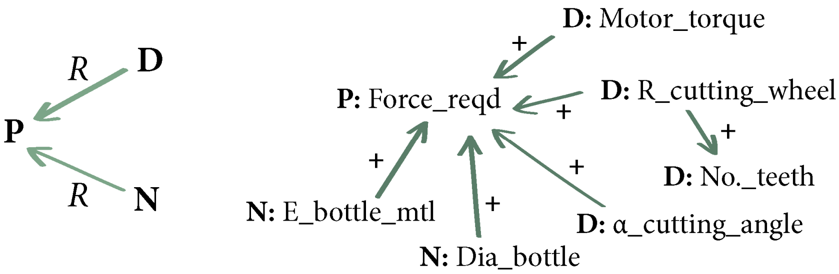


Figure 5.11: The qualitative modelling framework to the left, and an example of a partial model to the right.

P is performance, D is design, and N is noise. Thus – to the right – a certain performance depends on the design and uncontrollable noise, [van Wie et al., 2005].

Figure 5.11 depicts the qualitative modelling framework (to the left) and an example (to the right). The example includes a family of machines that shred plastic bottles for recycling purposes, i.e. in this case a rotating cutting device, hence the nodes "No._teeth" (Number of teeth), "R_cutting_wheel" (cutting wheel) etc.

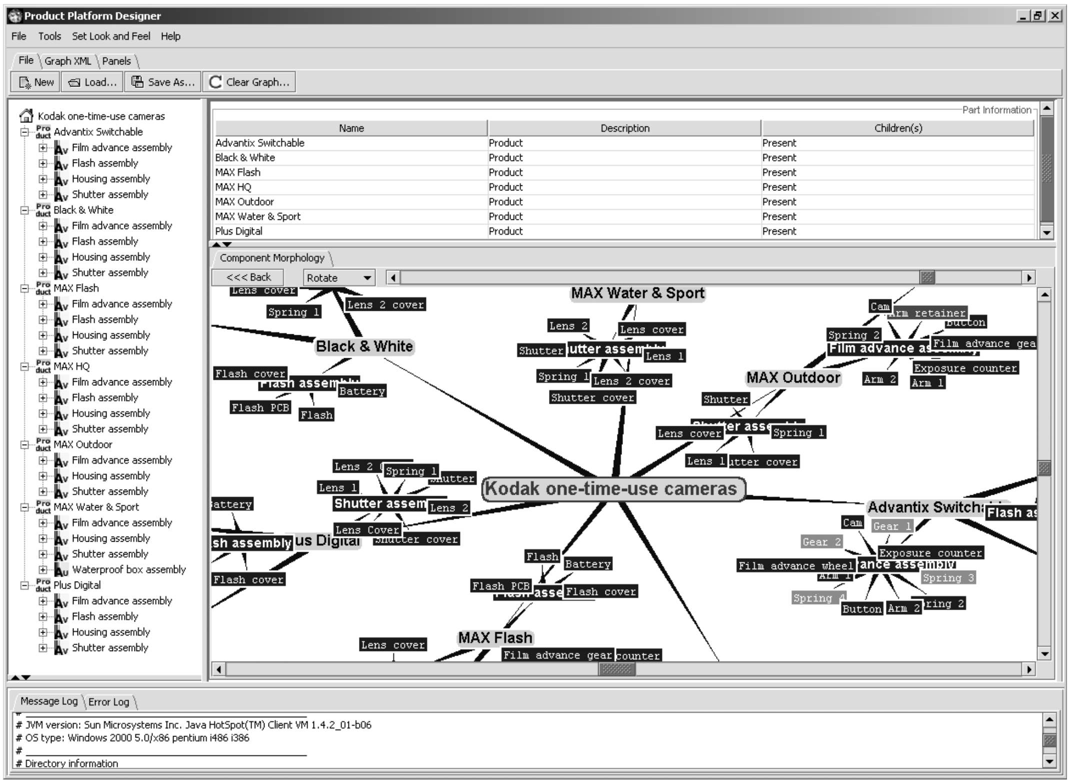
The framework to the left depicts P as a function of D and N. P is performance, D is design and N is noise, R is requirement. D is further described as the things that are controlled by the designer, and as examples are given the function, choice of modules, materials, manufacturing processes etc. N includes loading and other uncontrollable environmental factors. From a Technical Systems and domain perspective, D could resemble the parts, if strictly formulated and N the effects from the environment. The performance would be the outcome of the transformation. However, the subdivision of D and N is somewhat inconsistent with a sharp distinction between characteristics, inherent properties, relational properties and qualities (see chapter 3.2.5).

The modelling environment somewhat resembles the function and organ modelling types, and require a good of understanding of the syntax and the relatively abstract comprehension of the functional layout of the product. The approach is not visual in the sense that it gives an impression of the platform for a non domain expert; neither does it incorporate platform elements that are not directly related to the products.

5.3.2 Product structure

Some modelling attempts incorporate the idea of a product structure in to the models. A product structure is viewpoint dependent, yet some sort of *assembly hierarchy* often determines the sequence and subdivision of parts. Product structures focus more on *relations* (mainly geometrical/attachment) between elements rather than the *flow* of information, material or energy, which is often a key aspect of function models.

Figure 5.12 gives an example of a product family structured after product variant coherence. Each family is shown as nodes that can be exploded for further detail [Shooter et al., 2005];



Name	Description	Children(s)
Advantix Switchable	Product	Present
Black & White	Product	Present
MAX Flash	Product	Present
MAX HQ	Product	Present
MAX Outdoor	Product	Present
MAX Water & Sport	Product	Present
Plus Digital	Product	Present

```
# JVM version: Sun Microsystems Inc. Java HotSpot(TM) Client VM 1.4.2_01-b06
# OS type: Windows 2000 5.0/x86 pentium i486 i386
# ____________________________________________
# Directory information
```

Figure 5.12: An example of a visualised product family structure [Shooter et al, 2005]

The strength of the system reported by Shooter and colleagues is the ability to navigate through large amounts of information, to open and close different details very easily and thereby allowing the designers to maintain an overview while still having the opportunity to access design data.

The basic structure of the system is a parent-child hierarchy from which various product variants are built. The structure, however, does not give an intuitive impression of the constituents of the platform but is more focused on assessing data and information – i.e. serving as a directory. Thus, from a visual modelling point of view, this system has its strengths in information retrieval and not as a visual platform model.

STEP

A more formal – yet less visual – approach is the ISO STEP (Standard for the Exchange of Product information). STEP is a modelling standard mainly derived from the automotive industry, and now serving as an ISO standard for the exchange of information between various information storage systems such as CAD, ERP and PDM systems. A study from the Royal Institute of Technology, KTH, in Sweden reports on the use of STEP for product family modelling in an axiomatic approach, incorporating a customer, functional and physical domain respectively [Sivard, 2001]. The purpose of step:"*...has a long-range vision of product data management. Its intention is to define a uniform representation of product information and to provide mechanisms that enable the exchange of product data between different computer systems over the complete product life cycle*". [Männistö et al., 1998].

Despite the work on integration and that STEP actually holds methodologies for physical and functional modelling, STEP is – for the purpose in this thesis – considered to be out of scope as a candidate, since the purpose is that of a mainly computer model integration, and not a visual modelling representation.

5.3.3 Modelling variable and generic attributes

A fundamental aspect of product platforms and product families is the presence of variable and generic attributes, which is a natural consequence of the desire to get commonality and variety in a product family. And if a platform gives the possibility to derive thousands of product variants, all sharing a core of attributes, data redundancy is a major aspect to be aware of. Each instance of the platform is a potential product model. So, how does one go about the challenge of visualising and documenting various variants while avoiding en explosion of data?

The software industry has for many years used an *object oriented modelling* approach in order to grasp the problem of variable and generic attributes [Rumbaugh et al., 1991]. In the mechanical and industrial engineering field similar approaches have evolved. They all – in different ways – deal with the same fundamental problem of handling variable and generic attributes in the same model. It is evident that a platform strategy, with a modular approach to product development, fits very well with Mass Customization and configuration initiatives. Thus, many product modelling efforts within product platform research have a focus on models for configuration, [Riitahuhta, 2001], [Riitahuhta & Andreasen, 1998].

The role of the bill of material

The bill of material (BOM) is a typical product model in modern companies. Bills of materials are found in most commercial ERP systems, in which the assembly structure is shown in a navigable window. A bill of material gives an impression of a structure of a product, yet the assembly sequence does necessarily reflect the functionality of the product.

Fitting the production bill of material with design bill of material proofed to be a problem in the Danfoss case. The problem was that the assembly sequence was unknown early in the development phase while the design engineers would want to build their BOMs as a consequence of the assembly structure in their CAD system. In this case, a generic BOM, that could be restructured later, would have been beneficial. In the real world, all Bills-of-material in the ERP system had to be changed one by one later on, if changes were to be implemented. The reason was that the class hierarchy was not generic and shared by all variants, i.e. each subassembly was tied to a product code for a final product, and not a generic structure. Thereby changes will have to be made to every single BOM even if they are the same.

Object oriented modelling has been used to represent assembly structures and the according bills of material in order to ensure proper heritage of attributes and proper class relations, also incorporating the virtues of feature based design [van Holland & Bronsvoort, 1996].

The problem of variants sharing the same fundamental assembly structure of BOM is raised by numerous authors with van Veen & Wortmann [1987] as some of the first to point out the concept of a generic bill of material. The core of a generic bill of material (GBOM) is that the GBOM serves as a placeholder for variable items. This means that the class hierarchy is maintained in one structure rather than having to maintain each single instance of product variants.

The *variant-bill of materials*, are similar approaches in which multiple levels of abstraction is used to capture generic and variable product models, [Männistö et al., 2001].

The function means tree

The function modelling and organ modelling approaches discussed earlier, both have the challenge of clearly distinguishing function from design principle. It is often a matter of formulation, and "heat water" quickly become "water heater", thus changing from function to organ. The next step, when deciding that the water heater is a "electrical heater element" is the real transition from function to form.

Talking about a function structure – without a corresponding part structure – is somewhat wrong, following the consequences of the Function/Means law [Hubka, 1967], [Andreasen, 1980].

Andreasen & Hansen [2002] elaborate the law by quoting Andreasen [1980];

"In the hierarchy of effects (the functions), which contribute to realisation of the mechanical artefact's overall purpose function, there exist causal relations, determined by the organs (the means), which realise the effects",

...and further adding*;*

"The law tells that a means synthesised by the engineering designer for solving a required function seldom is sufficient in itself, but call for additional functionalities (like energy, control, support, and auxiliary functions) to be realised by additional means".

Determining the nature of an organ implies that the design engineer has an idea of the design principle, thereby making implicit decisions on the physical layout of the product. The Function/means tree is a way to model this sequential causality of functions and means. Figure 5.13 depicts an example of a function means tree [Hansen, 1995 originally from Svendsen & Hansen, 1993];

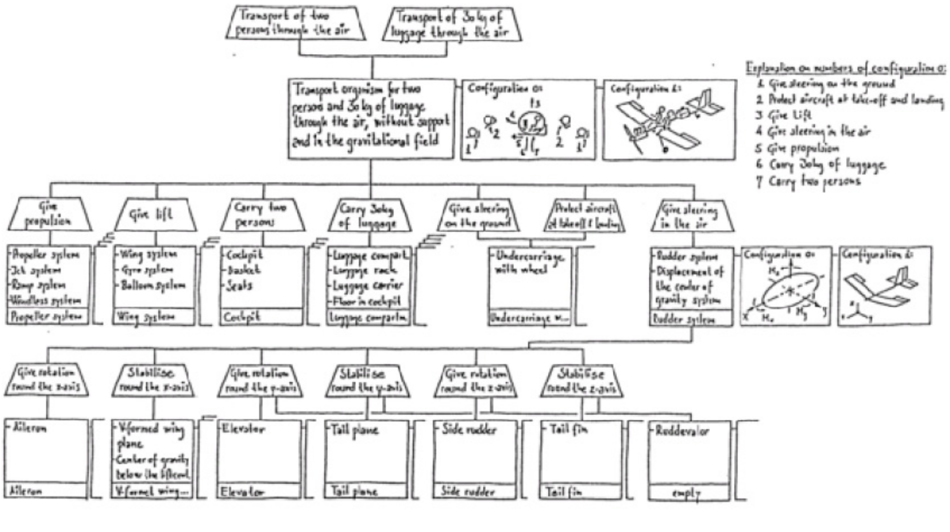


Figure 5.13: A function/means tree for an ultra-light plane. The functions are trapezoidal and the means in squares. Notice that there are alternative means shown underneath each other, giving the opportunity to model several configurations.

The example in figure 5.13 is in fact a special version of the function means tree in which several alternative means are shown. Thereby the function means tree become an approach to visualise a configuration. However, constraints and other design relations are not accounted for.

Drawings in the tree help to visualise concepts, design solutions and functional principles.

The extended function means tree

The function means tree has been extended and computerised, and the design history has been added as a modelling dimension [Malmqvist, 1997], i.e. the possibility for design engineers to capture the reasoning behind the design rather than just the design itself, and further extended to capture various kinds of stakeholder and life phase information [Schachinger & Johannesson, 2000];

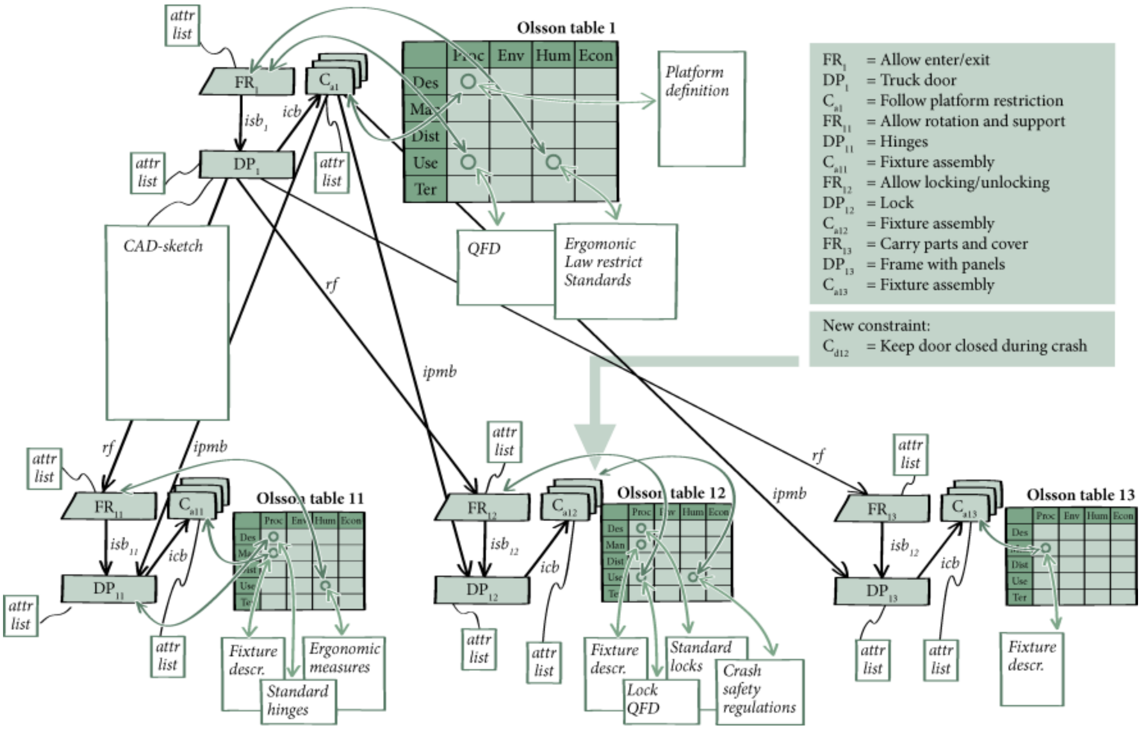


Figure 5.14: A case exemplar of an enhanced function means tree of a truck door. FR is Functional Requirement; DP is Design Principle; C is constraint, [Figure redrawn from Schachinger & Johannesson, 2000].

Figure 5.14 is an example of an extended function means tree. The fundamental modelling objects are the *Functional Requirements*, FR, and the *Design Principles*, DP, corresponding to the framework of axiomatic design [Suh, 1998], and thus largely to the concept of *functions* and *organs*. The *Contraints*, C, are the non functioncal relations, i.e. constraining the combinations and use of the Design Principles.

In order to understand the tree, users need to know the following syntax [Claesson, 2006];

- isb: A functional requirement *is_solved_by* a design solution
- rf: A design solutions *requires_function* on the lower hierarchical level.
- icb: A design solution *is_constrained_by* a constraint.
- ipmb: A constraint *is_partly_met_by* design solutions on the next lower hierachical level
- iib: A functional requirement *is_influenced_by* the choice of an interacting solution
- iw: Parrallel design solutions *interacts_with* each other

In the enhanced function means tree the *design rationale* is emphasised, i.e. to capture *why* a certain design solution is chosen to realise a given function. Moreover, the structure of the tree makes it possible to navigate through various types of information about the product. The *Olsson tables* are added in order to map various kinds of information on *process, (Proc); environment, (Env); human, (Hum);* and *economic, (Econ)* interactions in the fundamental phases of *Design (Des), Manufacture, (Man); Distribute, (Dis); Use,* and *Termination, (Ter).* The extended function means tree in figure 5.14 is made using a computer software tool.

The function means tree in its various versions is not as such a visual approach in the sense that it does not visually depicts the products, organs or design solutions. The extended and computerised versions of the tree [Malmqvist, 1997], [Schachinger & Johannesson, 2000] serves as a help to navigate through various amounts of data and thus have the virtues of a both overview and detail at the same tame.

Visual configuration modelling

The configuration task resembles (and in many cases equals) the execution phase of product platform development. Configuration is mainly the task of choosing between various variants for subsystems, while respecting certain design rules and constraints. Some configuration systems also handle more parametric choices, in which various parameters can be chosen within a set range (see also chapter 4.5.3 in Part 4 for a discussion on *scalable* and *configurational* platforms).

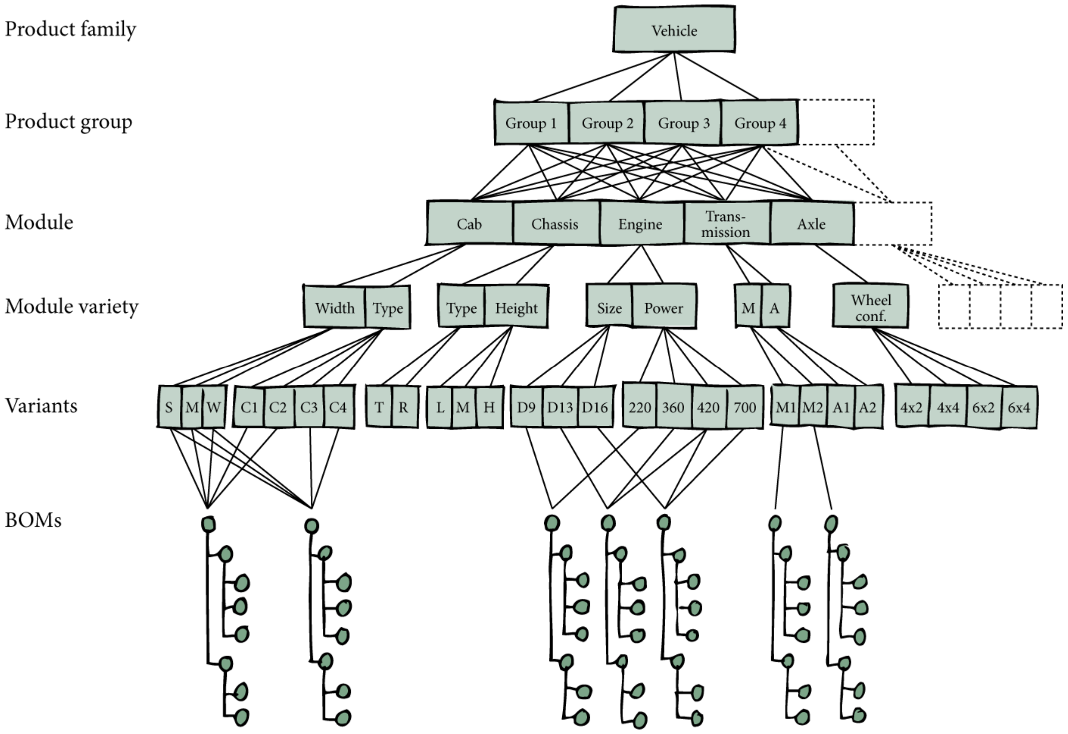


Figure 5.15: A product configuration model of a vehicle, [Mesihovic & Malmqvist, 2004].

Figure 5.15 gives an overview of variant BOMs and also of various configurations. In large product families with many variants and many constraints, the model will grow out of hand, unless kept on a certain level of abstraction. However, that is a condition most modelling schemes face and few seem to handle.

Many efforts in configuration modelling does not emphasise visual modelling, due to the fact that the models are mainly computer models meant for computer systems. Some of the widely used configuration modelling techniques are also reported in relation to modelling of product architectures and platforms. The *Unified Modelling Language* (UML) and its derivative *SysML* are but a few of the available techniques, [Rumbaugh et al.,1991], [Cerón et al., 2004], [OMG, 2008]. The strength of these techniques is the ability to handle objects and relations in a structured way. However the approaches are not visual, in the sense that the models – from a mechanical engineering standpoint - do not reflect the design of the products. However, in the case of product modelling for configuration, UML and other modelling languages have proved successful [Haug, 2007]. For the visual purpose in this thesis, such modelling techniques are kept out of focus, as they tend to require quite a lot of domain knowledge as well as knowledge on the modelling language itself. The understanding of such models relies relatively profound on an in-depth understanding of certain protocols and languages.

Generic variety structure

The *generic variety structure* of the Product Family Architecture (PFA) framework [Jiao et al., 2003] (see Part 4, chapter 4.5.2, and figure 4.6 depicting the PFA), is a proposal for a concept of an object oriented modelling approach with a generic part of structure, entity relations, and constraint information. Similar object oriented modelling approaches, in which generic class structures are inherited to entities are used by various configuration software vendors (such as Tacton, www.tacton.se). The Product Family Master Plan is an equivalent object oriented modelling approach.

5.3.4 Product Family Master Plan

A similar tool to the generic variety structure is the *Product Family Master Plan* (PFMP) also known as the *Product Variant Master* (PVM). The PFMP is a tool developed at the Technical University of Denmark, throughout various iterations and as a consequence of long collaboration with industry. A formalised version of the tool is described by Harlou [2006]. The PFMP combines an object oriented modelling approach with a theoretical standpoint founded in the Theory of Technical Systems and the Theory of Domains. The PFMP has been used in various research projects and also in a series of consultancy projects, mainly for the purpose of product family rationalisation and complexity reduction as well as for the purpose of documenting configuration system contents.

The PFMP is a graphical and visual tool mainly meant as a visual model on *paper* – not in a *computer*. The basis of the PFMP is constituted by the *Part_of structure* and the *Kind_of structure*. The Part_of structure is essentially a class hierarchy, depicting a generic structure of a product family. The Kind_of structure includes the variable entities in each class.

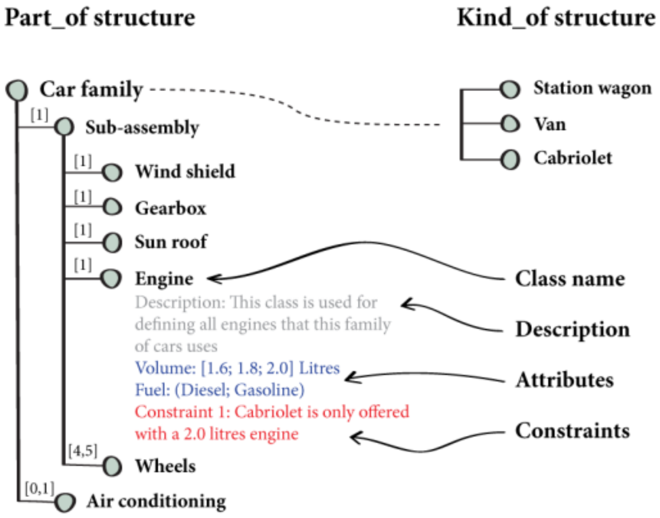


Figure 5.16: A basic example of a Product Family Master Plan,[Harlou, 2006]

Figure 5.16 shows an example of the PFMP notation. The Part_of structure to the left is a hieracrhy of classes. A class is a common denominator for a group of components, and for the purpose of a mechanical product, the classes typically match the subsystems of the product.

Harlou [2006 pp. 108 - 109] compiles the work of various authors within the field of object oriented modelling and presents the following perceptions of the elements within a PFMP;

- Object
  "An abstraction of something in a problem domain, reflecting the capabilities of a system to keep information about, interact with it or both; an encapsulation of attributes values and their exclusive services"..."An object has state, behaviour and identity ...".
- Class
  "A class is a set of objects that share a common structure and a common behaviour"
- Attribute
  "Any property, quality, or characteristic that can be ascribed to a person or thing"
- Instance
  "An instance is a specific object. Therefore an instance is an object with state, behaviour and identity"

Thus, in figure 5.16, the *Car Family* is a class, and the objects *Station wagon*, *Van* and *Cabriolet* are all "Kind_of" that class. There are a number of different choices beneath the Car family, thus *Air Condition* is another class, which is a *Part_of* the *Car family* class.

Attributes describe the objects and are used to distinguish different object from each other. Constraints are used to describe design constraints limiting the possible number of combinations of objects.

The PFMP has three main views; The Customer View, The Engineering View and The Part View.

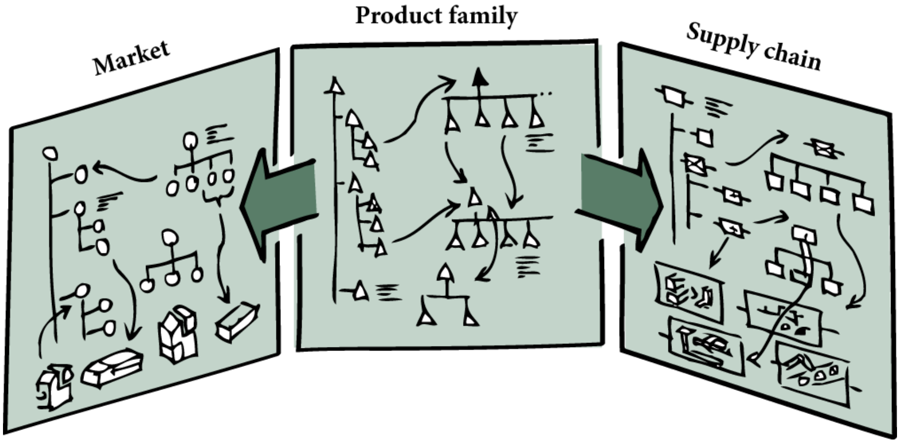


Figure 5.17: The three view of the PFMP: the Customer View, the Engineering View, and the Part View, corresponding to the Transformation, Organ and Part domains of the Theory of Domains, [Harlou, 2006]

Figure 5.17 gives a principal overview of the three views of the PFMP. Please note that all three view have a Part_of and a Kind_of structure. The Part View should not be confused with the Part_of structure;

Customer View

In the customer view the objects are modelled from a customer view, i.e. the choices a customer care about. From a perspective of the Theory of Domains, the customer view involves the main *transformations*. Figure 5.16 gives an example of how a customer view can look like.

Engineering View

The engineering view shows the working and design principles on a conceptual level, and thus corresponds to the *organs*. Figure 5.18(a) gives an example of an Engineering View;

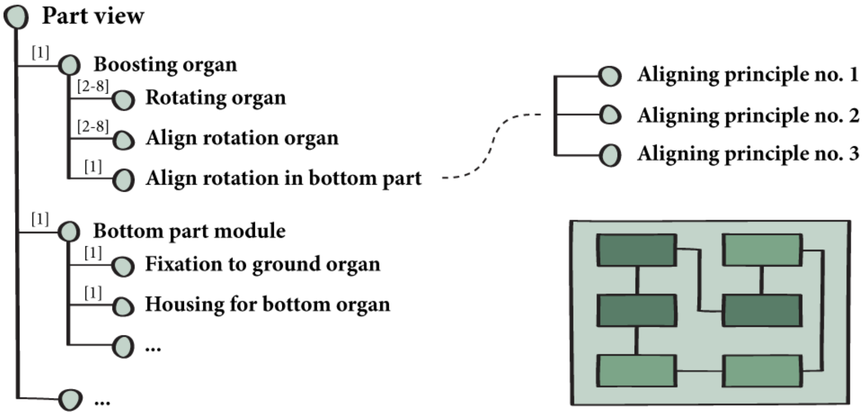


Figure 5.18(a): An example of an Engineering View in which there is a conceptual viewpoint on design principles, i.e. organs. [Harlou, 2006].

Part View

The Part View involves the *parts* that host the organs. The Part_of structure in the Part View is essentially a type of generic bill of material and the Part View as a whole is similar to the generic bill of material [van Veen & Wortmann, 1987] and the generic variety structure [Jiao et al., 2003]. Figure 5.18(b) gives an example of a Part View;

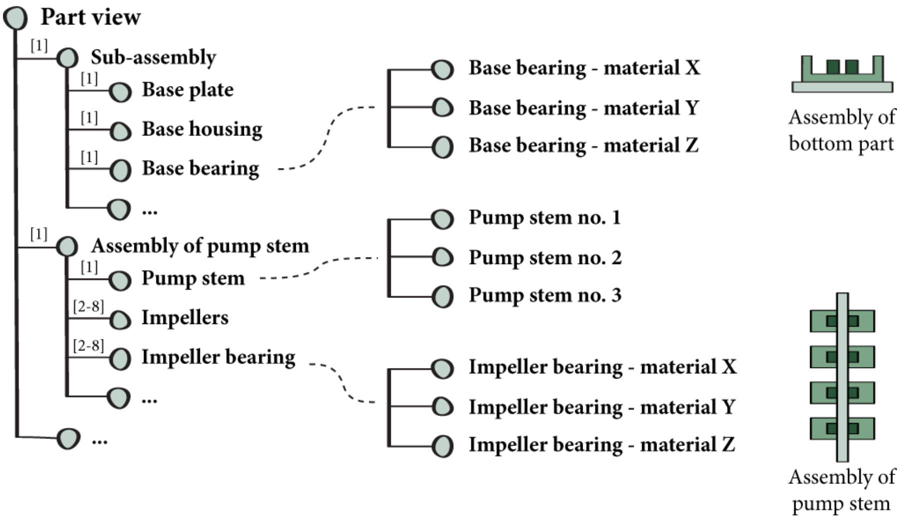


Figure 5.18(b): An example of a part view, in which the physical parts are in focus, [Harlou, 2006].

Highlighting non value adding variation and complexity

The strength of the PFMP is the ability to highlight commonality and variety on several levels of abstraction. This is mainly due to the combination of the three viewpoints of Customers, Engineering (concepts), and Parts, and then the object oriented modelling approach. The object oriented modelling approach makes it possible to model several thousand instances within the same product family, without losing an overview of the different the instances. Because each object is grouped and belongs to a class in the Part_of structure, it is relatively easy to navigate through large amounts of data and information.

The Part_of & Kind_of distinction gives an overview of generic and variable elements within the product family. From a *parts* viewpoint, it is mostly about parts reuse. From an organ viewpoint, the PFMP will highlight variation on a conceptual level, which is often an even more costly kind of complexity. Each new design principle will lead to different parts, even though the overall function may be the same. From a customer perspective, the PFMP will highlight if there are redundant options in the marketplace, i.e. specifications *almost* fulfilling the same needs or two product variants that are slightly different yet always sold to the same customer niche.

The process of identifying non value adding variety is a process of relating the different view with each other, constantly asking why a certain part is present, i.e. what organs the part supports, and what the purpose of that organ is, i.e. what customer value does the customer get out of that particular functionality. The other way around, each function can be carefully examined in order to understand how the function is supported by organs and how these organs are realised by parts. This top-down/bottom-up approach is shown in figure 5.19;

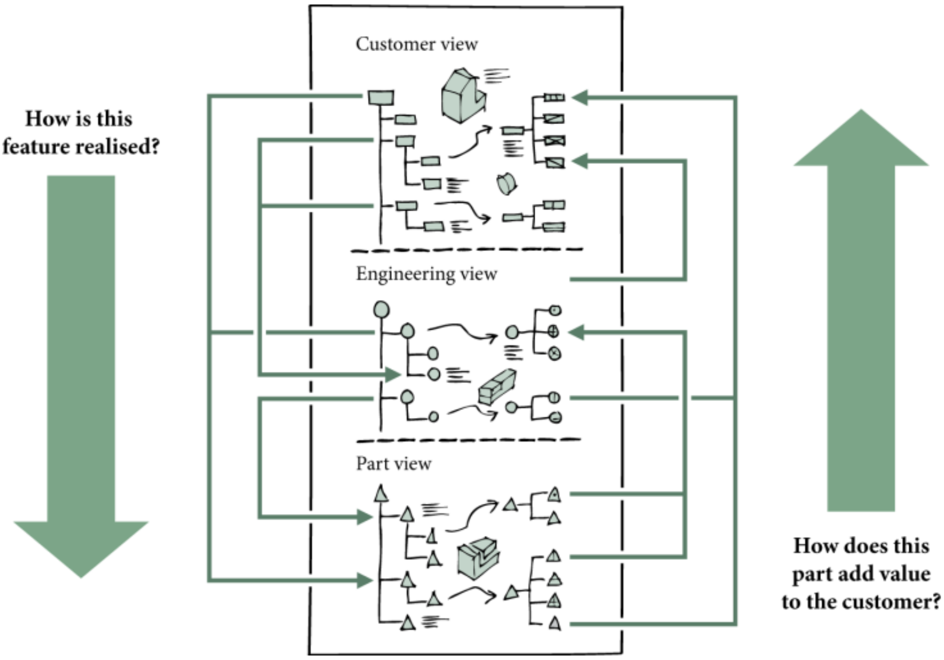


Figure 5.19: The PFMP is used to highlight commonality and variety in order to reduce complexity in the product range, from a customer, engineering (organ) and part viewpoint. The views are placed on top of each other. [Figure redrawn from Harlou, 2006].

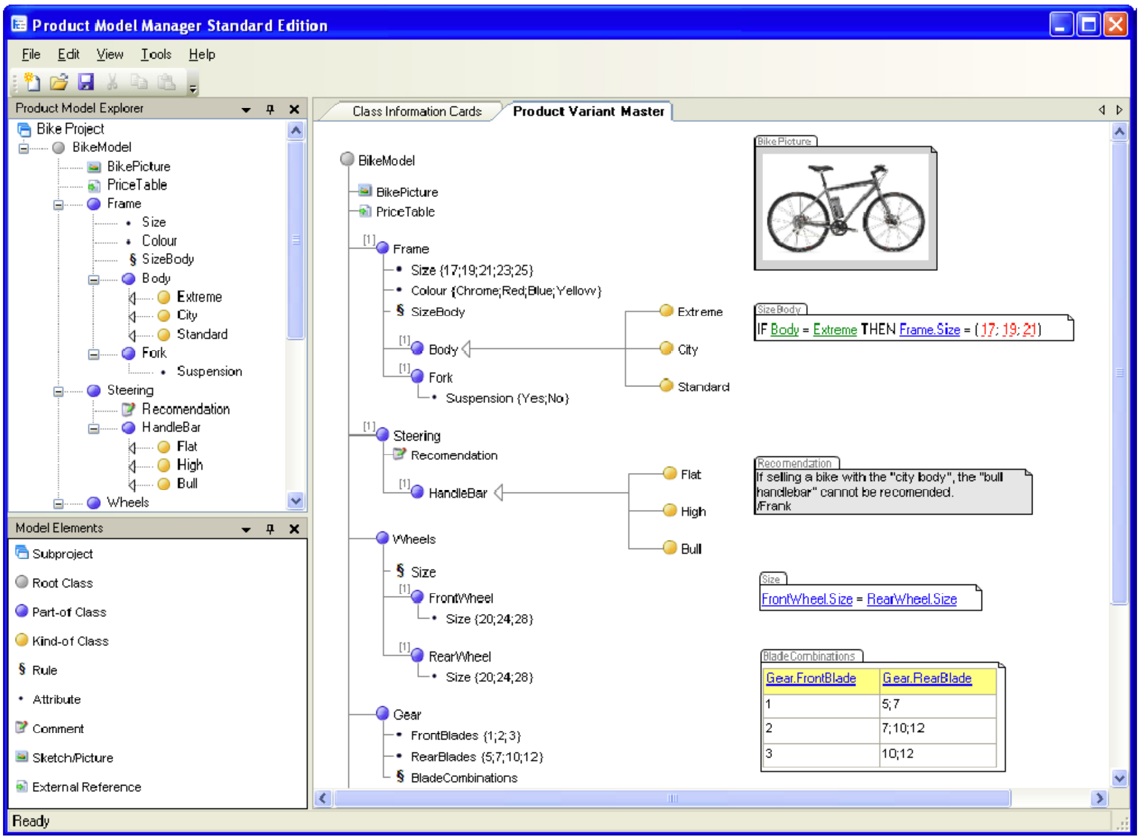
The Product Family Master Plan has recently been extended into the so-called PMFP^2-modelling formalism, in which critical aspects about customer needs, and production layout are included in various modelling dimensions [Kvist, 2009].

A poster approach

The PFMP is relatively different from other modelling product family/configuration attempts due to the fact that it is meant for paper, i.e. as a large printout. Usually the PFMP is plotted in A0 or larger formats and hung on a wall in the company, in order for various employees to use the tool, and to get an overview of the product range. Everyone can add comments and sketches, making it readily available and relatively interactive despite the low-tech solution of a poster format.

A computer modelling approach

A recent and promising development seeks to take the PFMP modelling formalism into a computer context. The software tool *Product Model Manager* [Haug et al., 2009], makes it possible to model the Part of and Kind of structures. However, so far, the tool is relatively focused on the Part_view, and the purpose of the tool is mainly as a preparation for configuration systems. The figure below gives an example of a screen shot from the modelling environment in which a bicycle is modelled. Notice the Part_of and Kind_of views:



IF Body = Extreme THEN Frame.Size = (17; 19; 21)

If selling a bike with the "city body", the "bull handlebar" cannot be recomended.
/Frank

FrontWheel.Size = RearWheel.Size

Gear.FrontBlade	Gear.RearBlade
1	5;7
2	7;10;12
3	10;12

Figure 5.20: A screenshot from the Product Model Manager tool. This is a software based agent for drawing Product Family Master Plans, also known as Product Variant Master. [Haug et al., 2009].

Figure 5.20 depicts a screen shot from the Product Model Manager modelling environment. A particular strength of the PMM tool is the ability to interface with commercial configuration systems. Thereby it is possible to build a visual product model in the PMM environment, integrating pictures and keeping a visual overview, while at the same time specifying constraints and other types of information on a more detailed level. This information can be spooled relatively automatically into a regular commercial configuration system regardless of the modelling environment in that particular system.

However, for the use in the industrial cases in this thesis, the tool was yet too immature because it was in a state of development, during the project. Thus, it was not sufficiently flexible, and due to the focus on product parts, neither useful for modelling platform elements other than those of the part domain (i.e. no ability to model activities for example).

The Product Family Master Plan and the Product Variant Master both imply a fixed part structure, i.e. a generic structure that is shared by all instances. This issue is dealt with by the Configurable Component Framework [Claesson, 2006] (see the following chapter).

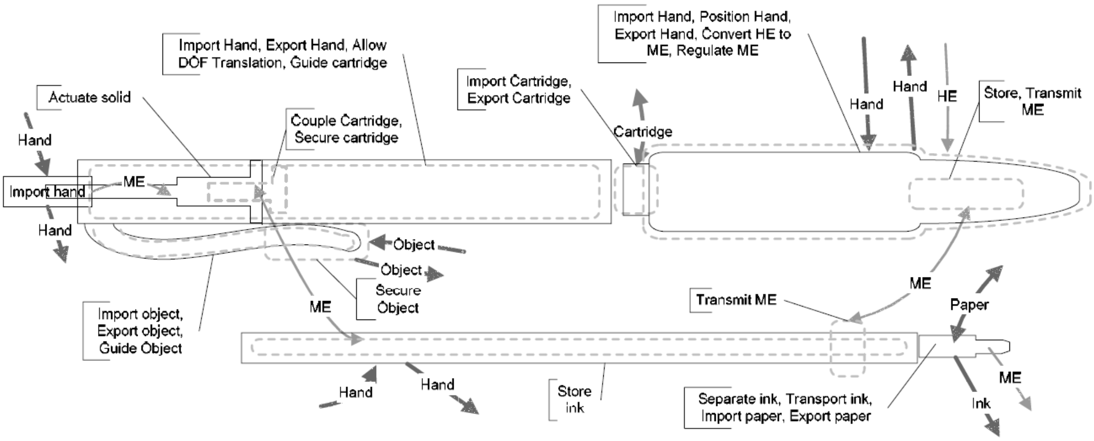
5.3.5 Configurable components

In many cases, the parts hierarchy is unknown before the actual configurations takes place, i.e. there is no generic structure. Rather, the final structure is a function of the configuration. Claesson [2006] proposes the concept of *configurable components*, of which the mindset is described in Part 4, at the end of chapter 4.5.3. The modelling attempts in the framework of configurable components builds upon the extended function/means tree, by adding Configurable Components as a level besides the Design Solutions and the Functional Requirements. The configurable components are modelled as links between design solutions and parts, meaning that a design solution is realised by a configurable component, and the configurable component – in a certain instance – needs a part with set parameters in order to be realised. Thus, the configurable component is an abstract group of attributes, giving the designer an impression of generic and variable attributes. Once the variable attributes of the configurable components are chosen within a range, the designer can move to the part domain.

From a modelling perspective, the visual outcome of the models is very similar to that of the extended function means/tree in figure 5.14. The framework is mainly useful for computerised product data, rather than as a graphical models. The strength lies in the ability to handle product structures (parts hierarchies) that are not constant, i.e. structures that depend on the configuration. This is an issue that the Product Family Master Plan [Harlou, 2006] and the generic variant structure [Jiao et al., 2003] does not handle.

5.3.6 Visualising and depicting the product

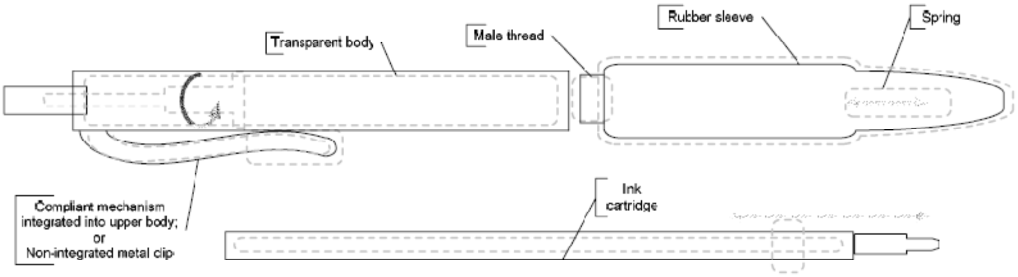
Very few authors try to give their functional modelling efforts a visual touch in order to make the models easier to recognise at a first glance, and easier to navigate through for a variety of different people, who do not necessarily know a certain modelling syntax or possess an in depth knowledge on the design of the platform. The work van Wie and colleagues [van Wie, et al., 2003] constitutes an example of such a modelling framework, in which the product is visually depicted in the model, see figure 5.21.

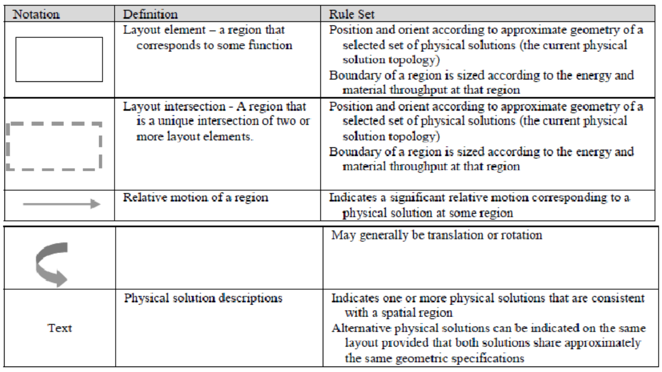


Notation	Definition	Rule Set
→	Energy, Material, or Signal flows external and internal to the product boundary	Show flows relative to the product boundary in terms of position and orientation Show flows from input to output along the same function path as the function structure
☐	Layout element – a region that corresponds to some function	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
⬚	Layout intersection - A region that is a unique intersection of two or more layout elements.	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
Text	Flow and function descriptions	Function information is shown for each layout element and layout intersection All functions from the function structure should be identified

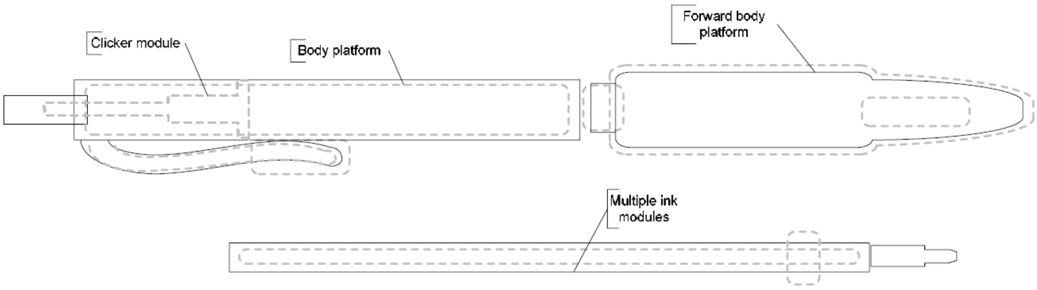
Figure 5.21: An example of a function structure resembling the physical layout of the product. In fact, it is very close to actually being an organ structure, even though the authors do not operate with the organ concept [van Wie, et al., 2003].

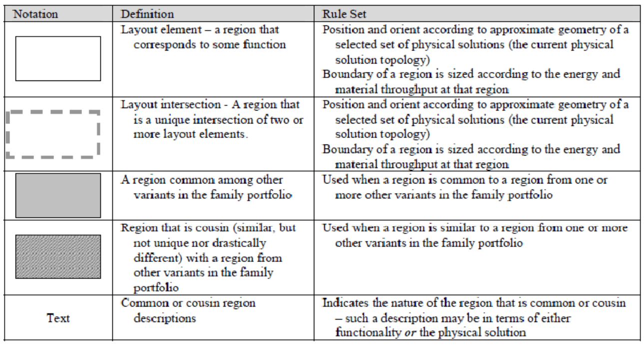
Figure 5.21 depicts what the authors call a *function structure* [van Wie, et al., 2003]. Nevertheless, the authors operate with so-called *layout elements*, shown as light grey squares in figure 5.21. They define layout elements as *"a region that corresponds to some function"*, and further state that the position and orientation of a layout element (when drawing the model) follow the approximate geometry of a set of "*physical solutions*". The physical solutions in turn are defined as;"*A physical embodiment of some set of functions. (A concept in the physical or form domain)."* Thus, the concept of regions corresponding to functions comes rather close to the concept of organs – i.e. seen as form from a function perspective – and the concept of layout elements comes close to the concept of wirk elements (which is also stated directly by the authors). However, the authors also state that "*physical solutions are partitioned into physical modules and components*". Thus, whether to see these physical solutions as organs, parts or something in between is unspecified. This detail does not change the apparent impression of the modelling approach as being more visual than the traditional boxes of most functional modelling attempts. It is also a strong advantage of the modelling method to try to include functional regions that are not bound by the physical design. The figure gives a rather intuitive first impression and guides the viewer through the model with small pieces of explanation. Apart from the functional layout, the authors also propose a spatial constraints diagram, in which important measures such as the length and diameter of the pen are drawn on a schematic of the product, a physical solution diagram showing the actual solutions to the organs/wirk elements in the function structure diagram, a manufacturing diagram depicting how different processes corresponds to different regions of the product, and finally a product family diagram, which is supposed to give an impression on the shared and variable components (grouped in modules) and an overview of the different modules. A few examples are provided below (fig 5.22);





Notation	Definition	Rule Set
▭	Layout element – a region that corresponds to some function	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
⬚	Layout intersection - A region that is a unique intersection of two or more layout elements.	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
→	Relative motion of a region	Indicates a significant relative motion corresponding to a physical solution at some region
↻		May generally be translation or rotation
Text	Physical solution descriptions	Indicates one or more physical solutions that are consistent with a spatial region Alternative physical solutions can be indicated on the same layout provided that both solutions share approximately the same geometric specifications





Notation	Definition	Rule Set
▭	Layout element – a region that corresponds to some function	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
⬚	Layout intersection - A region that is a unique intersection of two or more layout elements.	Position and orient according to approximate geometry of a selected set of physical solutions (the current physical solution topology) Boundary of a region is sized according to the energy and material throughput at that region
▒	A region common among other variants in the family portfolio	Used when a region is common to a region from one or more other variants in the family portfolio
▨	Region that is cousin (similar, but not unique nor drastically different) with a region from other variants in the family portfolio	Used when a region is similar to a region from one or more other variants in the family portfolio
Text	Common or cousin region descriptions	Indicates the nature of the region that is common or cousin – such a description may be in terms of either functionality *or* the physical solution

Figure 5.22: A physical process diagram and a manufacturing diagram respectively.

5.3.7 Concluding on the modelling approaches

From the above review of various modelling techniques, two main trends can be identified;

1. A mainly functional modelling approach focusing on *flow* and *transformations* – i.e. rather behavioural
2. A mainly structural modelling approach focusing on *relations* between *elements* – i.e. rather constitutive

Clearly, there are various combinations of the two trends, and each of these attempts may be classified as being more or less visual/graphical. Some have visual representations of the product or the effects. The ballpoint pen example in chapter 5.3.6 is an attempt to visualise function *and* form, i.e. a kind of mapping from the *constitutive* to the *behavioural*, while at the same time depicting a visual representation of the product. The engineering view of the PFMP is somewhat the same, because organs are grouped by their functions, and organs are physical. The function/means tree with successive function and means are also a kind of function to form mapping, although the overall structure of the tree is based on a relatively constitutive starting point. The extended function/means tree also depicts relations between *Functional Requirements* and *Design Solutions.* The design solutions are considered as the same nature as organs and thereby somewhat equivalent to the contents of the engineering view in the PFMP.

The function/means; tree extended function/means tree; and the PFMP, are concepts in which various pictures and sketches may be included to support a visual understanding. However, they do not depict the product as visually and recognisable as in the case of the ballpoint pen example. Clearly, the ballpoint pen approach would have challenges in a highly complex product, however, that may be a matter of information resolution and several viewpoints on various vertical causal levels.

There are many more product modelling attempts. Jensen [1999] provides a review of various product modelling tools. None of these truly implement a visual approach. Clearly, the past decade of development within computer visualisation techniques and CAD systems have greatly improved the ability to make models and visualisations of products. Some of these abilities (mainly the top down approach in Pro/Engineer) have been used in the Grundfos and Aker Solutions cases. Apart from already present programmes, it was considered to be out of scope for the purpose of this thesis, to address computer visualisation tools.

Poster approach

The PFMP is a 'poster approach' in the sense that is does not (apart from the parallel attempts of the Product Model Manager software) seek to build a computer model. The idea is to have a printout hanging in the company, in order to visualise on a large piece of paper, what a computer screen or projector may not. Moreover, employees in the company can write, correct and comment upon the contents of the PFMP. Until monitor and flat screen technologies become mature (i.e. until size, resolution and the ability to write on the screen) a poster will probably be the main media for the PFMP.

Organ encapsulation

The phenomenon of organ encapsulation is not clearly *visualised* in any of the above attempts. The closest is perhaps the ballpoint pen example, in which *functional regions* and *physical regions* are shown in the same illustration. A similar approach has proven useful in the Danfoss project, and will be described in that case later in Part 5, chapter 5.5.5. (The first attempts to visualise the organ and part encapsulations at

Danfoss, was originally developed in 2003 without the knowledge of the methodology proposed by van Wie and colleagues [van Wie et al., 2003]).

5.3.8 Choosing the right modelling approach

For the purpose of the three industrial cases no single model was chosen. The Part_of and Kind_of relations combined with the three views of the customer, engineering (organ), and parts, was used in all the three cases. An approach similar to the ball point example [van Wie et al., 2003] was used in Danfoss.

However, the vast majority of the modelling attempts were done by visualising various platform elements in various meetings *on the go*, i.e. to discuss with people in the organisation about the various platform elements and effects, and then visualise it *somehow*. And this *somehow* proved to be very different depending on the platform element and the life phase system in the concrete example. The following three cases span various modelling dimensions and methods. All of them can be mapped into the phenomenological framework from Part 4.

The modelling media, and the proportion of information and computer models is also different in the three cases. In some of the projects, computer tools played a vital role, and in two of the cases (Grundfos and Aker Solutions) CAD models held a great proportion of the platform model, where as the design rules the third case (Danfoss) was mostly held on paper based models.

The basic conclusion from the study of existing product modelling methods, is that there is not *a single* well established modelling environment suitable for platform elements of *Organ*, *Part, Software, Activity*, *Knowledge* and *People*, which are the platform object classes identified in Part 4.

The following three cases provide examples and discussions on how to model and visualise these six platform element classes and their meetings with various life phase systems.

5.4 Introducing the cases

This chapter will provide a short introduction to the general patterns in the three cases, and elaborate on the choice of the three companies.

5.4.1 Choosing the companies

The three cases have been chosen among a series of relevant and possible industrial collaborators. Clearly, availability has been one issue, yet the relevance of the projects has been the governing factor. The somewhat coincidental choice of cases has added an element of randomisation to the case material. A consequence of this has been three rather different companies, when it comes to business, product type, annual turnover etc. If anything, this should be a strengthening factor when it comes to claiming confidence in usefulness and thereby add validity to the results. On the other hand, three cases do not add significant statistical evidence to the empirical findings. A research study (and a PhD study in particular) has limits both in time and resources, and there is a trade off between the number of different companies one can be involved in, and the depth to which the cases are dealt with. In this case three companies turned out to be willing to cooperate, relevant for the research, and possible to include with the right timing.

5.4.2 The structure of the case chapters

The findings of the cases are reported in three separate chapters (5.5, 5.6, 5.8). All three chapters have the same basic structure. The last chapter in Part 5 is a conclusion on the three cases, and a discussion on modelling approach and the implications on theoretical and phenomenological studies from Part 4.

Each of the three case chapters includes (but is not limited to) the following sections;

- *1) The role of the author (Chapters 5.5.1/5.7.1/5.8.1)*
  A short discussion on the role of the author in the company, the duration of the engagement, and the relationship to the company and the employees in the projects
- *2) Introduction to the company (Chapters 5.5.2/5.7.2/5.8.2)*
  A general introduction to the company, organisation, number of employees etc.
- *3) Introduction to the challenges (Chapters 5.5.3/5.7.3/5.8.3)*
  An introduction to the initial state of the companies and the incentives to pursue a product platform approach.
- *4) Changing the state (Chapter 5.5.4/5.7.4/5.8.4)*
  A general discussion of the initiatives that where started in order to address the challenges in the company.

All cases then include chapters on the various models that were developed and tested during the case projects, followed by a discussion on the validation efforts and a conclusion;.

- *Modelling & implementation (Chapters 5.5.5/5.5.6/5.5.7/5.5.8/5.7.5/5.8.5)*
- *Validation (Chapters 5.5.9/5.7.6/5.8.6)*
- *Conclusion (Chapters 5.5.10/5.7.7/5.8.7)*

5.4.3 Establishing a mindset

In order to master the product platform approach, and in order to use the platform models, it turned out to be feasible with a certain *mindset* among the users of the models and in the organisation as a whole.

Thus, apart from the modelling efforts, there was a parallel task of establishing a mindset in the three case companies. That is, a mindset on product platforms among the employees who were to design the platforms, decide upon the platforms and to use the platform models. Sometimes the audience of this *mind setting* also included various stakeholders within the organisation.

Transferring and maintaining a mindset of product platforms in a company is sometimes overseen in academia. Many of the references with prescriptive methods and tools for product platform development does not explicitly state how to establish a mindset in a company, [Stone & Wood, 2000], [Farrel & Simpson, 2003], [Hölttlä-Otto & De Weck, 2007], [Tseng & Jiao, 1999]. Few of these actually delve into the challenge of implementing their methods and providing the employees within the company with a chance to understand the phenomena behind their methods and the models.

The task of providing employees with a mindset was done differently in the three cases and with different emphasis. In the Danfoss project, a series of consecutive seminars and courses with several hundred participants were held over a period of two years, while the job in Aker Solutions was mainly done through a few discussions with key employees. The difference has to do mainly with the scale and nature of the projects.

Regardless of the format and emphasis, the basic idea was to provide an understanding of the *concept of product platforms*, the possible *effects of platforms,* and the product *platform development context*, i.e. essentially the three main topics of Part 4 (chapters 4.2/4.5 and 4.6 and 4.7).

Mindset and models

From research point of view – i.e. in the context of platform modelling – a key reason to emphasise the *mindset* is that the mindset has an influence on the way the models are interpreted and understood. The understanding passed on *to* the users *from* the model, will depend on a pre-established knowledge already present in the minds of the users. A model is a kind of language, and the users have to know the language in order to understand it. Figure 5.23 depicts the importance of the mindset.

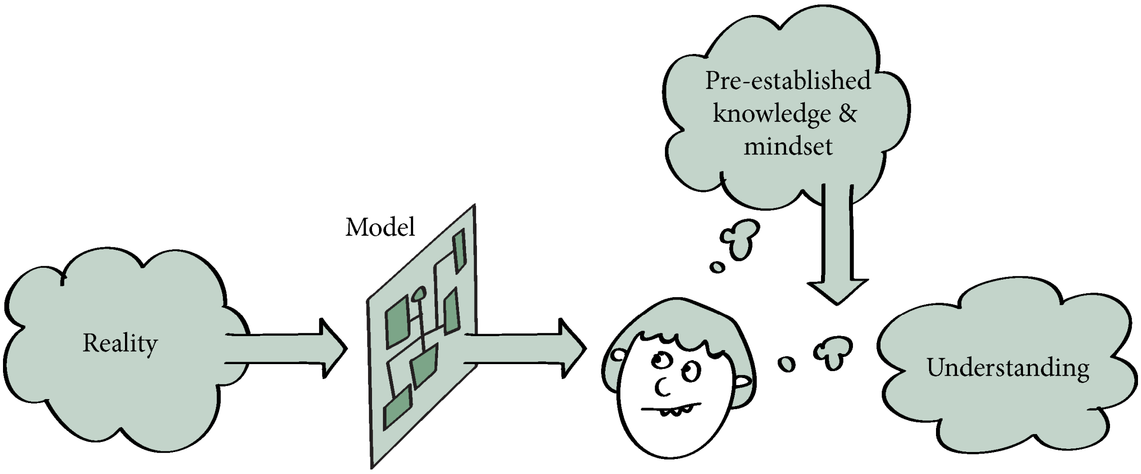


Figure 5.23: Knowledge and mindset of the recipient play a vital role when interpreting and understanding a model. A design engineer using a product platform model has to have a mindset and some degree of pre-established knowledge in order to understand the model.

The figure points to two challenges faced by the mindset efforts;

1. *Understanding the modelling object*
   The mindset has to provide the decision makers and users of the model with a sufficient understanding of product platforms
2. *Understanding the model coding*
   The users of the model have to understand the model itself, i.e. understanding the coding of the model.

Both purposes were addresses in the cases by means of various teaching techniques.

The mindset is a problem for validation

Thus, the right mindset is a prerequisite for understanding the model. However, the mindset being a part of the project also induces a certain preconception from the researcher to the employees, and then, when the employees are later used to evaluate the models, the feedback gets biased. This is however, a condition within the research setup, which was somewhat hard to get rid of under the current circumstances.

Ideally, the modelling efforts could have been tested out in companies with a long experience in platform based product development. The employees would then have had lesser needs for a certain mindset provided by the researcher and also a better experience to judge the soundness and usefulness of the models. However, this was not the case in the three companies within this study, and this is a limitation of the research.

5.5 Danfoss Automatic Controls

5.5.1 The role of the author

The author has been involved in activities in Danfoss over a period of five years from 2003 – 2008.

Much of the research and activities at Danfoss has been carried out in close cooperation with Morten Kvist, a fellow PhD student, whose results are reported in a parallel PhD thesis [Kvist, 2009].

The author has had the role as an advisor in and initiator of a platform start up in Danfoss. In 2004 a product platform project was initiated on the basis on an analysis made by the author and Morten Kvist. After project start the role of the author was to be part of the project team, which grew from a single Danfoss employee to more than ten full time resources and a total of some twenty R&D employees actively involved. During that period, the author spent time in Danfoss ranging from full time in the start, taking an active role in the project. The tasks were mainly to engage in various visualisations of the challenges and results made by the design engineers, but also to plan and conduct education of people in the company within the topic of product platforms.

Danfoss has funded the PhD project by roughly 2/3rds and is thereby economically involved in the project. However, it is the author's impression that Danfoss has not imposed any specific demands on the research work during the period, despite the fact that the industrial part of the project was fully managed by the company. Clearly, this is a subjective statement.

5.5.2 Introduction to the company

Danfoss Automatic Controls is a business unit within the Danfoss Group. The Danfoss Group is a global manufacturer of mainly mechanical, electromechanical and electronic controls products, e.g. contactors, valves, frequency converters, thermostats and a range of related products. Danfoss employ some 20000 people worldwide and had revenues of roughly 20 billion Danish kroner in 2008. Danfoss has a global stronghold in the refrigeration and air-conditioning business, and the most significant business areas are within such applications. Heating applications and motion controls are two additional business segments in which Danfoss operates. The corporation is divided in three divisions in accordance with these three market segments (figure 5.24);

Figure 5.24: The Danfoss Group. The three Divisions in Danfoss. Each division is made up of multiple Business units.

Each division is further split into business units. Each business unit is relatively independent and – in most practical contexts – serves as autonomous companies under the same brand name and corporate structure.

Danfoss Automatic Controls

Danfoss Automatic Controls is a business unit within the Refrigeration & Air conditioning Division, and sits in the lower left corner of the organizational diagram in figure 5.24.

The Automatic Controls Division has a focus on automatic industrial controls such as motor starters, contactors, pressure switches, and solenoid valves.

The solenoid valves business

The solenoid valves business is the focal point in this case. The business is divided in two general foci, one for *industrial controls* purposes and one for *refrigeration and air-conditioning*.

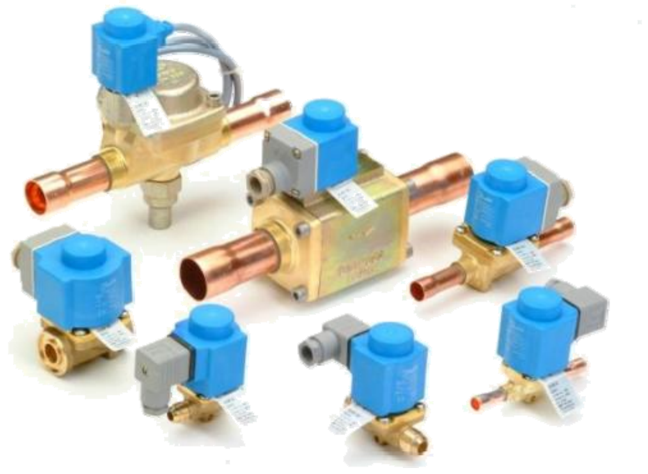


Figure 5.25: A typical series of different refrigeration solenoid valves. Note the cobber tubes. They are typical refrigeration connections, soldered to the pipeline in a refrigeration system.

The current design of the solenoid valves was laid out some 35 years ago (i.e. in the early 1970'ies). The products are developed, produced and sold to two distinct market channels; one for industrial controls applications and one for refrigeration and air-conditioning applications. The organisation was changed a few years before the case study project was initiated (in 2002), and now has two 'value streams' that complies with the dual business focus, as seen in the figure below (5.26).

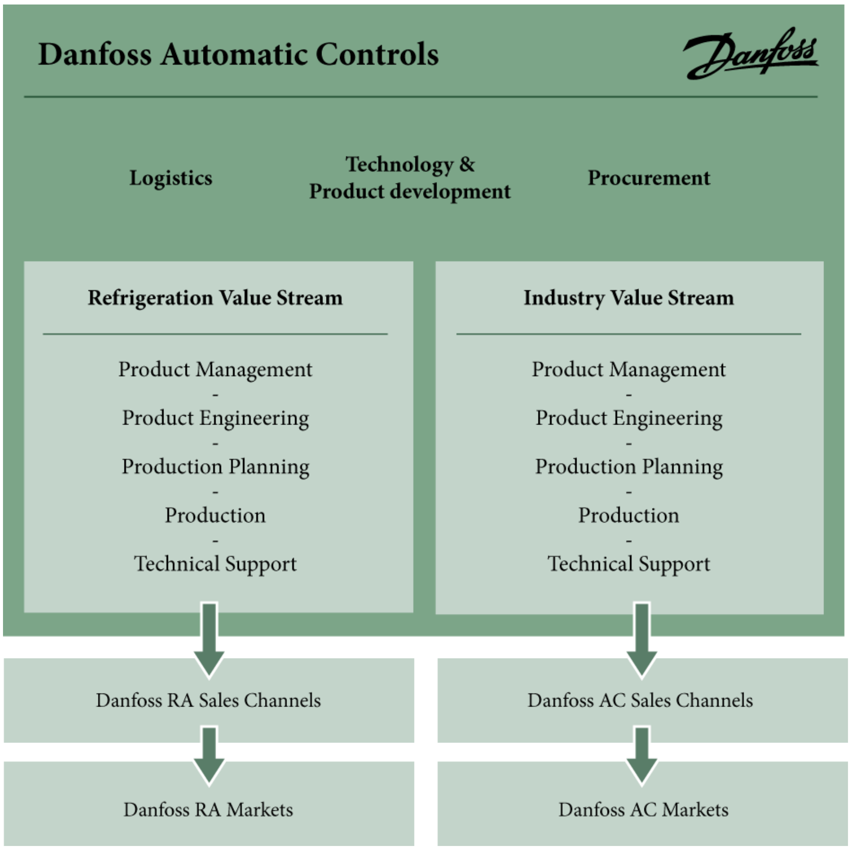


Figure 5.26: The two value streams of the Danfoss Automatic Controls solenoid valve business. Product Engineering (i.e. Engineering design) is separated into the two value streams, whereas the long term Technology and Product Development is held common for both value streams. RA is Refrigeration and Air-conditioning, AC is Automatic Controls.

The solenoid valve business is basically hosted in one factory building, accommodating all the necessary development and operations functions. The logistics, Technology & Product development, and Procurement departments are serving both value streams, i.e. they support the automatic controls business (AC) and the Refrigeration and Air-conditioning (RA) business. The rest of the supply chain and value chain is split in two separate factories within the factory, as seen in the figure. These two organisations are called Value Streams. From the value streams, the products flow further out in the sales channels of the two different businesses.

Product development arrangement

The development efforts on solenoid valves in Danfoss Automatic Controls are grouped in three different organisations. These are;

1. The design engineers in the Refrigeration and Air-conditioning value stream
2. The design engineers in the Industrial Controls value stream
3. The product developers in the Technology & Product Development department

Short term: Value stream engineering

Design engineers in the two value streams are focusing on the steady stream of customer requests coming from the sales organisation. Such requests are usually satisfied by smaller incremental changes to the product design. The requests are divided into;

- *Standard options*
  Few or no changes made to the products. They just make sure that the design is feasible for the customer request
- *Minor Specials*
  Light changes to the product design that takes some product development efforts but are still within the limitations of the current design and production capabilities
- *Major specials*
  Major specials are projects that are outside the scope of the value streams and should be passed on to the technology and product development department. Such projects are usually for bigger customers or requests that may form the basis of a strategic decision to include a new product variant in the standard range, and therefore to make this feature available to other customers.

The value stream engineers also handle customer complaints.

Long term: Technology & Product Development

The Technology & Product development department has a focus on long-term and strategic product development. They distinguish between three different types of development projects:

- *Market initiated projects*
  Projects initiated to expand into new markets or to satisfy new trends and requirements in the existing markets.
- *Customer initiated projects*
  Projects initiated to accommodate a request from an important customer. These are often requests that are not easily made on the basis of existing products
- *Technology projects*
  Long-term technology development projects that focus on new technology and does not necessarily have to be linked to a specific product development project. These are both manufacturing technologies, such as new welding techniques, and product technologies, such as new actuating principles for the valves.

Figure 5.27: Typical automatic industrial controls valves. Note the thread connections. They are the typical way to mount industrial valves to the pipeline. The valves on the picture are used for water, oil, steam and other pipelines. The blue and black parts are the coils.

The solenoid valve

In order for the reader to understand the visual models later in this chapter, a short introduction to the solenoid valve and some drawings are included here. Figure 5.28 depicts the working principles of the solenoid valve.

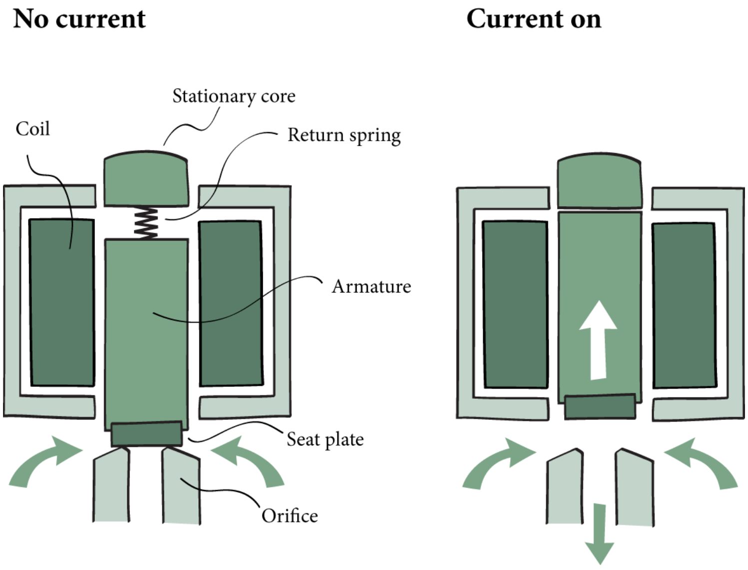


Figure 5.28: The principles of a solenoid valve. The coil is wound around the stationary core and the armature. A spring forces the armature to close the orifice. When the coil is electrified, magnetic forces bring the stationary core and the armature together, thereby opening the valve.

In the solenoid valve, a coil is wound around the stationary core and the armature. A spring forces the armature to close the orifice. When the coil is electrified, magnetic forces bring the stationary core and the armature together, thereby opening the valve.

The following two figures show to different valves. Figure 5.29 shows a cross section of a typical industrial valve, with a coil on top. The valve in figure 5.30 is a typical refrigeration valve with cobber tubes as connections. The valve is shown without its coil.

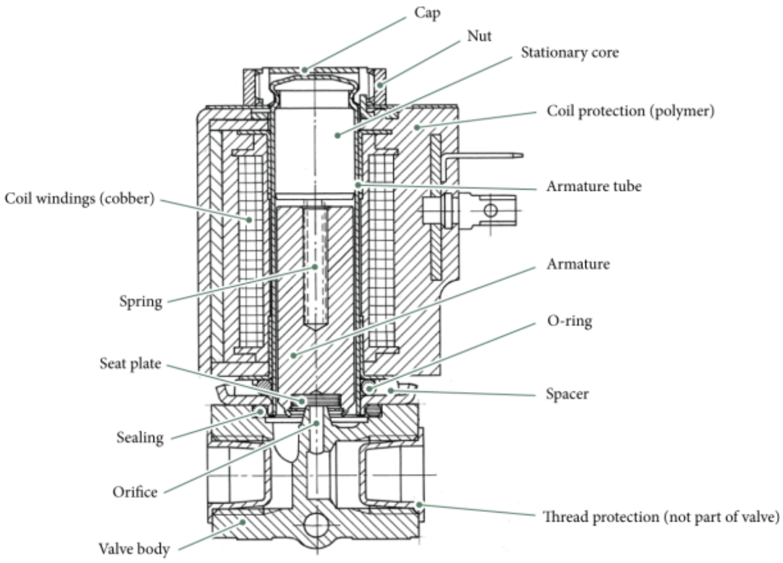


Figure 5.29: A cross section of a typical industrial valve. The valve is closed. The coil is mounted on the Armature Tube. Note the seat plate at the end of the Armature. The seat plate is a gasket which is pressed down on the orifice in the valve body, thereby sealing off the valve. Once the coil is energised, the armature will move upwards, towards the stationary core inside the top of the armature tube, while compressing the spring. This valve operates without a diaphragm, contrary to the valve in figure 5.30.

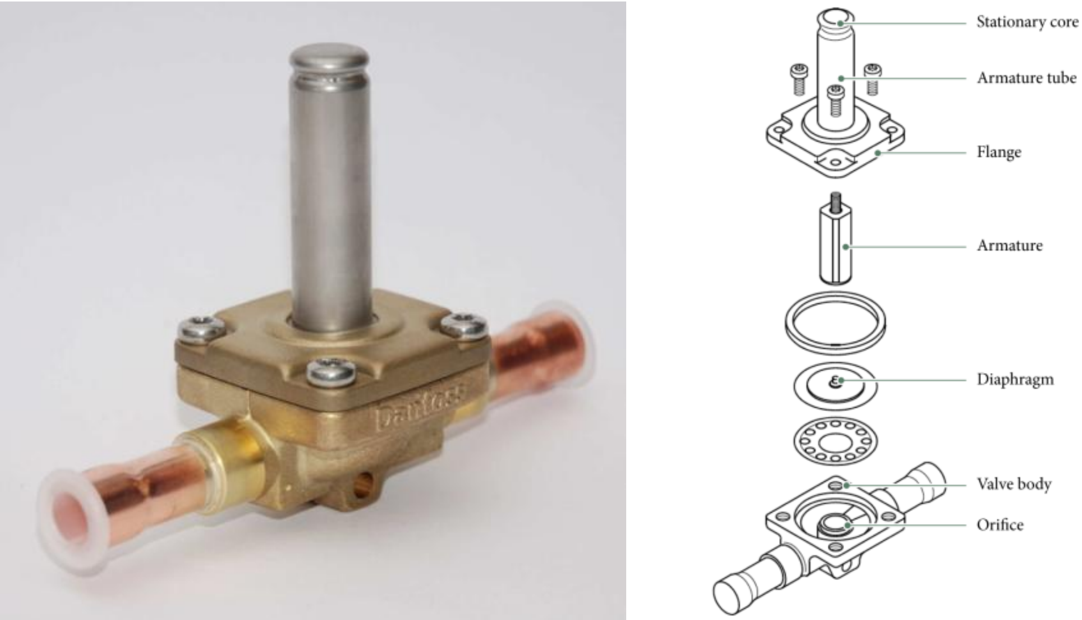


Figure 5.30: To the right: A typical refrigeration valve without a coil. The coil can be mounted on the stainless steel tube on top of the valve (the "armature tube"). To the left: An exploded view of the valve. The armature moves inside the armature tube and the stationary core is mounted inside the armature tube. Some valve types have a diaphragm, and some operate without. This valve comes with cobber tubes as the connection type (see the picture). Cobber tubes are soldered to the pipeline and are used in refrigeration systems.

Direct operated and servo operated

The two valves in figures 5.29 and 5.30 are slightly different in the way they operate. The valve in figure 5.29 is a so-called *direct operated valve*, because the gasket in the armature rests directly upon the orifice.

The valve in figure 5.30 is a so-called *servo valve*, because the gasket in the armature does not rest directly on the orifice but on a diaphragm. This concept utilise the diaphragm and the pressure difference between inlet and outlet, to open orifices that are larger than the diameter of the gasket in the armature. Understanding the details about the valve is not important for this thesis; however, the reader should bear in mind the two principles. Later, two different visual models are shown (in the top and bottom of figure 5.36 and 5.37), and they correspond to these two different working principles.

5.5.3 Current challenges

The organisation is a complexity driver

There are a few problematic characteristics of the organisational layout in Danfoss. The division of the product engineering, i.e. the short term daily engineering design efforts in the two value streams is one important aspect. The split results in two distinct departments in which the day to day customisation takes place. This has been the case during a relatively long period of time even though the organisation is fairly new. The original reason to make this split was to move the design engineers closer to the sales organisation and eventually to the customers. Danfoss soon realised that the split was a major driver for the product complexity to grow, since there was no structured way of sharing design knowledge between the two value streams. Even within the two value streams one could experience a serious growth of complexity due a lack of a structured sharing of concepts and knowledge, and a strong focus on variable cost optimisation that forced engineering designers to optimise single components and thereby creating a steady and growing stream of new designs that were slightly different. Having said this, it is notable that the two value streams are profitable under the current circumstances. Moreover, several important product features are developed for both value streams, and so the two product families do share some components and production steps, and Danfoss have already made some standardisation efforts, with great success mainly in the refrigeration part of the business.

A history of complexity

Nevertheless, some 35 years of engineering design, customisation of existing products to suit new customer needs, acquisition of competitors, and other activities, has driven a growing number of different components and designs, thereby creating a large internal complexity in the organisation. Despite the fact that the Technology & Product development Department serves both value streams, it still had not – at the time of the start of this study – been possible for Danfoss to stop this growing complexity.

The valves are not that complex from a single product viewpoint. They consist of some 20 – 30 different components, and the overall functions are relatively simple. But the shear amount of different designs throughout the product portfolio accounts for a significant complexity in the whole supply and value chain in the company, all the way from suppliers to procurement, production, development and into the sales and communication efforts made by the front office sales staff.

5.5.4 Changing the state in Danfoss

A few key managers in Danfoss had recognised the long term strategic problems inflicted by the growing complexity, and had a desire to change the state. Based on this, two major initiatives were started;

1. A current state *Product Family Analysis* of the existing product portfolio using the *Product Family Master Plan* (PFMP) methodology, (see Part 5, chapter 5.3.4 for more on the PFMP). This part of the work has been described in by Kvist [2009]. Focus has been to highlight *non value adding variety* in the product assortment, from a market-, product built up-, and production point of view.
2. Based on the findings of the product family analysis to initiate the development of a new product platform. This work is further elaborated in the following, and was carried out with the participation of Morten Kvist and the author, in corporation with employees in Danfoss. It was not given beforehand that a product platform was the evident answer to the problems. Several other initiatives, such as a higher automation in the factory was discussed, and even initiated as parallel activities.

Product platform development in Danfoss AC

On the basis of a Product Family Master Plan certain proportion of the solenoid valves business was chosen as the ‘test ground’. The test sample to which the research has been applied included the equivalent of 231 existing commercial product variants, which accounted for an approximate annual sales volume of 2 million pieces sold and an annual turnover of nearly DKK 400 (€53-54) million.

First, several platform concepts were proposed and one concept was chosen thereafter. This work was carried out by the two researchers in cooperation with key employees in the engineering staff at Danfoss. Then, a project team was formed and a project manager was hired to lead the project.

The methodology of this work is described by Pedersen et al., [2005a+b] and Mortensen et al., [2008], and briefly discussed this thesis in Part 4, at the end of chapter 4.7.2. Here, the focus is not as much on the sequence of the methodology, but more on the modelling framework. The models, which were part of the synthesis process, as well as other models made during the project, are described in the following.

5.5.5 Visual platform concept modelling

This chapter gives examples of various models, which have been used in Danfoss. The models have been used in various phases of the platform project, from the early concept work, before the platform was established, to the later stages, in which the parts were designed and had to be managed in ERP and CAD systems, prototypes were beginning to form etc.

In the concept phase

The basis of the concept work was an analysis based on a Product Family Master Plan, pinpointing the root causes to the *complexity* in the organisation. The main issues for the concept phase to solve were;

1. Non value adding variation on part and organ level, i.e. essentially little reuse and a lack of commonality.
2. Late variegation of parts, i.e. a limited utilisation of postponement. [See Part 4, chapter 4.6.2 for an explanation on variegation and postponement].

Thus, a key challenge was to redesign the products and the production systems to better fit each other, in order to gain commonality and to be able to postpone the variegating processes. Moreover, a challenge was to change the *decoupling of organs and parts* in order to enable reuse and sharing without compromising product variety towards the market place.

Choosing a visual strategy

When designers and production engineers in Danfoss communicate, they tend to draw cross sections of the valves. Figure 5.31 depicts a typical cross section of a solenoid valve without the coil on top.

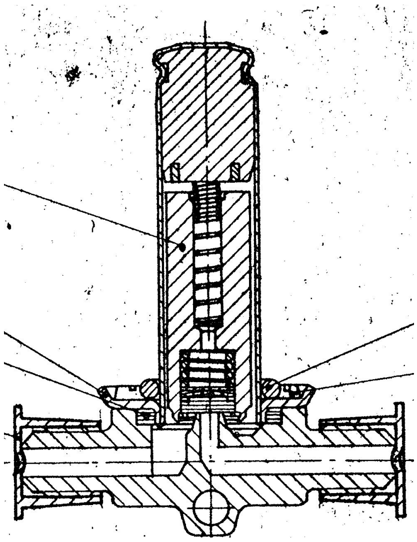


Figure 5.31: A detail from a typical technical drawing of one of the high runners in Danfoss.

A lot of information is embedded in the above drawing, and for the design engineers in Danfoss, a cross section reveal the working principles of that particular variant of a valve, whether it is a direct or servo operated valve, the connections to the pipe line, etc. During conceptual work, workshops, meetings etc. the cross sections of valves on several levels of details, were the predominant communication tool in many situations and discussion. Thus, it seemed natural to take a starting point in the cross section as a visual representation. Clearly, this is a deliberate choice of representation, and other choices and concepts of visualisation could have been feasible.

Establishing an overview of organs using the cross section

A generic organ model – somewhat similar to the generic organ diagram [Harlou, 2006] (see chapter 5.3.1) – is proposed here as a starting point for the modelling task. However, the generic organ *model* is different from the generic organ *diagram*, in the sense that it depicts the relative position of organs, and somewhat resemble the cross section in figure 5.31. The resemblance to the cross section made it instantly recognisable for the design engineers, and thereby served as a good starting point for discussions.

Figure 5.32 depicts the organ model;

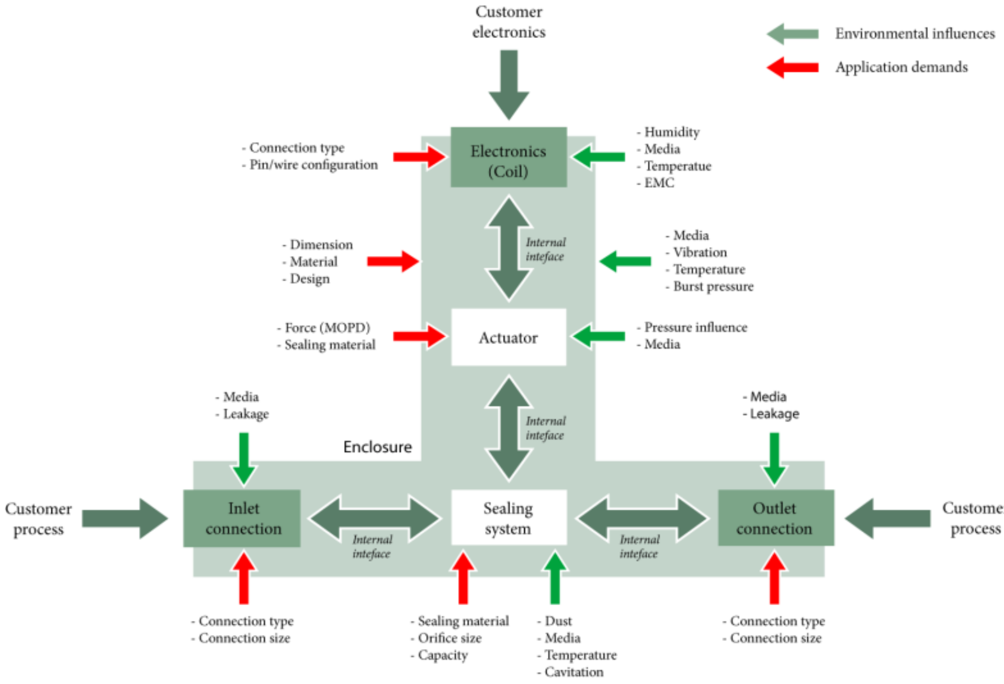


Figure 5.32: A conceptual organ model of a principal solenoid valve including the coil.

The generic organ model depicts the main organs including the coil. The model also reflects the major points of variation towards the customers, represented by the red arrows. Without taking the coil into consideration the valve itself has some 12 major variation possibilities in order to accommodate different customer needs. The most important of these are the;

Connections

- Type (such as different types of thread, solder connections, etc.)

- Size (the principal diameter of the connection following various standards)

Valve performance

- The flow capacity when open (media volume per time unit)
- The maximum pressure difference between inlet and outlet, which the valve can overcome and open at.

Media

- Whether the valve can take aggressive, dirty, water based and/or oil based media etc. The possible media are directly influenced by the materials in the valve, especially the metals and rubber types chosen.

These variation possibilities are often related to distinct regions, wirk elements or organs within the valve. Thus, each variation resides in certain organs in the model in figure 5.32.

Parts encapsulation and function to form mapping

From a commonality/variety viewpoint, it is important to visualise various encapsulations of parts matching the organ layout. The goal was to have a single representation of the mapping between part encapsulation and organ encapsulation, i.e. something close to the function–to–form mapping following the perception of modularity proposed by Ulrich [1995].

Based on a typical cross section of a valve and the organ model above, the following generic part structure was visualised. The coil was left out of this analysis;

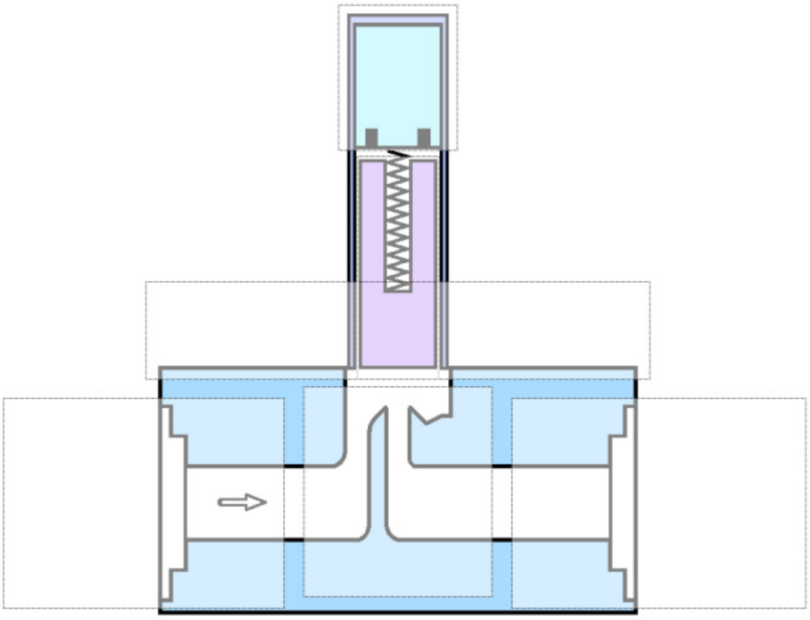


Figure 5.33: A principal cross section of a solenoid valve. It served as a template for the platform design concepts. Each framed area corresponds to a functional region of the product, i.e. to generic organs on a certain level of abstraction. (Published earlier in the Int. J. of Mass Customization, [Mortensen et al., 2008a]).

In the generic part structure, the organs were visualised as functional regions. The regions are shown as shadowed rectangles in figure 5.33. The armature is shown in simplified design in order to avoid implying a certain working principle. Thus, the model in figure 5.33 served as a generic pictogram of the valve. The conceptual work was then done on the basis of this relatively simple representation of the product.

Two important aspects were central to the model;

1. *Alternative organs as part of the conceptual work*
   Establishing an overview of different concepts for various organs, as a part of the general problem solving towards the best working principles of the valve
2. *Alternative grouping and decoupling of parts*
   Visualising alternative encapsulations of parts using a variation in the grouping and decoupling of parts and organs

In order for the design engineers to actively use the model as a design and modelling tool, a jig saw puzzle was made. The variable entities of each organ were depicted as puzzle piece fitting the generic structure. Using this approach, both alternative means to the organs and alternative encapsulation strategies could be designed and varied.

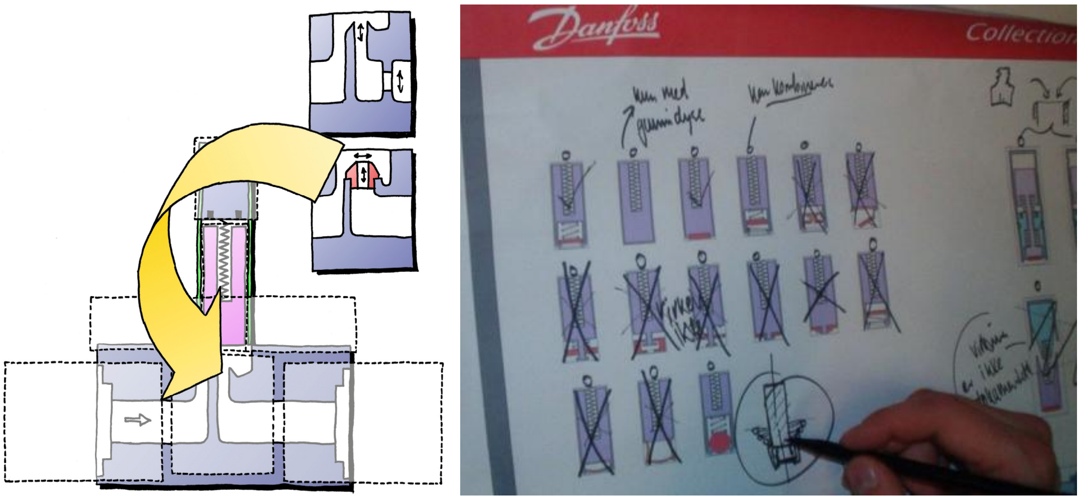


Figure 5.34: An object oriented visual modelling approach; To the right the concept of the model as a jig saw puzzle is shown. On each functional region of the product a variety of different alternatives would match, like puzzle pieces in a jigsaw puzzle. To the right: A poster with all the alternative means was printed, in order for design engineers to add information and cross out alternatives, during the conceptual work. (Published earlier in the Int. J. of Mass Customization, [Mortensen et al., 2008a]).

Figure 5.34 depicts the principles of the jig saw puzzle.

- *The generic model and two alternative orifice organs* to the right. The generic model is used as a template for generating alternative concepts by adding alternative means on to the template.
- *An overview of alternative organs* to the left. A picture of a poster with all the variable organs to choose from. In the picture, alternative armatures are worked on.

Figure 5.35 is a picture of the puzzle in action. The generic structure was printed on posters, and the various puzzle pieces were then placed on the generic structure using semi-adhesive glue. Figure 5.36 and 5.37 give examples of two alternative posters after a brainstorm session.

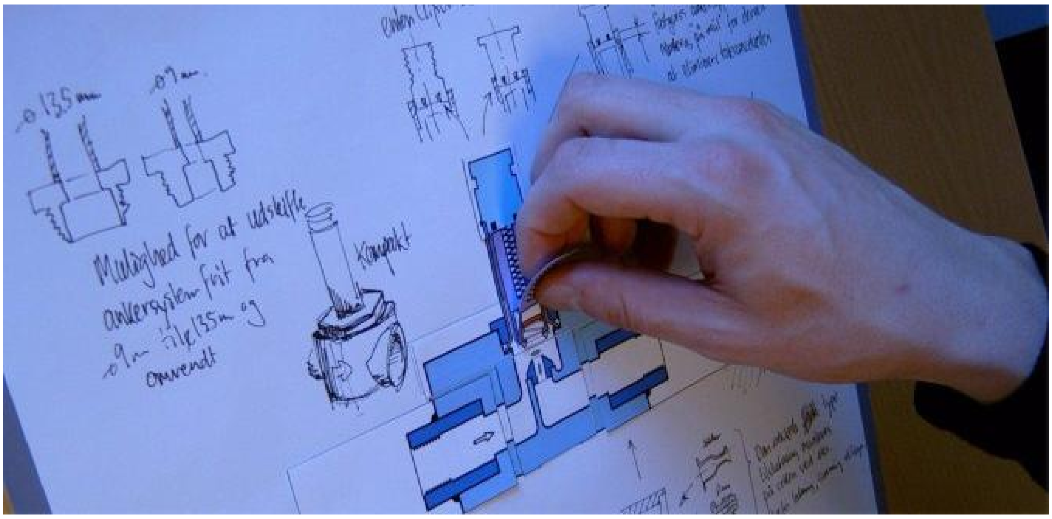


Figure 5.35: The puzzle in action. Different pieces are put onto the generic structure to form alternative concepts for organs and for part encapsulation. (Published earlier in the Int. J. of Mass Customization, [Mortensen et al., 2008a]).

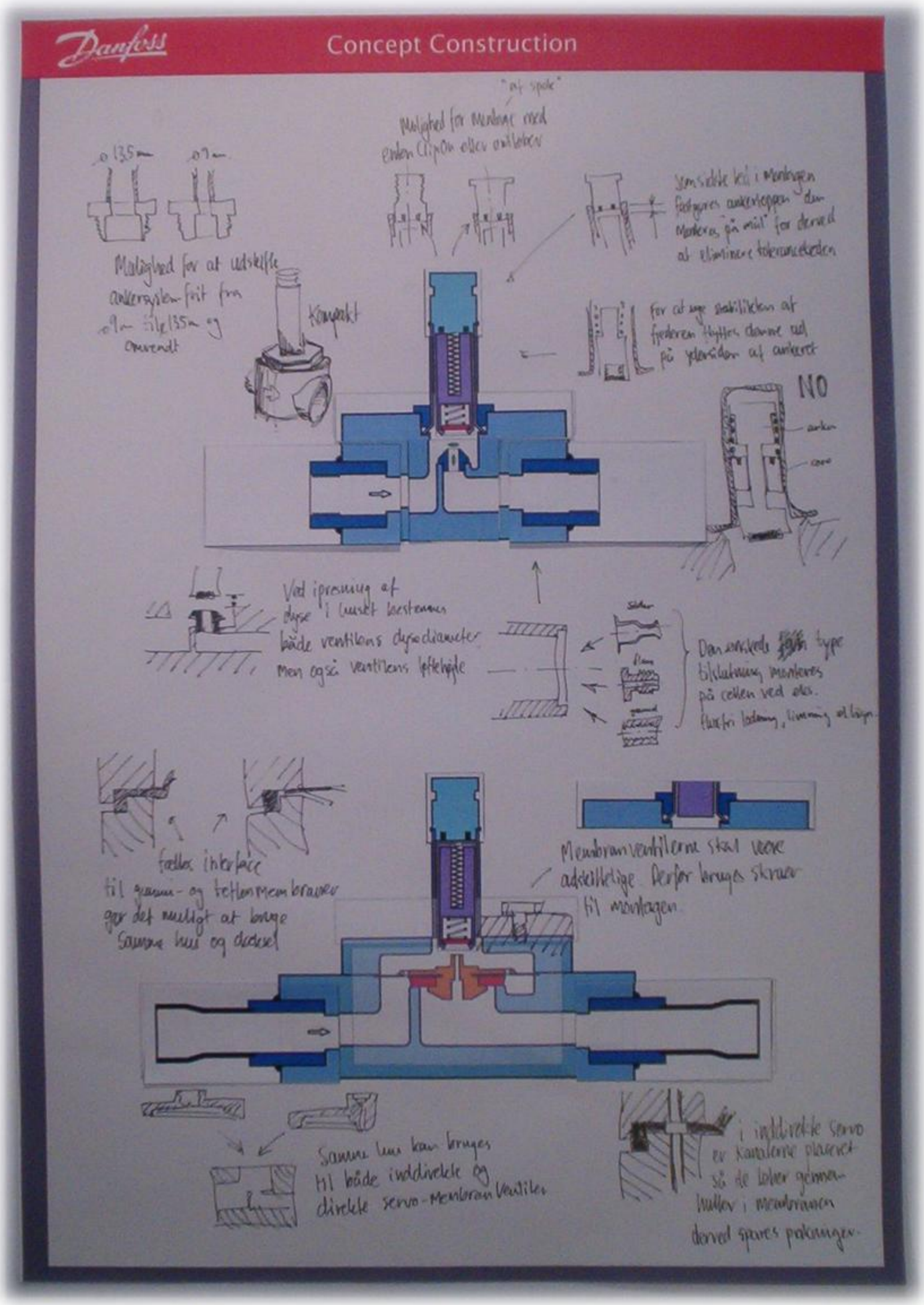


Figure 5.36: A picture of a concept puzzle after a brainstorm session in Danfoss. The top picture is a direct operated valve, without a diaphragm and the lower picture is a servo operated valve with a diaphragm. Design engineers have drawn extra concepts, added comments etc. onto the model during a brainstorm.

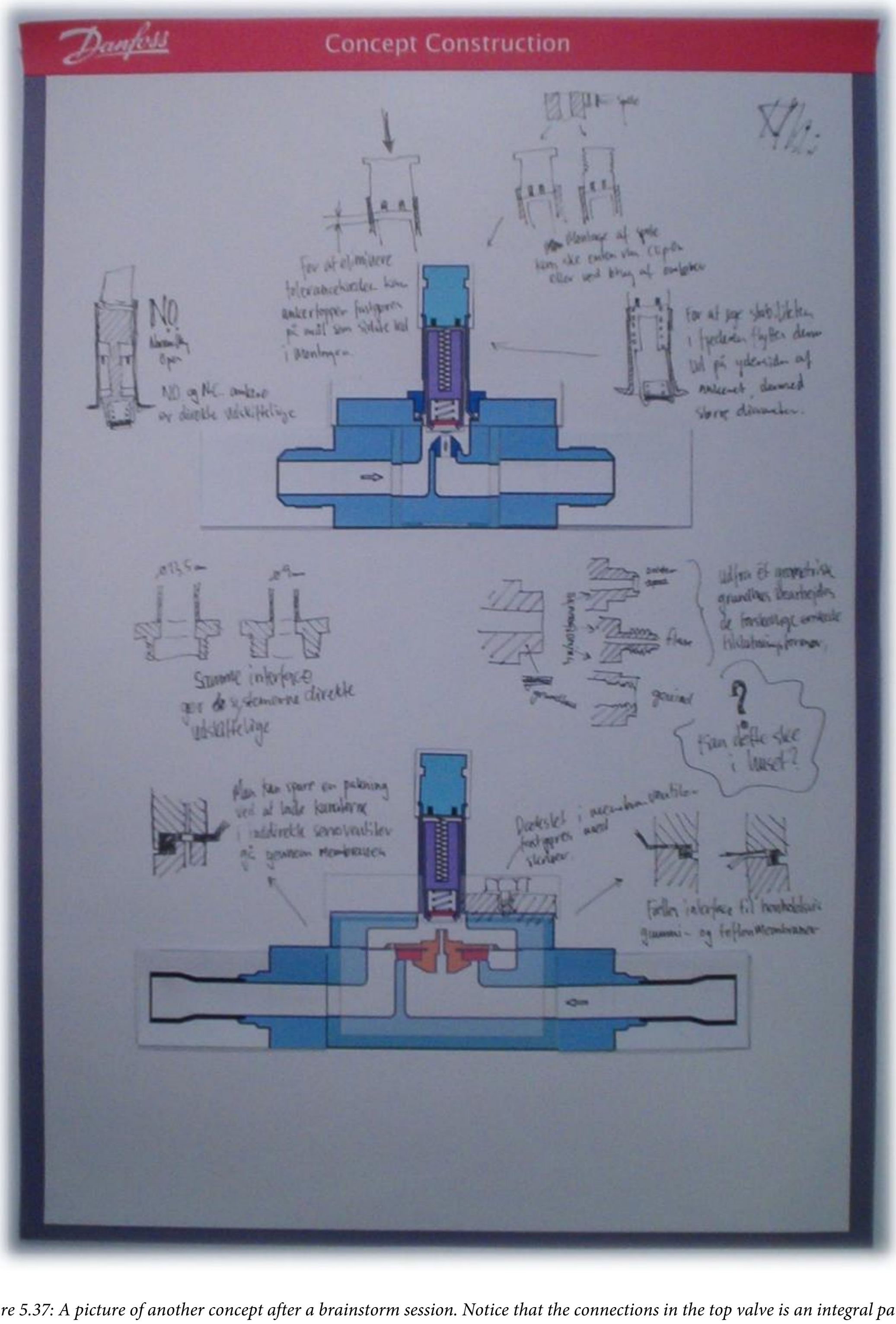


Figure 5.37: A picture of another concept after a brainstorm session. Notice that the connections in the top valve is an integral part of the valve body, while they are loose parts in the same concept in figure 5.36.

The jigsaw puzzle made it possible for designers to compile various different concepts of organs and encapsulation of parts. The figure below depicts two alternative puzzle pieces, representing two different organs and part encapsulations.

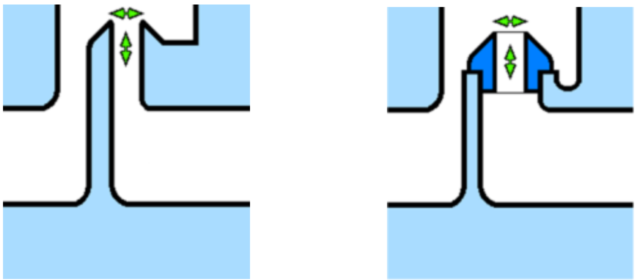


Figure 5.38: Two alternative concepts for the adjustment of the flow characteristics of the valve; one is an integral part of the valve body made by means of organ encapsulation, while the other is made by means of parts encapsulation. The green arrows represent the diameter and height respectively. Both are attributes that have an influence on the flow characteristics of the valve.

Figure 5.38 gives an example of a detail from two roughly identical organ structures embodied in two different part structures. To the left the *height* and *diameter* of the orifice are integral attributes of the valve body. To the left a loose part is mounted in the valve body. The difference in the two design alternatives may seem simple yet it has a profound impact on the supply chain, and thereby the possibilities to postpone the point of variegation;

- *The integral solution* to the left puts demands on *process flexibility* due to the design of the valve body. Postponement in this case will imply that the geometry is changed at a late stage in the production, in order to avoid a lot of different expensive items in stock. Thus, it has to do with the flexibility and lead time of the CNC milling processes in one or several steps that the valve body has to go through. However, the organ is still decoupled from the other organs in the valve.
  Thus, in this case, organ encapsulation takes place through the use of process flexibility.
- *The loose orifice* to the right results in a different production setup. In that case, the relatively cheap orifices, which are easily mass produced in various variants with a short lead time, can be produced close to or after the order entry point. The *assembly* then gets important, and the process of assembling valve bodies and orifices is essential. Also in this case the orifice organ is decoupled from the rest of the organs in the valve, yet in this case the organ is decoupled through a physical interface in the part domain.
  Thus, in this case, part encapsulation takes place through the use of assembly flexibility.

In the final concept, both solutions are implemented. The integral solution is the most cost efficient for high volumes, whereas the loose orifice is efficient below a certain annual volume.

A similar example is shown in the two picture in figures 5.36 and 5.37. Notice the valve connections on either side of the valve in the top part of the two pictures. The connections in the top model in figure 5.36 are integral features in the valve body, while they are separate parts in the top model in figure 5.37. Again, these differences are representations of alternative organ (wirk element) and part encapsulations, resulting in two very different production flows and postponement possibilities.

Sales volume as a driver for encapsulation principles

The decision on whether to make part encapsulation or organ encapsulation was – in many cases – based on the expected sales volume of different product variants. There were some high runners, which were given a dedicated valve body in which connections and orifices were machines – thus, no loose components were added. In the case of low volumes, it was decided to have separate connections and separate orifices. This is an example of the part encapsulation (modularisation) being more efficient that organ encapsulation. The reason is that the decoupling of generic and variable attributes was too costly in the organ encapsulation solution, due to constraints in the fabrication life phase system (the CNC milling machines).

The visual progression from drawing to model

During the work there was a development of the visual representations from a cross section of the valve, to the final product puzzle model with all the variable organs.

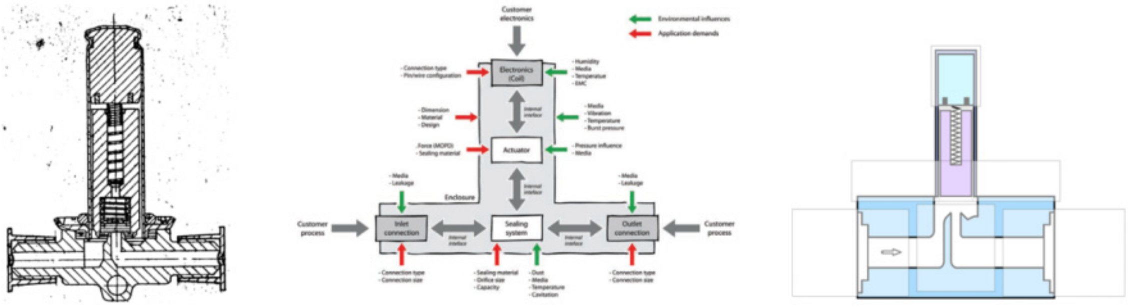


Figure 5.39: The progression from a technical drawing of a cross section through a generic organ model to a generic product structure serving as a template for the product puzzle.

Visualising the production transformations and meetings

In order to visualise the implications from the alternative organs on the production setup - and in particular on the *postponement* potential (see Part 4 chapter 4.6.2 for more on postponement) - a puzzle approach was used to visualise the chain of *fabrication* and *assembly* steps. The production is thought of as distinctive *steps of transformations*, in which the various parts engage in *meetings* with the production system. With a basis in the theory of technical systems (see Part 3, chapter 3.2.2), the product parts in the production are considered to be *operands*. In each fabrication and assembly step the operands undergo a transformation. From a production point of view, two characteristics were important for Danfoss to consider:

1. The *process type* with which the transformation takes place
2. The *handling of parts*, i.e. whether the process was automatic, semi-automatic or manual.

Other more or less generic events could have been taken into account (such as material flow, energy consumption, duration of the transformation in time etc). However, for the purpose of this particular case, the *transformation*, the *process type*, and the *handling*, was chosen as the modelling objects. Figure 5.40 depicts a visualisation of a fundamental production step, i.e. a transformation;

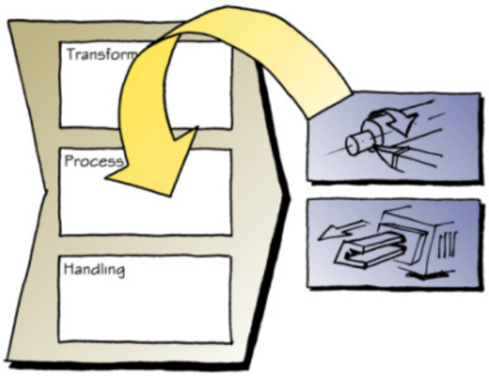


Figure 5.40: A principal step in the visual production model. The step is a model of a transformation, i.e. a meeting between a product part and the production system. The top area fits alternative puzzle pieces with visual models of the transformation. The middle is used for alternative puzzles depicting the process, in the example above whether to use extrusion or a lathe. The handling is used to visualise whether the process is automatic, semi-automatic or manual.

Figure 5.40 is an illustration of a generic production step, with transformation above, process type in the middle and handling below. For each of these three aspects, a series of alternatives can be added, as visual models. The concept is the same as for the product puzzle models. The following two figures, depicts examples of transformations and processes respectively, displayed on puzzle pieces which will fit the process step in figure 5.40;

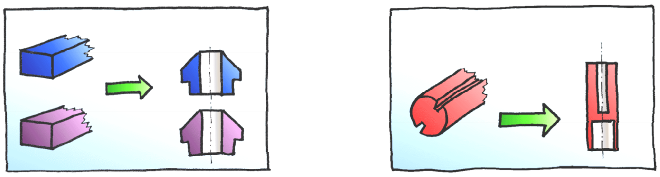


Figure 5.41: Examples of different visualisations of transformations. To the left two different metals are transformed from a rod raw material into orifices. To the right another rod in stainless steel is transformed into the basis of an armature. The profiles are easy to recognise for the users, as they are a typical part of the cross section of the valve.

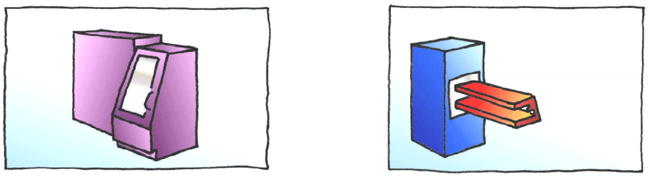


Figure 5.42: Two alternative processes: A CNC machining to the left, and an extrusion to the right.

Visualising postponement

Each transformation can be added in a series of sequential steps forming a conceptual visualisation of the production. In fact, the concept can be extended to the suppliers, thereby adding parts of the supply chain, if that is important for an evaluation of the various concepts. This was not done in Danfoss, though.

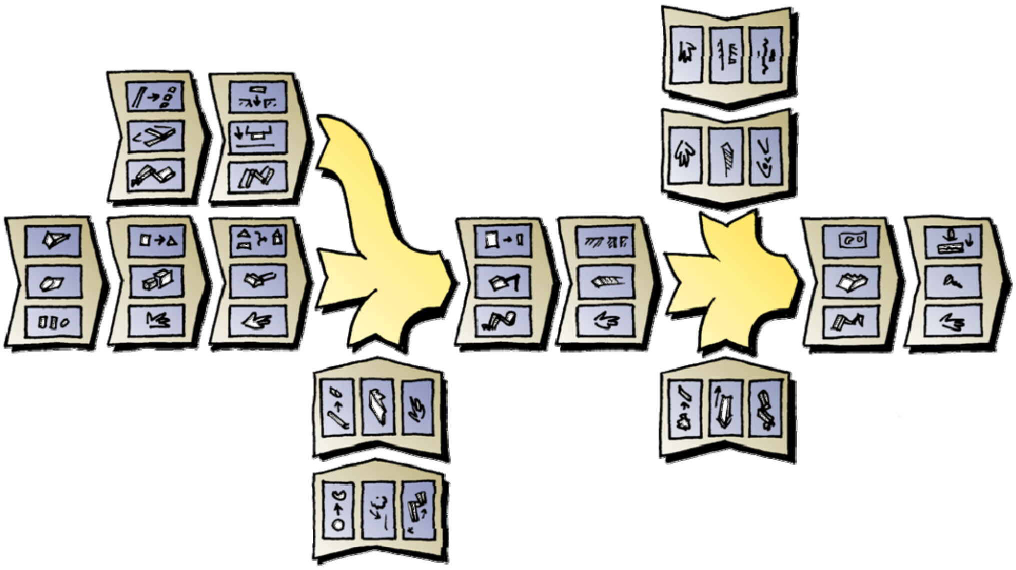


Figure 5.43: Several transformation steps can be added to form a total visual model of the production that fits the concept in the product puzzle. Thus, various part and organ encapsulations can be relatively quickly assessed on the basis of a visual model. The puzzle approach makes it possible for decision makers to change details relatively quickly and to play around with various alternative solutions.

Figure 5.43 depicts the concept of the total production puzzle. Each step corresponds to a transformation, i.e. either a *fabrication* or *assembly* step. In some cases, moving parts, orientation of parts and stocks were also of interest, and the above puzzle has similarities to the *Value Stream Mapping* techniques known from various lean production approaches [Rother & Shook, 1998]. However, focus here was to highlight the *points of variegation*, while also keeping the layout on a very conceptual level. Therefore, aspects like order cycles, volumes and other logistic information was not included. Focus was on transformations taking part through fabrication and assembly.

The figure below depicts an example of the production puzzle in action. Pictures of transformations, process types, and handling types, are added to the steps, thereby forming a production layout;

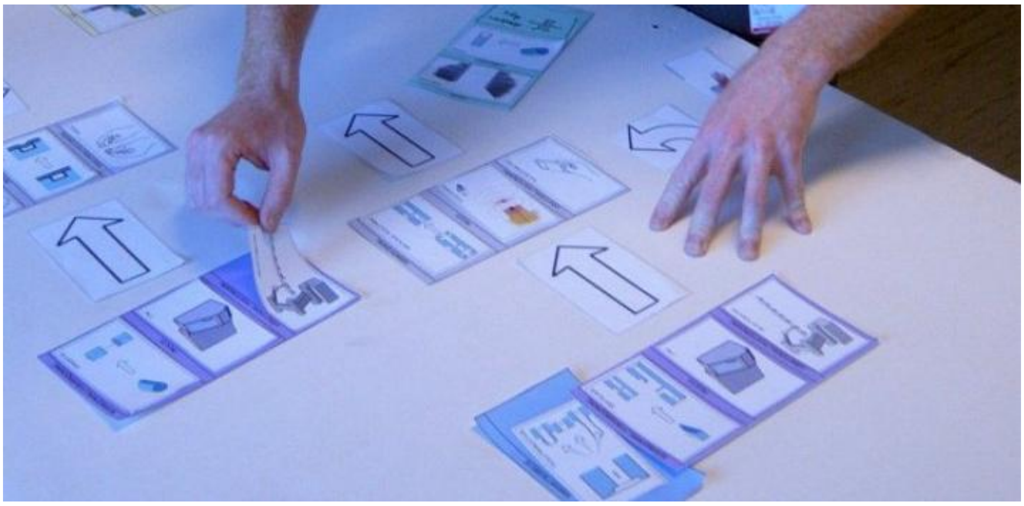


Figure 5.44: A prototype of the production puzzle in action. Various transformations are visualised in the different puzzle pieces. (Photo published earlier in the Int. J. of Mass Customization, [Mortensen et al., 2008a]).

When a production concept is built, it is possible to assess the postponement on a qualitative level. By highlighting customising and non-customising processes in alternative production scenarios, the different implications of a concept on postponement can be assessed. A particular strength of the tools is the interactive engagement of employees who may play around with the puzzle pieces. The figure below depicts the conceptual highlighting of points of variegation as the customising processes.

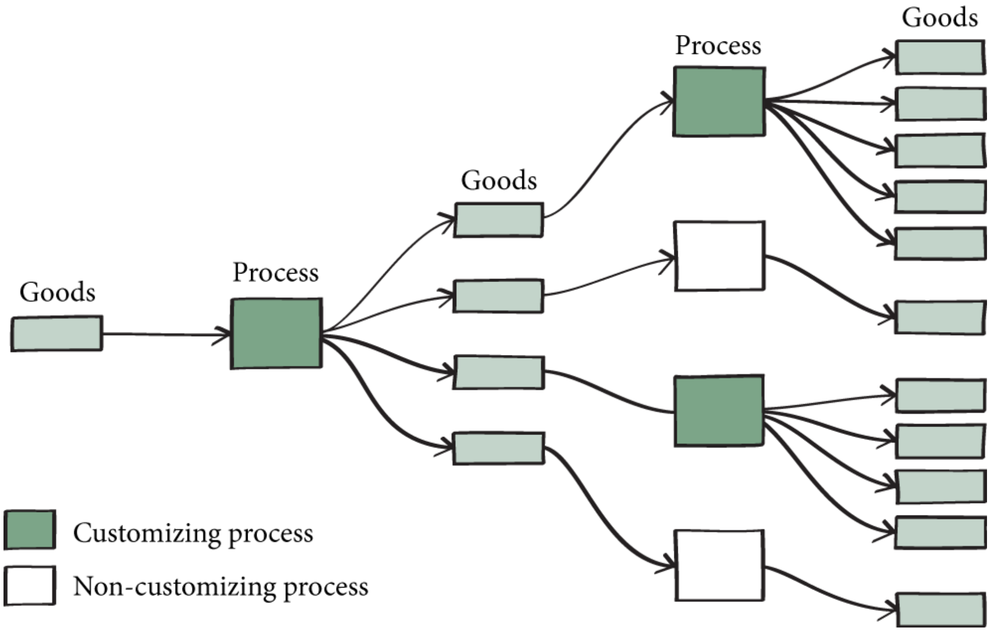


Figure 5.45: By adding steps to the production model it is possible to build a visual model of the supply chain with an emphasis on postponement and points of variegation. (Published earlier in the Int. J. of Mass Customization, [Mortensen et al., 2008a]).

Product and production puzzle as a meeting model

The two models form a visualisation of the meeting between a particular design and the production equipment. If the encapsulation of parts and organs are modelled in the product puzzle (as with the orifice example in figure 5.38) and the corresponding transformations are modelled in the production puzzle, then design engineers and other decision makers, such as production managers, get a visual model of the consequences of a platform design in the production meetings. The conceptual sequence is depicted below;

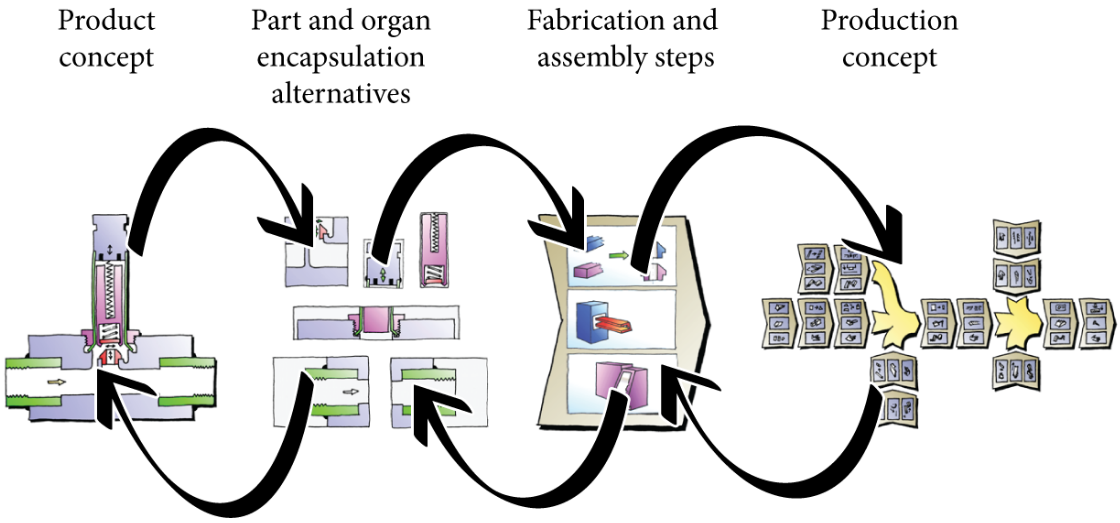


Figure 5.46: The process from choosing a product concept consisting of various organs, establishing the alternative solutions with various part and organ encapsulations, to a corresponding fabrication/assembly process that in turn results in a certain production concept with implications on postponement and points of variegation.

Figure 5.46 is an illustration of the iterative approach enabled by the two puzzles. There is no hindrance for the production scenario to be built first, and then a product scenario to be setup subsequently. However, most concepts were built in a concurrent approach moving back and forth between production setup and product design.

The puzzle as a visual object oriented model

The modelling puzzle – in particular the production puzzle - has many of the same virtues as the object oriented models like the *generic variant structure* [Jiao et al, 2003] and the *Product Family Master Plan* [Harlou, 2006] (see chapters 5.3.3/5.3.4 for more on these modelling methods).

The background, the generic part structure, resembles the Part_of structure of the PFMP, yet as a visual representation. The alternative organs somewhat resembles the variable entities in the Kind_of structure. Thus, the puzzle unites (to some degree) the virtues of object oriented modelling with a visual approach, in which design engineers can get a qualitative foundation to base their decisions on.

Decision making using the puzzle

The puzzle was used to form eleven concepts. Design and production engineers were encouraged to use the puzzle as a design tool, and engaged in sessions, in which various concepts were made. From these sessions it turns out that the two puzzles can be used as a foundation for discussions, and as a way to unite various professions into a concurrent design activity. Because a lot of the visualisation work is done beforehand, limited drawing and sketching abilities are not as much of a barrier for the engineers as it could have been.

Clearly, the approach is very qualitative in the sense that cost, lead time etc. are not explicitly modelled and have be assessed on the basis of best guesses from the employees engaging in the work.

The tool was used in Danfoss to form a concept finally chosen by management to form the core of a platform project. Thus, usefulness point of view, the tool proved useful in this case, and served as the single uniting concept tool for the start up of a product platform concept with heavy investments over a prolonged period of time (at that stage it was by far the largest single product development project in that division in Danfoss).

Thus, the models and the final visualisation made it possible for management to choose between alternative designs and – despite a very limited amount of hard facts and data - feel confident in the decision making.

Limitations of the approach

Clearly, there are two characteristics of the tool, which set some limits on applicability of the tool:

1. *The valves are quite simple products*
   The valves are quite simple making it possible to represent their working pattern in a 2D drawing. Larger installations have not been tested with this approach and the author expects the tool to have an upper limit regarding complexity of the products and the spatial layout of parts and organs.
2. *The generic structure put limits on the creativity*
   Using the generic structure as a visual template for the puzzle clearly restrains the designs, and directs the design engineers into certain concepts. However, the design task in Danfoss was quite closed in many dimensions. It was given that the armature tube (containing the armature) had to be perpendicular to the flow direction. It was also given that the two connections had to lie coaxially opposite each other in order for the valve to fit in a pipeline. These two demands actually gave the structure of the valve. Thus, the tool is useful for a closed reengineering design solution space, but maybe it is too restraining in a more radical innovation step.

How to use the puzzle for more complex products or in radical innovation projects is speculative, yet with some small alterations, it might be possible. This is not tested further in this thesis.

How to replicate the puzzle

If the puzzle and the approach are to be replicated in other businesses or by other researchers in order to make full scale test of the effects of the approach, the following sequence is noteworthy. It is compiled from the experience in Danfoss, and should probably be changed slightly to suit another business or context, yet the fundamentals are the same.

1. *Visual means for communication*
   Find out which visual means the design engineers use to communicate with each other and with their colleagues in other departments. This is typically a drawing of some kind, and many companies have a specific cross section or flow diagram (general arrangement drawing or the like) that is often used. Thereby this particular set of drawing become a pictogram in people's minds and is useful for replication in a visual model.

2. *Generic organ encapsulation & organ model*
   Establish an understanding of the organs in the product and create a model of the organs. The organ model is proposed in this chapter. It is a model of various organs and their spatial position relative to each other. The task of creating this model is essentially to perform a grouping of wirk elements into organs, and deciding which organs to decouple from each other (not deciding HOW the decoupling takes place!)
3. *Organ variation*
   Establish an understanding of how these organs vary, i.e. what alternative design principles each organ can be realised with. The alternative design principles are established by means of normal brainstorming with key personnel from the company attending. Whoever is in charge of the visualisation and for making the puzzles will have to gather the input from such brainstorm sessions and transform it into the puzzle pieces. This takes some visualisation skills as well as a minimum of product understanding or at least help from the design and production engineers.
4. *Part encapsulation*
   Establish an understanding of how these organs are distributed into parts and how these parts are related to each other. This is essentially the final decision on the parts encapsulation

A comment on organs and functions

From a strict function/means viewpoint, there is a problem with bullet 2 in the above list. Some might argue that variable organs serving the same function are not variations of *an organ* but alternative means to a function. This is why the term generic organ is used. The term is adopted from the generic organ diagram proposed by Harlou [2006].

5.5.6 Visual platform modelling – after the concept phase

The platform at Danfoss eventually developed into a ‘classic’ modular product platform, with a high degree of decoupling in the part domain, and thereby with physical interfaces between parts. Consequently, the constituents of the platform were called *building blocks* (which are essentially modules), and the focus of the production was to maintain a high degree of flexibility in the assembly lines.

The PFMP as a starting point

During the platform development project, the Product Family Master Plan (PFMP) was used as an important modelling tool. The starting point of the project was the PFMP^2 tool proposed by Kvist [2009].

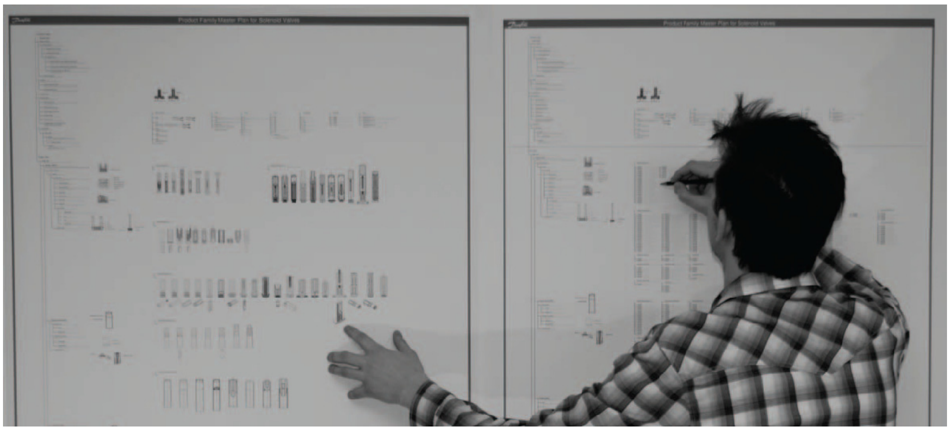


Figure 5.47: The initial analysis of the product range lead to the production of large posters, in which the original product range was visualised using the PFMP^2 *formalism. [Photo from Danfoss].*

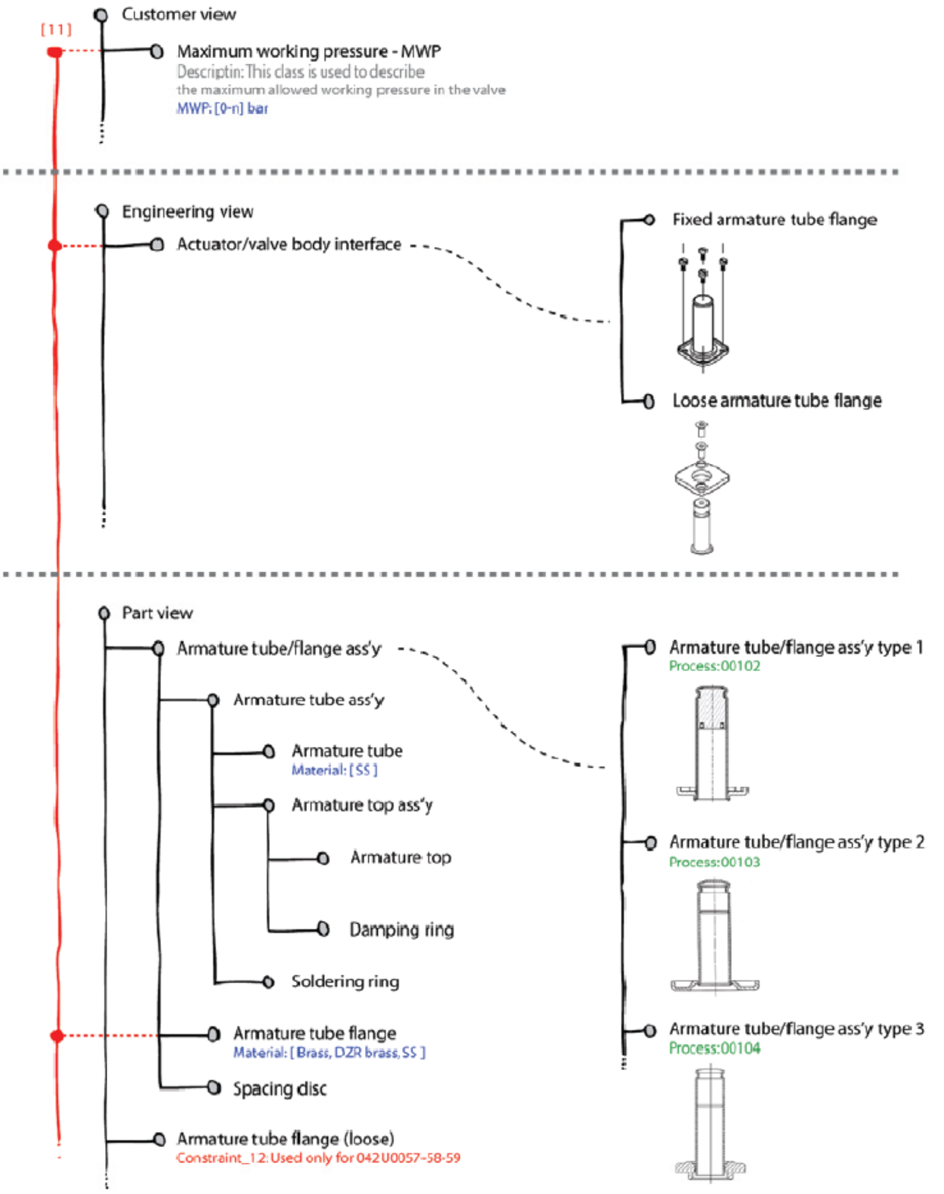


Figure 5.48: An example of a detail from a solenoid valve PFMP. [Figure from Kvist, 2009].

Figure 5.49 provides an example of a PFMP visualising a solenoid valve product family. This was the starting point of the platform project, and the PFMP could have been used as the primary modelling tool for the new platform. However, the PFMP formalism was changed substantially in order to accommodate the needs of the design team in the later stages of the platform project. One of the main ideas of the model was to serve as a design tool within the design team, and as a presentation tool towards external stakeholders, i.e. a variety of different employees with various educational and departmental background by hanging on the wall in the team surroundings in an updated version (with the newest updates added by hand). At the same time the tool was supposed to serve as a presentation of the platform before different employees within the organisation.

The PFMP turned out to be hard to understand for a number of different reasons;

- The PFMP does not give a sufficiently *visual* overview of the product family – the Part_of structure is the closest, yet it is rather schematic and does not give the reader an idea of the product. The idea was for non-engineers to be able to see and understand the platform in the model, and the Part_of notation turned out to be too complicated to understand at a first glance. The first glance is important, because it proved
- The idea of organs tuned out to be hard to comprehend for a variety of different employees. They thought it to be rather theoretical. Due to the fact that the model was mainly a design tool for the platform team (and secondarily a presentation tool towards the organisation) the customer view was taken out. The engineering view and the part view were eventually melted into one view.
- There was a need to get a quick overview of the platform constituents while also being able to access a lot of information on detailed parts. Therefore the model had to serve both purposes in order to be useful in that particular context.

Visually representing the product platform

The visual representation of the model was done by means of a generic structure formed as an exploded view of a typical design – much like the fundamental concept of the product puzzle. The generic structure is split into three fundamental parts of the product;

1. The actuator building blocks
2. The valve building blocks
3. The actuator – valve body connection

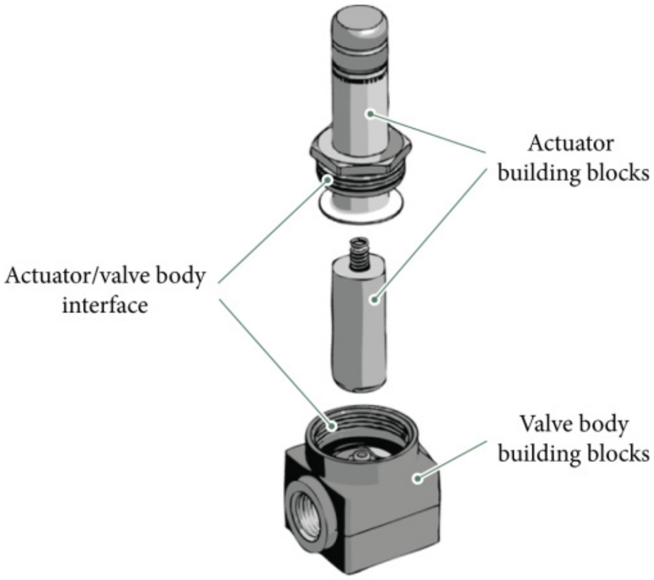


Figure 5.50: The division of the product into three groups of building blocks. This particular valve is a direct operated valve, i.e. a valve without diaphragm. The servo operated valves have a diaphragm assembly which considered being part of the valve building blocks.

On the basis of the grouping of building blocks in figure 5.50, three generic structures were visualised according to these groups. The following figure is an example of the servo operated building blocks;

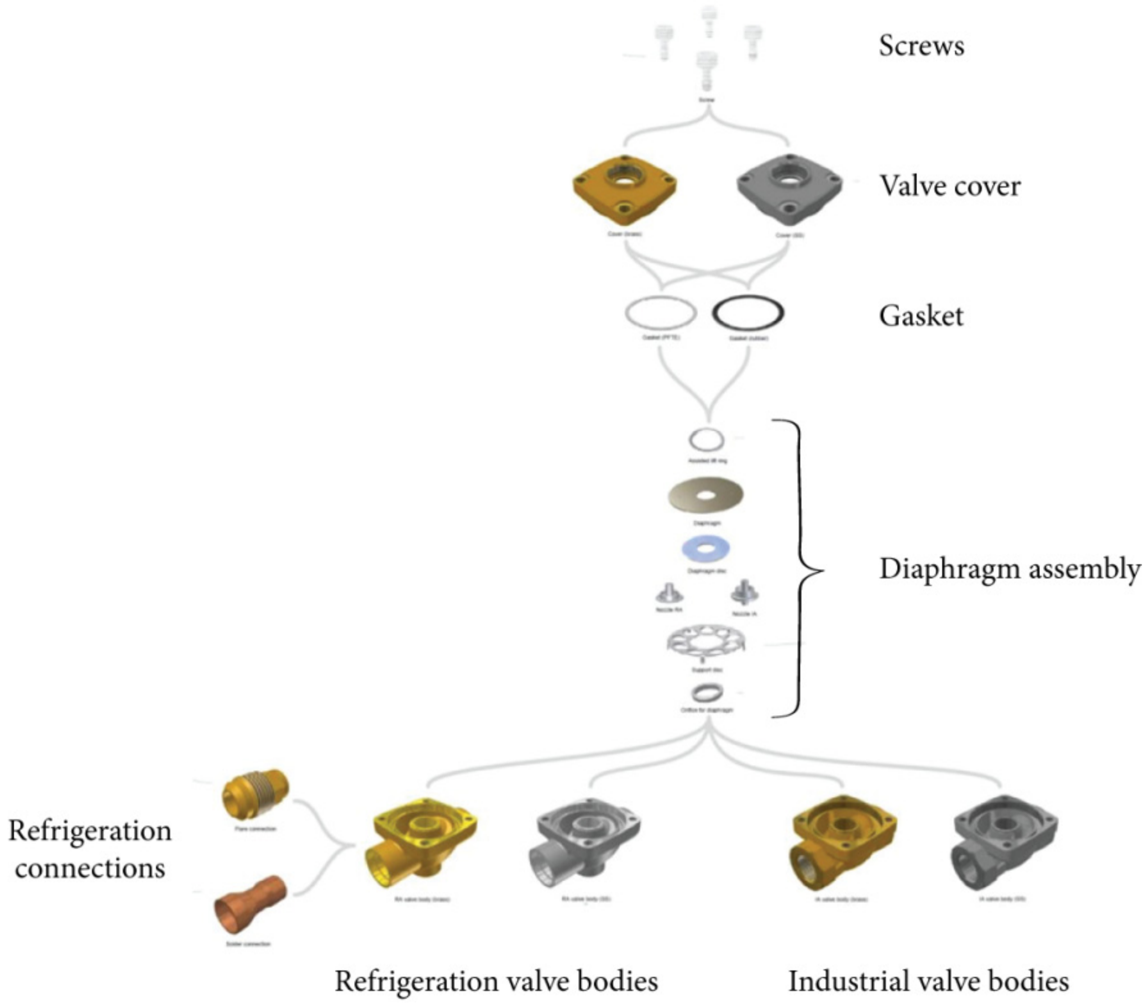


Figure 5.51: A detail from the product platform model. The figure shows an exploded view of the building blocks for servo operated valves. The pictures are taken from the CAD system. Some of the parts are far in the design phase, while others are just mock-ups.

The above illustration in figure 5.51 had the primary objective to present an overview of the various constituents in the platform, i.e. an equivalent to the generic Part_of structure of the Product Family Master plan. Rather than depicting all the variants in a Kind_of structure, it turned out to be feasible to depict them in matrices, in order to be able to provide detailed information on the different parts. The following picture is an illustration of the whole platform model, showing the overview of *building blocks* (figure 5.52);

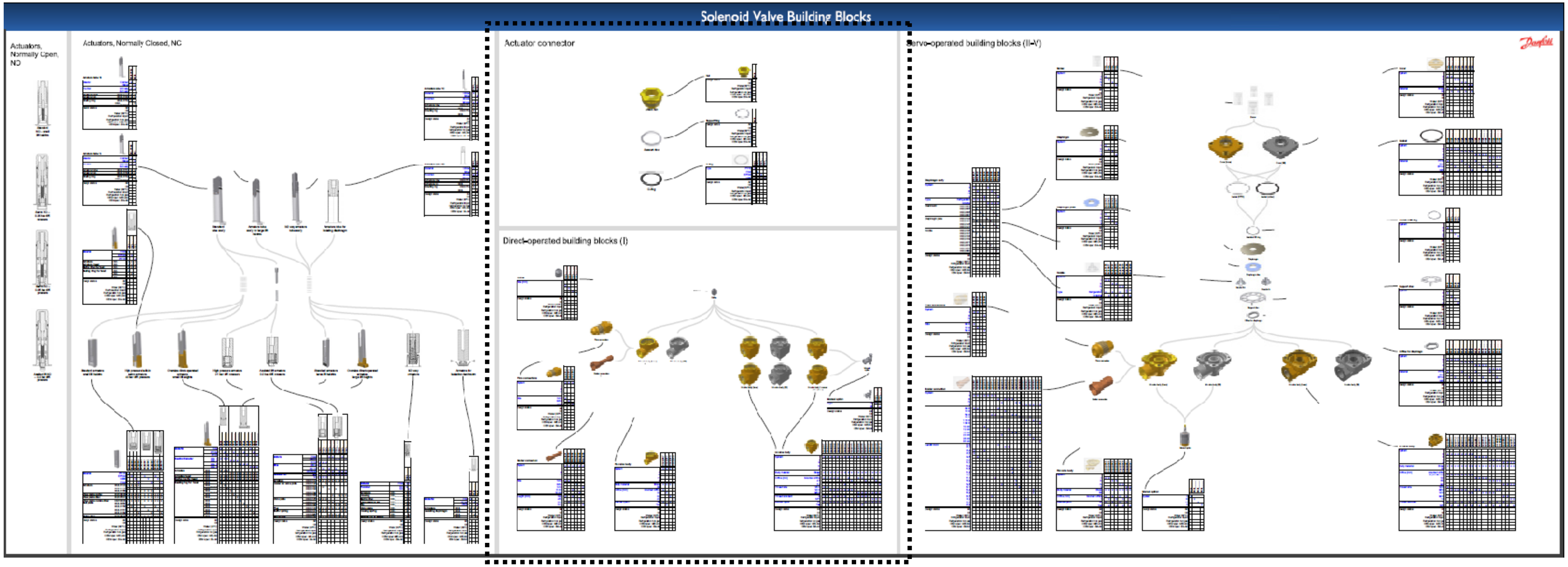

Solenoid Valve Building Blocks
Actuators, Normally Open, NO
Actuators, Normally Closed, NC
Actuator connector
Direct-operated building blocks (I)
Servo-operated building blocks (II-V)

Figure 5.52: The poster is turned 90 degrees counter clockwise. It gives an overview of building blocks in the Danfoss platform. The poster gives a rough overview of the structure of the products within the product platform. In the tables, details on various parts are listed. Thus, from afar, the poster gives an overview, and when the spectator moves in closer, more detail is available. The dashed area is enlarged in the following figure (5.53). The original poster is some 4,5 metres long and 1,5 metres tall.

Detail and overview in the same model

The poster in figure 5.52 is originally some 4,5 metres long and 1,5 metres tall. It hangs in the team member's project meeting room, to illustrate the progress of the platform development efforts. From a distance of a few metres, the viewer can get an overview of the various building block principles through the use of illustrations. When moving closer, the viewer may see various detailed information in tables, linking the information on the poster to information in the CAD and ERP systems. Once the parts get a part ID number, they can be tracked to the systems using the ID number.

Figure 5.53 is an enlarged extract from figure 5.52. This detail shows the direct operated building blocks;

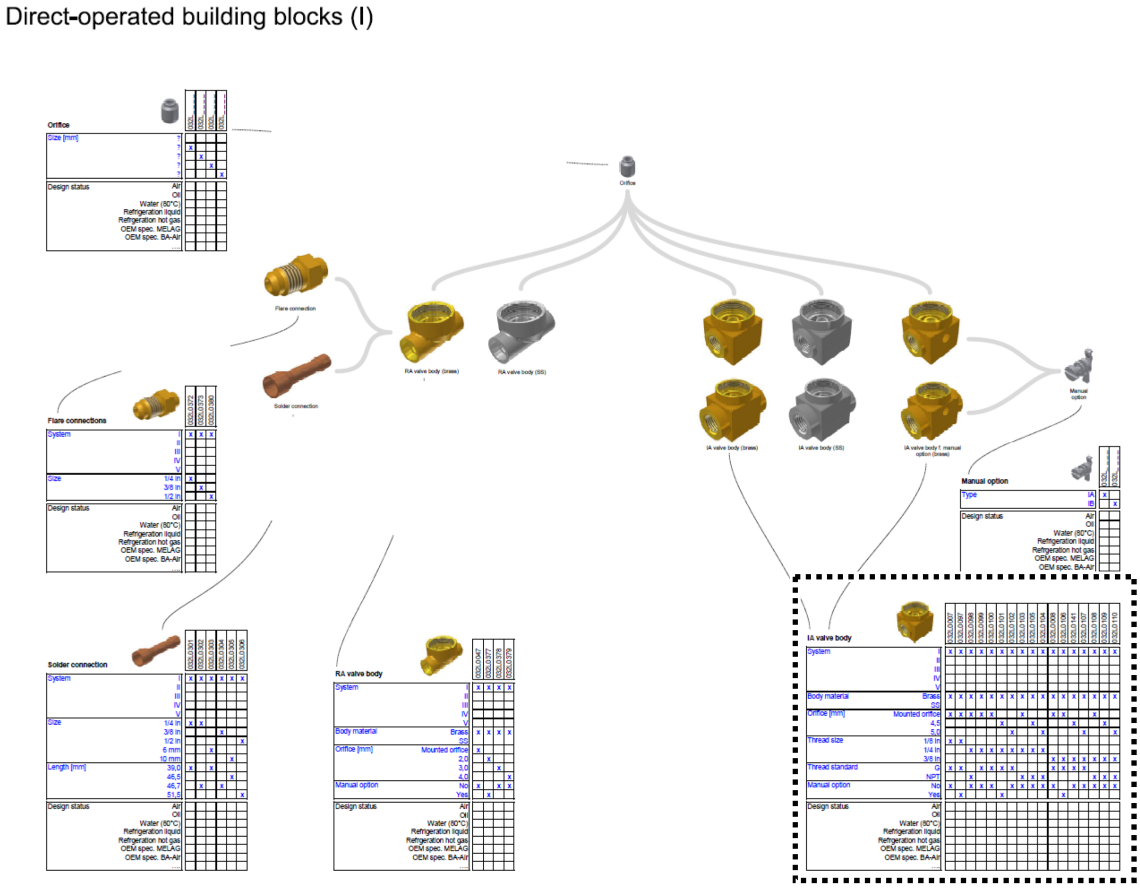
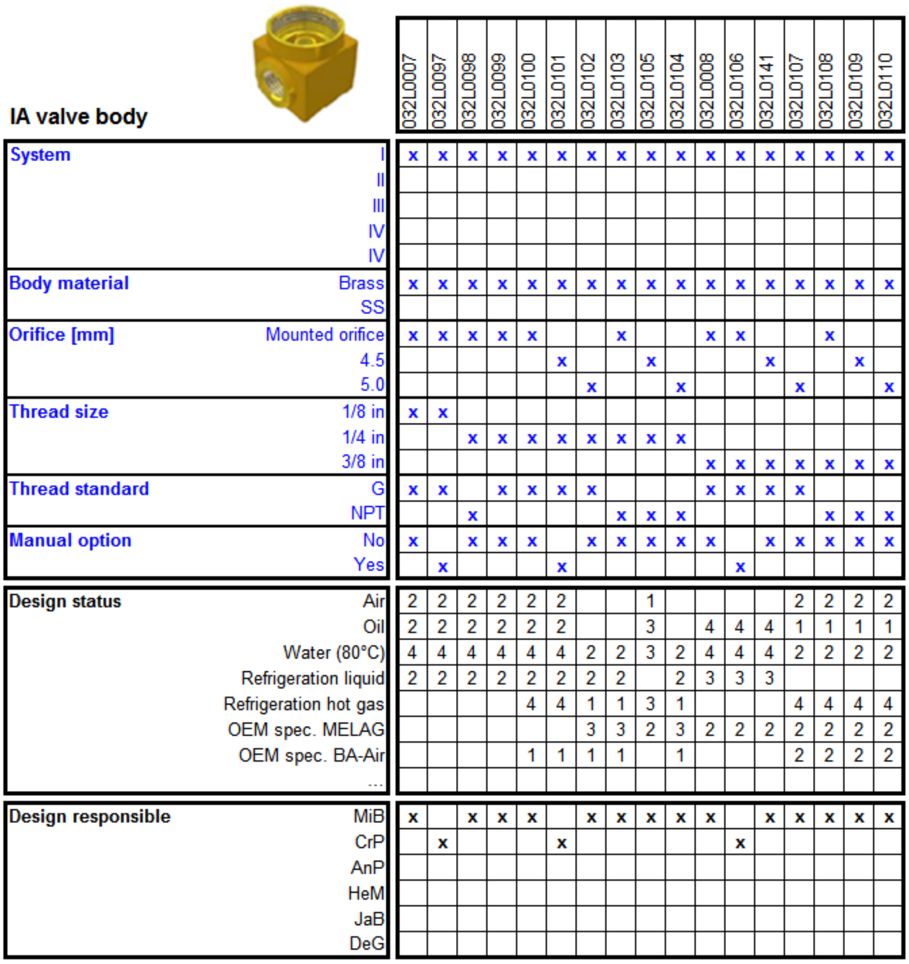


Figure 5.53: Illustrations and combination tables giving the overview and the details of the building block design and combinations. The orifice is in the top middle of the figure. Orifice variants are shown in the table in the top left. The dashed area is enlarged in the following figure (5.54).

The detail in figure 5.53 depicts how various direct operated valves can be designed on the basis of a series of parts. To the left, the refrigeration components are shown, and to the right the industrial components are shown. The orifices are in common between the two value streams (remember that the refrigeration and industrial businesses are called value streams – see figure 5.26).



IA valve body		032L0007	032L0097	032L0098	032L0099	032L0100	032L0101	032L0102	032L0103	032L0105	032L0104	032L0008	032L0106	032L0141	032L0107	032L0108	032L0109	032L0110
System	I	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	II																	
	III																	
	IV																	
	IV																	
Body material	Brass	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	SS																	
Orifice [mm]	Mounted orifice	x	x	x	x	x			x			x	x			x		
	4.5						x			x				x			x	
	5.0							x			x				x			x
Thread size	1/8 in	x	x															
	1/4 in			x	x	x	x	x	x	x	x							
	3/8 in											x	x	x	x	x	x	x
Thread standard	G	x	x		x	x	x	x				x	x	x	x			
	NPT			x					x	x	x					x	x	x
Manual option	No	x		x	x	x		x	x	x	x	x		x	x	x	x	x
	Yes		x				x						x					
Design status	Air	2	2	2	2	2	2			1					2	2	2	2
	Oil	2	2	2	2	2	2			3		4	4	4	1	1	1	1
	Water (80°C)	4	4	4	4	4	4	2	2	3	2	4	4	4	2	2	2	2
	Refrigeration liquid	2	2	2	2	2	2	2	2		2	3	3	3				
	Refrigeration hot gas					4	4	1	1	3	1				4	4	4	4
	OEM spec. MELAG							3	3	2	3	2	2	2	2	2	2	2
	OEM spec. BA-Air					1	1	1	1		1				2	2	2	2
	...																	
Design responsible	MiB	x		x	x	x		x	x	x	x	x		x	x	x	x	x
	CrP		x				x						x					
	AnP																	
	HeM																	
	JaB																	
	DeG																	

Figure 5.54: An example of a table mapping valve body ID numbers with attributes and the design status. The numbers in the top row are part ID numbers for valve bodies.

Attributes

A table showing the fundamental differences in attributes for a valve body. This corresponds to the Kind_of structure of the PFMP. The table give information about variants and their differences:

- *System*
  Gives information about the size range. The size of valve bodies range from I to V.
- *Body material*
  The valve bodies are either made from brass or stainless steel. This particular size only comes in brass.
- *Orifice*
  The orifice is either machined directly in the valve body or mounted as a separate component, i.e. different encapsulation principles based on volume.

- *Thread size*
  The connection threads are important for the customers and come in various standard sizes. The sizes are given in inches.
- *Thread standard*
  The thread types are also different depending on the design and angle of the threads. There are two available standards for this particular valve body, thus, a 1/8 inch connection are found in two standards, the G$^3/_8$ inches and the NPT $^3/_8$ inches.
- *Manual option*
  Some valves come with a manual operation making it possible to open and close the valve in case of a power loss of an error in the coil.

The point of the table is that it forms a relatively simple way to visually depict possible configurations of components. Combined with the illustrations of the overall structural relations, the poster forms an overview of possible designs within the platform.

The design status

The design status is an important part of the model. In this list, various approvals are listed. Each line represents the most important aspects of the failure and endurance testing program that all the designs of the platform has to go through. Yet still unresolved, it is the intention of the project to change the working procedures for the approval of solenoid valves, making it possible to approve *building blocks* and *assembly processes* rather than final assemblies. This makes it possible to approve the platform as a design template and then have all configurations approved automatically. The *design status* field gives an overview of the status of this approval process. Each line (Air, Oil, Water (80°C), etc.) corresponds to a series of tests with various media and opening/closing cycles. This particular valve body has no approvals so far. The tests would otherwise have been shown in the matrix as crosses.

The design responsible

In the bottom part of the table, a list of designers and responsibilities is given. This makes it possible to track down each design and who to go to for information. The list also has another function, that is, in cases of negotiation of various design changes, and interface changes, it is possible to make the changes propagate to the design engineers.

The Bill of material

The bill of material is a topic not accounted for in the model. There were two bills of material to take care of. One was a *design bill of material* reflecting the assembly structure in the CAD system. Another was the production bill of material resembling the final assembly sequence in the production and thereby the structure in the ERP system. Ideally these two are the same, yet the assembly structures in CAD are needed before than final the assembly sequence in the production is known (at least that was the case in this project). Despite the use of the production puzzle, the detailed process steps remained unaccounted for throughout a prolonged period of time. The problem was then, that any updates to the bill of materials had to be done manually – both in the ERP system and in the CAD assemblies. Each product ID had its own unique bill of material, and therefore updating several bills of material in a batch process was not possible. A generic or variant bill of material approach would probably have solved this issue. Nevertheless, such concepts were neither used in the project nor within the limits of this thesis to account for.

The interfaces

Some of the interfaces were regarded as design objects in the platform just like the components. They had their own CAD models and drawings. The interfaces are also mapped in their own visual model – an interface model. A simplified representation of an interface model is shown in figure 5.55. The model depicts the interface between the actuator and the valve bodies and covers. The smaller valves are directly attached to the actuator, while the larger valves have a cover on the valve body, and the actuator is then mounted on the cover. The small valve bodies and the covers for larger valves share the interface to the actuator.

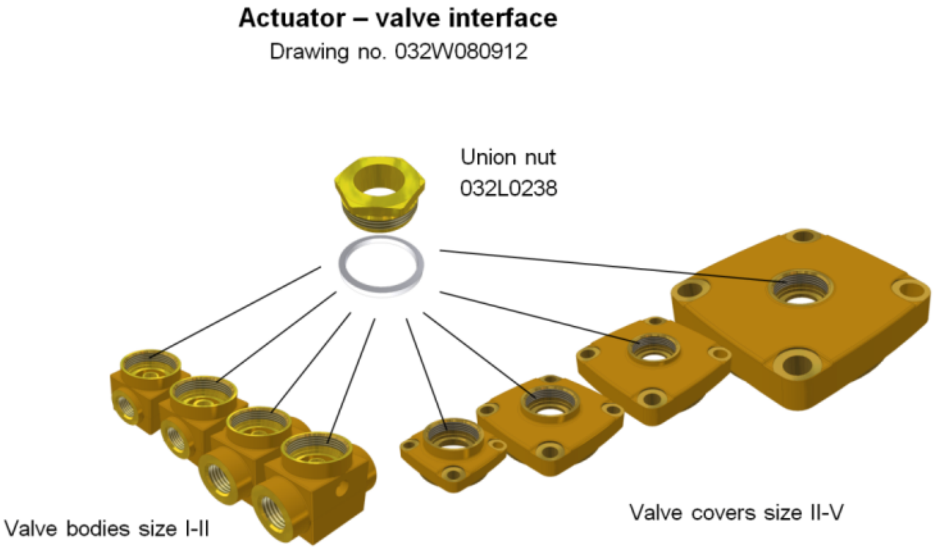


Figure 4.55: A visualisation of one of the most important interfaces in the product platform. The interface is controlled by a feature in the CAD system, which is loaded on to every single instance of covers and valve bodies. The interface has its own technical drawing for design. Likewise, an assembly instruction in the assembly step gives information about the torque and other types of mounting instructions.

In Danfoss, the design engineers chose five important interfaces that were documented in separate technical drawings and separate CAD models. The choice of interfaces was based on an estimation of the costs of change in the production. The interfaces were highlighted an assigned to the project manager, and was later on to be assigned to an interface manager. Thus, these interfaces could not be changed without the authority of an interface responsible, which was one reason to give them their own models and drawings.

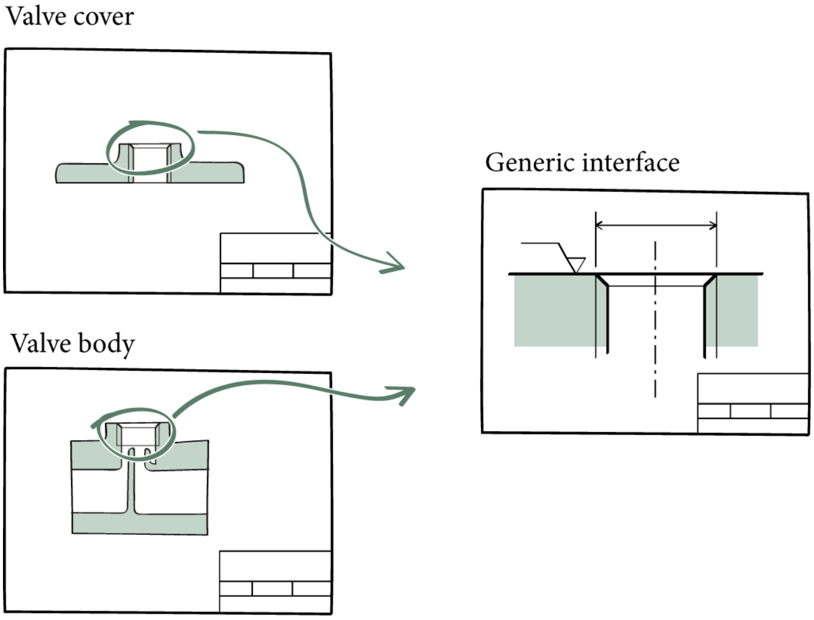


Figure 5.56: A very simple concept of how to document generic attributes shared by several components. A certain part of the instance drawings refer to a generic drawing, in this case of the interface between valve and actuator.

Figure 5.56 depicts a rather low tech solution to the problem of sharing attributes in several parts. However, the links are not only secured manually. The CAD system used to generate the drawings is *Inventor*, and the interfaces are modelled as surface features in a generic part file, and then inherited to the single instance models by use of a so-called family table. The family table makes it possible to publish geometry from a single source to multiple instances, and in the multiple instances, to choose between varieties of alternative features in the family table.

A drawback of keeping two drawings is of course that more than two drawing is needed to document a single and relatively simple part. However, this was a deliberate decision, because the interfaces were standardised, and thus not to be changed on a regular basis. Therefore all the information was already at hand in the various design and production steps, and job of retrieving the information from the interface drawing became less important. The solution with two drawings is a temporary solution, and in the future each instance will be on a drawing, with a clear demarcation of the standardised area. The feature based design makes it possible to generate drawings based on the instance part and the generic feature.

Interfacing to the computer systems

Using part ID numbers and drawing numbers as an interface to the ERP and CAD systems respectively, made it possible for design engineers and other stakeholders to gain a visual overview from the posters, and through the ID code system to access the detailed information in the CAD and ERP systems. The information on testing status and design responsible was only maintained in the platform model. However, the whole picture was only possible to get by a combination of the CAD system, the ERP system and the platform model, that is, the poster hanging on the wall. The poster was also available on the intranet in a PDF version for external access.

From a very fundamental viewpoint, the posters (the building block and interface models) served as an overview, with some degree of details in the tables, while the rest of the information (such as bill of materials and details in CAD drawings) was available in the computer systems.

> The platform model was thereby a combination of the posters and the computer models.

5.5.7 Establishing a mindset in Danfoss

The project in Danfoss is a full scale product platform project, in the sense that a whole product range has been redesigned. The models described in the former chapter, along with drawings and partially ready-made CAD models, serve as design tools.

The design engineers had a year long experience and practice of optimising *single products* and the idea of a product platform was not always clear to the employees. Nevertheless, many employees had made their own standardisation efforts, and were well aware of the cost of complexity. Thus, the challenge was not only to sell the idea of platforms, because many had already bought in to the idea of reuse of designs. The question was also about how to provide hands on tools and methods as to how they employees could change the state of the company.

As discussed in chapter 5.4.3, a mindset was provided to the employees through various means of education, in order for them to better understand the models and the context in which the models were to be used.

There were two main education activities in Danfoss;

- *Platform Thinking Seminar*
  A series of seminars held in a class room as regular teaching with industrial cases and a light version of the theory behind platforms presented to the audience. The seminars were part of the internal course program in Danfoss.
- *Platform Design Game*
  A one-day gaming session enabling the employees to experience the effects of a product platform approach in a short period of time. This session had two purposes: To be part of the mindset education and also to serve as a model or simulation of the platform design process.

The Platform Design Game, apart from serving the mindset purpose, also served as a kind of activity model, and it is therefore presented in its own chapter (chapter 5.5.8). In the following section, the *Platform Thinking Seminars* are described.

Platform Thinking Seminars

The seminars were a series of lectures introducing different aspects of product platforms. The contents of the seminars were as follows:

- *Introduction to product platform development*
  Introduction to the conceptual framework used in relation to multi-product development including product development based on platforms, the concept of modularity, reuse and encapsulation, modularisation, mass customization, and postponement. The Module Drivers [Ericsson & Erixon, 1999] were used as examples of various incentives to strive for product platforms.

- *Introduction to the Product Family Master Plan tool*
  Introduction to the structural principles used in the PFMP tool, including object oriented modelling, customer, engineering and part view, part-of & kind-of structures, class definition, attributes, constraints, causal links, etc. The PFMP was used as the starting point to analyse the existing product range [Kvist, 2009]. Thereafter an introduction to the building block poster and the modelling formalism in that poster, with the combination matrices was given.
- *Lessons learned*
  Case stories. Lessons learned and experiences from other companies and industries working with product platforms. External speakers were brought in, such as a consultant with experience from various companies and industries, and a project manager from another division in Danfoss, in which a product platform based product development, had been implemented in a similar approach and with similar products.

There were a total of 93 persons participating in three consecutive seminars held over a period of 18 months.

5.5.8 Modelling the design activities

The Design Game

In order to simulate the activities in a product platform development project, a game was developed (jointly by the author and Kvist [2009]).

There were several reasons to design a game rather than a series of lectures:

- The game could satisfy both a *research* and a *teaching* purpose at the same time. This was done by providing a virtual design environment in which:
  …the researchers could *stimulate certain effects* that would otherwise take months or even years to test in a real industrial case
  …different *key employees of the company could experience* a series of different challenges and effects happening while manipulating and developing a product platform.
- It was the intention to make a setup that would be inspiring and interesting for the employees to participate in, thereby creating a positive feeling about the change process to come (there were mixed feelings about the project in the organisation)

The main drivers, which were discussed in the introduction to the thesis (Part 1), were also to become major drivers in the game setup. Before the game, all the participants had taken part in the Platform Thinking Seminars described in the former chapter.

The main drivers played the following role in the game:

- *Generic & Variable* split in the product portfolio i.e. how a split in the generic and variable proportions of the product portfolio can be done and what the effects are. The idea was that the game eventually had to lead to a better understanding of the phenomenon of product platforms and the notion of commonality and variety among the participants.
- *Preparation & Execution* as two different development activities. It was important to simulate and express how a company may plan the product development efforts differently and make a split between preparation and execution of product development with a platform approach.

- *Standard & Special* products: Gaining an understanding of how the order-to-delivery process could change with different product platform setups.
- *Long term product planning*, i.e. how a product platform leads to new planning challenges when dealing with spatial and generational variety within and across different product generations.

Participants and locations

At first, the game was set up at the Technical University of Denmark. It was performed as a part of the curriculum of three different post graduate courses during two semesters. This gave the researchers the chance to test and adjust the game setup using a total of some 90 students.

Thereafter, two one-day game workshops were held at Danfoss with a total of 61 participants. A very important point to make here was that the participants came from a variety of different positions within the company, and not just from the engineering departments. In general there was a participant mix including people from;

- Product development (long term development)
- Engineering design (short term development, standard products and minor customisation projects)
- Marketing and customer support
- Product planning
- Operations management
- Technical service department

The game was held as a one day session including lunch. A conference facility was chosen in order to get the full attention of the participants and avoid people entering and leaving the session due to interrupting phone calls and emails.

More or less all white collar workers were given the change to enrol, and the researchers then set up teams of participants based on their background in order to obtain a mix of all of the above categories of positions.

The chosen site of the session had a conference room large enough to fit at least 50 persons, and an adjacent room with dining facilities. The idea was to provide a good working environment with fruit, cake, coffee, plenty of lunch etc. in order for the employees to have a positive experience during the day. This may have influenced their relatively positive feedback of the day, yet some of them did not hesitate to give constructive feedback and critics on possible improvements.

Game setup

The overall idea of the game is to have competing teams in a virtual business environment. Each team has to play the role of an *automotive company* competing with the other teams in a changing business environment with varying customer requirements. Thereby the different teams are forced to accommodate changing customer requirements while eventually building up a common core of experience. This serves as a basic driver for simulating and stimulating a situation in which commonality and variety are important characteristics of a product range.

In order for the teams to actually be able to perform development and design activities, a system of LEGO bricks was chosen. LEGOs are polymer bricks in different shapes and colours used for toy construction. The use of LEGOs enables the teams to build toy cars based on specifications, which are given to the teams.

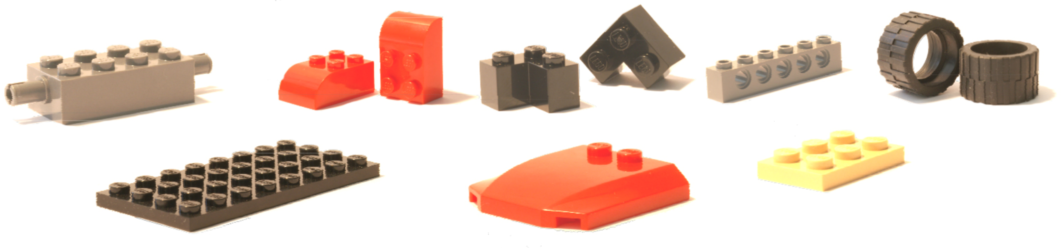


Figure 5.57: A selection of LEGO bricks. They fit together with standardised interfaces and give the opportunity to build toy cars.

The participants are divided into teams of four to six persons. Each team forms an automotive company that is supposed to build and market toy cars in the virtual game world. There were a total of some five to six teams at each game session during the sessions in Danfoss.

The teams are given a series of *marketing memos* as a starting point. The marketing memos serve as specifications for how to build the cars and also give an impression of the importance of different parts of the design of the cars, rated by customers.

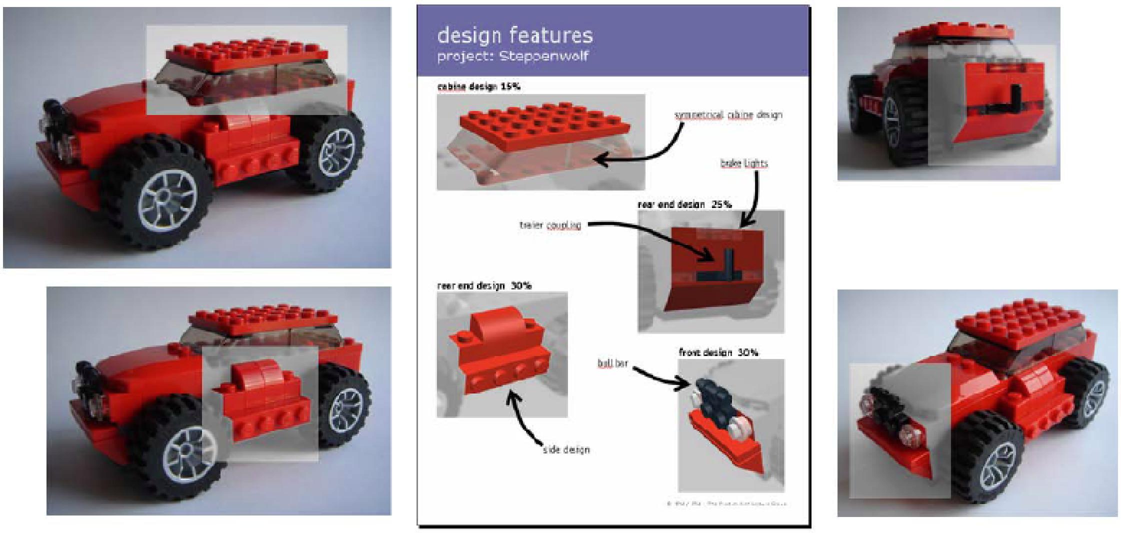


Figure 5.58: A marketing memo is an A4 sheet describing different demands for the design of the toy cars, and the importance (in percent) of that particular design. Each detail adds up to 100% and if the participants fail to meet the details in a design correct, the turnover on that car is reduced accordingly.

Game sequence

The game is first introduced to the participants during a presentation of the rules and the idea behind the *game world*. Then, the game starts and the sequence is made up by a series of consecutive play rounds or *business seasons* in which the teams have to choose which customer segments to go for, and then design car models accordingly, put them into production, and bring them to the marketplace while at the same time making sure that there is a fit between their *designs* and the *customer preferences*.

The first round is introduced with a description of the overall business environment of the fictive world, customer preferences and habits. Thereafter, the first marketing memos are handed out and the teams are given a period of time to come up with a strategy for their company. The teams have to decide which of the possible customer segments to address, how they will plan their work, e.g. launching one car at a time or work in parallel on several designs etc. Then the game starts, with each round lasting some 30 minutes.

After 30 minutes of buying LEGO bricks, designing cars and maybe even (for the fast movers) launching cars to the marketplace, the round stops and the cash flow of the teams is calculated and presented to all the teams in order for the teams to compare to each other and to hold a competitive environment.

After a short status, new business opportunities, customer segments, preferences and a forecast for the future rounds is given to the teams. New marketing memos are handed out and serve as the specifications of the customer preferences in the next round. Then the next round starts with the teams trying to adjust their strategy to new opportunities and threats, while still continuing designing their existing product portfolio. After 30 minutes the round stops again followed by a new status and so forth.

Figure 5.59: Two typical cars. Each car is representing a customer segment with different preferences.

Game contents

The fundamentals of the rules are that the each team or automotive company earns money as a function of their ability to perform in a series of different dimensions. The turnover and costs of each company is calculated on the basis of the LEGOs they buy, the time they spend, the car models on the market, and how close they match customer preferences. The most important aspects are the following:

- *Meeting customer requirements*
  The ability to design LEGO cars that have a close match with the customer requirements in the marketing memos is an important driver for the turnover. The marketing memos hold a series of details with an importance rating in percent. Failing to fully meet a requirement with an importance of 10% might give a reduction of some 3 – 5 % on the turnover based on a review of the models that the companies put on the market. If a team totally fails to meet the requirements, all 10% will be deducted. The customer reactions are determined by the game leaders, who play the role as both customers and suppliers of LEGOs. (In the sessions at the university and at Danfoss, the researchers and two colleagues had that role),
- *Choosing the right customer segments*
  The earnings on a specific car model are calculated on the basis of the number of competitors on that particular customer segment. Choosing a unique setup of models with limited competition is a key player in order to get a good turnover.
- *Responsiveness to market changes*
  Each round gives new inputs and opportunities while also quickly changing the business environment. Being agile and flexible is important.
- *Timing the product launch*
  Timing the product launch has a significant impact on the company's turnover. The turnover is a function of the time during the round, in which a certain car is actually in the market. If the team spend half of the time during a round to design and build the car, that team will only get the car on the market in the other half of the time, thereby loosing half of the possible turnover of the car.
- *Reusing components and design solutions*
  When calculating the costs of the company, there is a commonality advantage built into the calculation. If the teams can utilise the same LEGO brick in several car designs, they will get a discount in the brick costs.
- *Ability to manage supplies*
  Ordering the right bricks at the right time is also important for the teams. Each time an order is placed at the suppliers, there is a payable fee. This encourages the teams to plan their purchasing efforts carefully.

Figure 5.60: Scene from a game session at Danfoss. Different toy cars are put in 'the marketplace' at a table. Different teams have brought different product variants to the market. In the background the teams are working hard on their next move.

Variety and commonality – encapsulation and reuse

The effects of the different stimuli in the game, was a simulation of different important business processes that are all affected by changes to a product platform, and also important drivers for pursuing a product platform strategy. The game setup forced the teams to try to optimise for reuse of LEGO bricks, while at the same time being promoted to address a number of different customer segments with a number of different product variants. Thus, they faced the fundamental contradiction of achieving *variety* and *commonality* at the same time. The teams had no idea before the game started, how the designs would evolve and was not in any way encouraged to try any holistic approaches such as that of a product platform approach. Rather, the limited time frame in each round lured the teams into a rather strict single product focus even though the game rules would award reuse of LEGOs and promoted a multi product approach. There was no time, and the teams had no tools to share their knowledge.

Some teams all worked on the same design while others split up and formed teams within the teams. Clearly, the teams with parallel developments were faster, but they later paid the price because they did not fully utilise the hidden opportunities of reuse benefits that were built in to the game.

Revealing the generic attributes of the products

After having played several rounds, each team starts to form their own response to the different customer preferences, i.e. a product portfolio of toy cars. After six rounds the game is paused and a discussion is held with the participants. During the last two rounds before this break, the customer preferences are suddenly changed dramatically. Promising variants turn out to have declining sales volume and new and different customer segments emerge. This poses possibilities to the flexible teams and threats to the inflexible teams. Several things determine the flexibility and agility of the teams, one of which is the set of their product range. Only few teams had a change to actually start a retrospective analysis of their past and current designs, looking for patterns that could reveal an optimisation of the products and possible design encapsulations. None of the teams in any of the workshops had any tools or methods with which to utilise the potential.

Discussing a platform potential

The performance of different teams was discussed and the way they did their business and built up their products. After this, a suggestion for a product platform was presented. It is in fact possible to make a large proportion of the variants on the basis of the same core of LEGO bricks. When the teams realised this, it gave a very efficient way to discuss different platform layouts and to bring forward the idea of a more object oriented approach, in which the design teams could form a generic structure of their models, and think about variable entities in their design portfolio. This also led to an understanding of *commonality* and *variety*, enabled by the use of *encapsulation* and *reuse*.

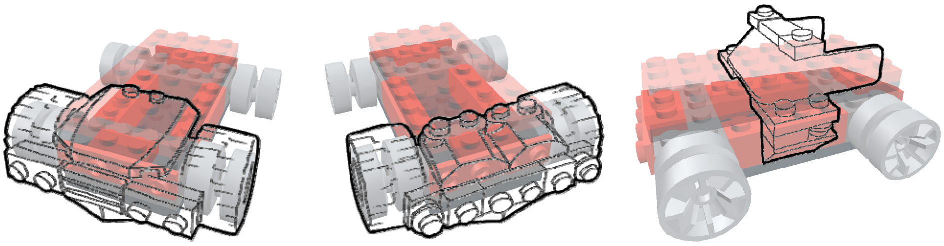


Figure 5.61: Many of the customer preferences were possible to satisfy using the same core of LEGO bricks. The design suggestions in these pictures reveal a certain split in generic and variable components, giving the course participants the change to better understand the value of reuse and encapsulation and the possibility to obtain variety and commonality at the same time.

After having revealed the pattern to the participants, the game continued. Thereafter, the strategy of many teams changed and they started to pursue the benefits of a product platform approach. After another six rounds, the game was stopped and the winners were announced.

The game as a laboratory

The game served as an artificial design environment in which it was actually possible to simulate effects that would otherwise have taken months or years in large scale projects. The fundamental idea of the game seem useful not only in a product platform context but in a variety of different engineering design and product development contexts. An intrinsic problem in engineering design is the fact that the design process is hard to replicate or simulate. The Design Game makes is possible to set up a simulation of a design process. Clearly, the cost calculations reflect the preconception of the game leaders, for example in the case of the commonality benefits that were installed in the Danfoss case. However, it has more to do with a qualitative understanding of the effects rather than a specific quantitative measure on commonality. Thus, changing the different effects in the calculation – or adding new effects – should be no problem.

Testing visual models using the game

A very interesting study – which was unfortunately never carried out – would have been to test a *before* and *after* situation *without* and *with* a visual modelling approach respectively, thereby using the design game as a means to add validity to the other modelling tools proposed elsewhere in the case. Thus, the game participants could have played a number of game rounds or perhaps a whole day without the knowledge of the platform and without any detailed instructions on how to model the platform. Then they could be introduced to the platform played a number of rounds, and finally get introduced to the modelling tools, and then given the chance to use the models. It would be interesting to see the different implications in the three different design situations, yet that is left to future studies.

The game is itself a model

The game itself is a representation of a certain design and development context. In that respect, the game is a kind of activity model. As such, the game is part of the platform in Danfoss. It is not an information model hanging on the wall as a poster or computer model saved in the CAD system. It is of a different topology.

Conclusions from the game

A Design Game has been proposed as means to simulate a platform development context and to provide a mindset of commonality and variety, encapsulation and reuse.

The Design Game proved to have two interesting characteristics;

1. *The game served as an activity model representing a design context*
   It was possible to make several hundred students, and industrial employees engage in process resembling the product development context quite closely, including conceptual and detailed design phases. By using various metrics, certain benefits and penalties were installed, and by means of a competitive environment, these benefits would be reflected in the winner of the game.
2. *The game was a very successful means of education*
   The competitive element in the game and the cross functional mix of team members was a huge success. It was difficult to make the team members leave for lunch even after some five hours of intensive work and instructions. They were completely involved in the process, and very eager to perform within the game setting. The various roles in the team, which also reflected the real background of the participants (at least in the case in Danfoss, not including the students) sparked a great enthusiasm in the teams.

The author will expect the Design Game to be applicable in other engineering design and product development contexts, in which a research test of a certain method or an education task can be done by means of the Design Game, or a modified version thereof. It would be an interesting future study to actually use the design game as a platform for testing the models proposed in the thesis. However, this opportunity evolved too late in the process, and is therefore not done within this study.

5.5.9 Validation at Danfoss

The validation square [Pedersen, et al., 2002] (see Part 2, chapter 2.5) propose a series of acceptance steps in the validation of a *design method.* It is noteworthy that the steps are primarily for design methods, i.e. prescriptive synthesis methods. However, the steps are found useful also in the context of the proposed platform models. The six steps are;

1. *Accepting the validity of the construct*

   In this case the models involved are considered as the constructs to evaluate, thus evaluating the contents and structure of the models.
2. *Accepting the consistency of the method*

   In this case the consistency of the models proposed during the Danfoss project
3. *Accepting the cases involved*

In this case the Danfoss project as a valid and representative case of an industrial platform project

4. *Accepting usefulness of the method within the cases*

   Testing and claiming the usefulness of the proposed models in a the Danfoss project

5. *Accepting that this usefulness relates to the application of the method*

   Testing and claiming that positive effects arise from the models. This is hard to do directly under the circumstances of the project. The model in figure 2.9, Part2, is an illustration of the chain of assumptions and arguments linking the measurable criteria of *decision base* to the performance. From this perspective no empirical performance is directly validated. However, using the decision base as the primary measurable criteria, employees in Danfoss were asked whether the models enabled them to make better decisions. In Research Question 2 the *experienced* improvement of the decision is research object. Thus, validating is testing how the users in Danfoss receive the models.

6. *Accepting the usefulness of the method in a broader application outside the case setting*

   By inductive inference claiming a general usefulness of the models. In the Danfoss case such an inference is purely speculative and cannot be validated within the current setup of the project.

Figure 5.62 depicts the validation efforts in this work. The validations are slightly different from the puzzle, to the building block poster and finally to the Design Game. In the case of the puzzle, the work has been published at conference proceedings and in a journal paper, thus the structural aspects are somewhat accounted for and has been accepted by academic review (three times). That accounts for steps 1 through 3 in the validation square. In the case of the building block poster, only academic and industrial colleagues have been actively involved in the process of validating the model. Thus, no objective and unbiased persons have really reviewed the work. The case is the same for the Design Game, yet is has been used extensively as a teaching methodology at The Technical University of Denmark and as at Danfoss – but again with the involvement of the same group of people i.e. colleagues of the author.

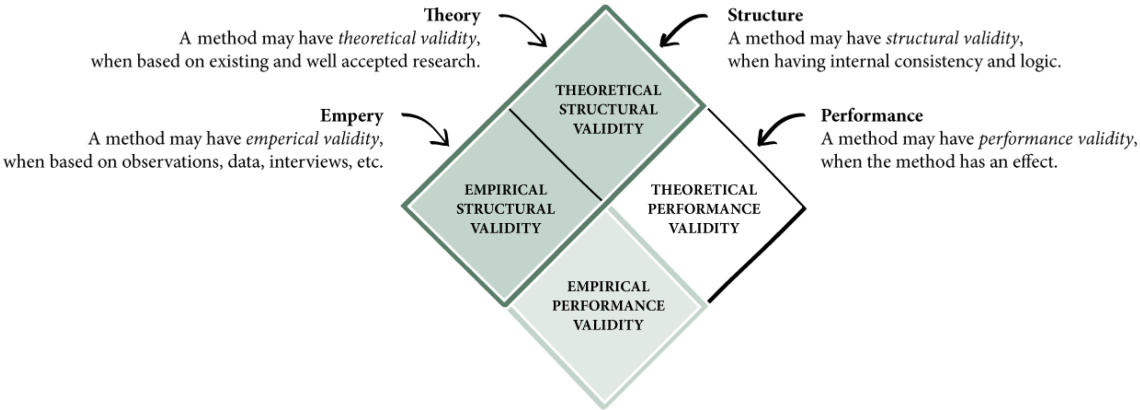


Figure 5.62: The main validation of the results from the Danfoss case is done by means of structural validity. Attempts to claim empirical performance validity are relatively speculative, yet the Danfoss employees were asked to assess the improvement of their decision base as a result of the models.

Figure 5.62 depicts the Validation Square and it is shown how the main validity lies in the structural aspects, i.e. claiming that the right constituents of the model are present and that the model is consistent. The constituents of the models are mainly based on the review of various phenomena and platform models in Part 4 and the review of modelling methods in Part 5. However, depending on the scope of the research *effects* and the measurable criteria, some degree of empirical performance validity can also be claimed. In figure 2.9, the main object of research is the *decision base*, even though the *performance* of the model is eventually considered to have an impact on profit, improved lead time or the like (i.e. improved efficiency and effectiveness as discussed in chapter 4.6.1).

In Research Question 2, the performance of the models has to be measured as an improvement of the *experienced decision base*. Thus, when assessing the decision base and gaining input from the users of the models, some sort of empirical performance validity is added to the study.

Assessing the true impact on business performance is a different and much more difficult study to carry out, and that is left out of scope of this research.

Observing the models as a decision base

The study was based on action research, and the researcher took an active part as a team participant in the project. There are no systematic surveys done or questionnaires given to the employees. Instead, the use of the models and the effects of the models have been observed on a regular basis throughout several years;

The product and production puzzle

On the basis of the concepts built by means of the two puzzles, Danfoss chose to initiate a project, which already from the beginning received significant funding compared to other initiatives at the time. The puzzles served as the primary conceptual working method, and the project became part of the budget on that basis, before any further detailed calculations were carried out. Thus, from that perspective, the puzzles proved successful as a decision base and several managers stressed that the visual approach gave them the ability to make qualitative decisions based on the models and their experience – and feeling confident while deciding.

Selected quotes from employees in Danfoss during the years of using the puzzle:

"This is a very efficient way to put on paper, what is in our heads", design engineer.

"The puzzle makes it possible for me to express concepts, despite the fact, that I am not a very skilled illustrator. My limited sketching talent sometimes restrain me from really taking part in brainstorming. Now I can engage like my colleagues and express my ideas – and now I end up drawing solutions that are not part of the puzzle when we begin", design engineer.

"Based on the visualisation we now have a tool to make decisions on a very early stage in the product development project – and it is even more important now that we start the platform project", product development manager.

"This is the first time we've had a good tool that actually makes it possible to conduct truly concurrent concept development, of product and production concepts in one go, and decide what concepts to go for", production technician.

"Finally we can have a say during the product development projects", production technician.

"This puzzle approach makes it possible for me to understand what is going on in the development department", marketing assistant.

The building block poster

The poster ended up being an important means of communication between the team members and externally to other stakeholders within the organisation. Some of the information was found in the poster and nowhere else, and the combination of overview and detail was stressed by several of the team members as a great help when navigating through the solution space (i.e. when deciding), and when keeping track of the progress in the project.

Selected quotes:

"We have really no overview of the status of components and design responsible in our systems, so the only place to turn to is the poster", design engineer.

"I would have liked the poster to give me some guidance on where to find the CAD files, other than just the ID numbers – why not include the path to the file on our serves and make hyperlinks in our PDF version?", design engineer.

"Now I see the platform!", product development manager.

"This poster is my primary navigation tool in the project, when I seek update on what the other guys are doing, I can turn to the poster", design engineer

"I like all the visual models you have in the team room. It makes it very clear what you are working on", operations manager.

The Design Game

The Design Game was in fact a major success from an educational point of view, given to the feedback from engineers in Danfoss and the more than 120 students from the Technical University of Denmark, who participated in the various course sessions. It was chosen as an integral part of the internal education programme for employees in Danfoss, and was also adopted as a means of teaching in several courses taught at the Technical University of Denmark.

However, the primary purpose of the game was to strengthen the comprehension of the concept of product platforms. The course received very positive feedback from the employees in Danfoss in that dimension.

Selected quotes:

"This is an extremely well suited means to make my people understand the concept of product platforms, and I think that they'll think twice, next time they order a new O-ring without checking in our existing designs. Thus, it has an effect on our decisions even before we reach the fully implemented platform", Vice president.

"*This is simply the best course I have ever had!*", engineer - from the product development department.

"I liked the game, yet I would have liked to try some of our tools during the game. I still do not fully know how we are supposed to make the models ourselves", design engineers

"Now I understand what all this platform talk is about", marketing assistant

"Now I get the point of the platform project. I thought we already reused components today, but I see that it takes more than just that", production technician

Being unbiased

One major issue makes the project biased from an evaluation stand point, and all the quotes above suffer from the fact that nearly all education efforts within the company was made by the author and Morten Kvist [Kvist, 2009] in cooperation. Thus, the employees were first told throughout a period of some three years that visualisation and product platforms combined is a sound way to go about product development, and later their opinion on product platforms and visualisations is used to validate the work. This is off course a major limitation when assessing the work. Nevertheless, many of the employees were not at all positive towards the platform project in the beginning and continued to have many rightful and correct statements, mainly about the risk related to the discontinuation of product variants. Despite this, the vast majority of the employees were positive towards the models and the Design Game as a means to improve decision making.

The transfer of knowledge and mindset *from* the researcher *to* the design engineers, and to other employees in the company, was considered - under the given circumstances – to be a prerequisite in order to stimulate the necessary effects, and to get the project going. Therefore the empirical validity of the effects of the tools cannot be fully stated in this thesis.

5.5.10 Concluding the Danfoss case

The above chapters have described various models;

- *The product puzzle*
  Mainly useful for conceptual work, and to provide qualitative visualisations of organ and parts encapsulations as well as alternative working principles.
- *The production puzzle*
  Like the product puzzle, mainly for qualitative models during conceptual work. The puzzle is useful for visualising postponement and alternative supply chain setups.
- *Building block poster*
  The Building Block model was mainly used during the later preparation phases and the early execution phases of the platform development project to;
  - Keep track on the status of the different platform constituents, by expressing the design status of various parts, such as status on tests
  - Serve as a part of the design template in the execution phases, bu giving a visual overview of the whole platform and then detailed overview of the combination of attributes and variants in relation matrices.
- *The Design Game*
  The design game served two main purposes;
  - The Design Game was an activity model of the design context
  - The Design Game was an educational instrument to help bring about a certain mindset in order for the employees in Danfoss to better understand the models and the context in which the models were to be used.

The models reflect various instantiations of product platform phenomena. The concept of commonality and variety are intrinsic in all the models, and so is reuse and encapsulation as the primary means to obtain variety and commonality.

The difference in encapsulation of parts and encapsulation of organs is mainly raised in the product and production puzzle, in which design engineers may play around with various parts encapsulations for a number of organs and see how that reflects the needed fabrication and assembly flexibility while also being able to build a visualisation of the whole production setup and evaluate postponement potential and decide from that basis.

In general, all models have received positive evaluation from the employees and managers in Danfoss, who feel that their decision base have been improved through the use of visualisation and modelling as a part of their future toolbox.

5.6 Using Top Down Design in CAD

In the following two cases, the Grundfos case and the Aker Solutions case, the concept of Top Down Design will be discussed. This chapter gives a short introduction to the basic concept of a Top Down approach and the concept of skeleton modelling in CAD systems.

Top Down Design

The fundamental approach in Top Down Design is to generate generic attributes and relations as a first step. The layout of the system is designed before the elements are designed. It resembles a process of defining *structure* before *elements*. This means that spatial relations and sometimes key features are designed before the physical embodiment of all parts is known.

Figure 5.63 depicts a simple example of the difference between a Top Down and a Bottom Up design approach.

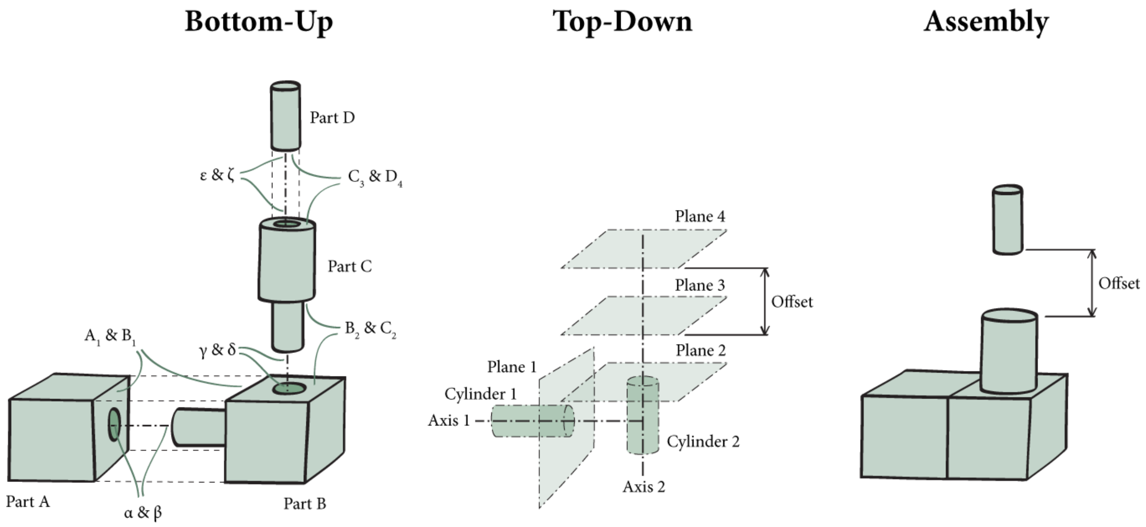


Figure 5.63: The principal differences between a Bottom Up (left) and Top Down (middle) approach for an assembly of four parts (right). In the Bottom Up approach, parts and features are references to each other. In the Top Down approach parts, generic features and generic interfaces are linked to a common reference – in this case a so-called skeleton.

Look at the example in figure 5.63.

The assembly to the right has to be built. The assembly consists of four parts (which are better seen to the left). Part A is a box with a hole. Part B is a box with a cylinder on the side and a hole in the top. Parts A & B have an interface to each other formed by the hole and the cylinder. Part C is a cylindrical part with two different nominal diameters. Parts B and C fit have an interface formed by the cylinder in the bottom of part C and the hole in the top of Part B. Part D is a cylinder. It has to be positioned with an offset above part C and has to be coaxially placed in space above Part C.

The assembly to the right is put together in two different ways:

The Bottom Up Approach

- *Part A* is constrained to *Part B* by mating the surfaces A_1 and B_1, and by constraining the axes of the hole, α and the cylindrical part β.
- *Part C* is constrained to *Part B* by mating the surfaces B_3 and C_3 and by constraining the two axes to each other (γ and δ).
- *Part D* is constrained to *Part C* by creating an offset between surfaces C_3 and D_4 and by constraining the two axes ε and φ.
- All parts are constrained to a global vertical direction.

There are several potential drawbacks of this approach;

- *Removing a part*
  If a Part is removed, the whole assembly is likely to collapse, because the parts are constrained to each other. If for instance Part B is removed, Parts C and D will lose their vertical position and the axis to which they are constrained. Some Cad systems will move the parts to the centre of the global coordinate system, while some systems will make arbitrary movements of the parts in the modelling space.
- *Changing a part without changing an interface*
  A designer changes the length of Part C. Then Part D will follow, because surface C_4 is moving. However, he would like the offset to change as well, so that the height of Part D above Part B is held constant. He will have to change the offset manually, if the offset is a direct constraint between the two surfaces of Parts C and D as suggested.
- *Changing an interface*
  If the cylinder on Part B changed, the two parts will no longer fit each other, unless the designer manually changes the hole in Part A.
- *Creating a product family with variable and generic attributes*
  Image that the Parts A, B, C, and D come in various variants. Sometimes, the attributes will collide with the constraints, making the change in one part propagate to another part in the assembly. Every time a new part variant is introduced, some of the constraint work will have to be done again. Moreover, the designer will have to draw the interfaces on each single new variant, even though the geometry is generic and reused across all parts.
- *Updating product variants*
  Imagine that certain parameters are to be changed on all the variant instances of a part, for example that the offset suddenly have to be changed on all copies of the assembly. This work has to be done manually on all instances of the product.

This is a very simple example of some of the drawbacks of a Bottom Up approach. Some of the drawbacks can be overcome by simply changing the way parts are constrained to each other. Feature based design [van Holland & Bronsvoort, 1996], is one way to reuse geometry, and avoid making the same geometry over and over again.

Top Down Design using skeletons

Top Down Design does not to the same extent suffer from the above drawbacks.

In figure 5.63 a Top Down Design approach is represented with a so-called *skeleton* is shown. The *skeleton* is an important concept in Top Down Design. The skeleton is a generic structure in which spatial relations of various features and geometry are controlled. The skeleton is used as a *relation repository*, from which relations, certain shapes etc. can be published to a number of different part and assembly files.

In figure 5.63, the skeleton controls the relations between the parts;

- The *interface between Part A and Part B* is governed by *Plane 1*, *Cylinder 1* and *Axis 1*. If the diameter of cylinder 1 is changed that change will propagate automatically to Part A and Part B thereby changing the diameter of the hole in Part A and the cylinder in Part B.
- The *interface between Part C and D* is controlled in the same way using *Plane 2*, *Cylinder 2* and *Axis 2*.
- The *surfaces* A_1 *and* B_1 are controlled by *Plane 1*. (Likewise with surfaces B_2 & C_2 and Plane 2)
- The *length of Part C* is controlled by the distance between plane 2 and 3.
- *The offset* is controlled by the distance between plane 3 and plane 4

The designer may choose to assign even more generic attributes of the parts to the skeleton, depending on the use of the assembly, and the need to change various attributes.

The skeleton has several interesting properties in a product platform context, of which three are emphasised below;

1. It can hold generic spatial relations
2. It can hold generic form features
3. It can hold generic constraints and design limitations

...all of which can be inherited down to variable instance assemblies. Thus, a skeleton is a seemingly handy way to control generic and variable attributes in a product platform.

Top Down Design has received extensive interest in industry, yet many companies still use a predominantly bottom up approach. The main design practice in all the three case companies in this work is a Bottom Up approach. The reason may be that the Bottom Up approach provides a rather intuitive way to build an assembly, while the skeleton approach is more abstract and needs more planning before the actual physical embodiment designs are made.

From a general experience in projects in various Danish industries, it is the impression of the author that many small and medium sized companies fail to use a Top Down approach, yet the extension of the use of Bottom Up relative to Top Down Design has not been studied further in this piece of work.

Despite a relatively profound review of literature it has not been possible to identify academic references specifically reporting on the use of Top Down Design and skeletons in a product platform context. However, examples of the use of Top Down Design and skeletons in similar applications, also incorporating a functional viewpoint on the features and geometries are available [Aleixos et al., 2004].

Hierarchies of skeletons

Skeletons can be placed in a hierarchy and refer to each other. Using different levels of skeletons, makes it possible to control different levels of generic geometry, meaning that a set of products share some features, while other products share more features etc.

Family table

A family table is an addition/alternative to the skeleton approach. The family table is a repository from which alternative parts (i.e. CAD part files) can be interchanged and put into an assembly with shared interfaces and relations to the assembly. The family table makes it easy to interchange one part with another part.

Combinatorial platform versus attribute quantification

From a design point of view, the family table approach resembles the task of combining different parts, i.e. the *combinatorial platform approach* as opposed to the *attribute quantification*. (See Part 4, chapter 4.5.3, [Fujita, 2002], [Muffatto, 2002], [Simpson & Mistree, 1999]). The attribute quantification on the other hand, somewhat fits the skeleton approach better, because the skeleton allows a more detailed control of single attributes to take place, while the family table is more suitable for interchanging alternative parts instead of changing parameters on the parts.

The organ skeleton and the CAD skeleton

In Part 4, the term skeleton is used to denote *the spatial relations between entities of organs*, i.e. the spatial relations between wirk elements. The term is used in an abstract systems perception related to the Theory of Domains. However, from certain viewpoints, the skeleton of the organs and the CAD skeleton may become very similar.

Jensen [1999] stresses the difference between a form element and a wirk element, in that wirk elements depend on a certain viewpoint, whereas a feature or form element only belongs to a geometrical class (this is also discussed in Part 4 chapter 4.5.4, with the power plug example in figure 4.18). And since organs consist of wirk elements and the CAD system is used to model form elements, the same distinction exists between the CAD skeleton and the organ skeleton. The wirk surface is an abstraction, and it depends on the functional perception and decomposition of the product.

CAD skeletons/form features & Organ skeletons/wirk elements

If the geometrical form elements are modelled in order to resemble the wirk elements, and the relations in the CAD skeleton resembles the relations between wirk elements, it is possible to gain a high degree of similarity between the organ skeleton and the CAD skeleton. The organ skeleton is a matter of viewpoint, but so is the design of the CAD skeleton.

Clearly, there are limitations to the above statement. Since the CAD system is a geometrical tool, the possible wirk elements are mainly limited to surfaces and volumes. A wirk media is difficult to model.

Why bother about wirk elements?

The reason to grant the subject of skeletons and wirk elements attention is that the viewpoint of wirk elements proved to be of use in the Grundfos case. Having a mindset of *wirk surfaces* while placing *form features* in a skeleton, enabled ways to control the *grouping and decoupling* of wirk surfaces. Thus, the Top Down approach became a tool to manipulate *organ encapsulation* in a practical way. Thereby, organ encapsulation changes from something rather theoretical to something of practical use.

Wirk elements do not necessarily follow the boundaries of parts. They can be put in the skeleton and inherited to different parts. The inner geometry of the pump house for instance is relatively easily placed in a skeleton as a single wirk surface from which the different parts of the collapsible core (the segments and the pyramid) can inherit their functional geometry. The generic geometries of the collapsible core can also be placed in the skeleton, leaving the designer with very few design tasks, and enabling easy updates of design and design reuse.

Top Down Design and object oriented design

Top Down Design has another interesting characteristic in that it resembles the object oriented perception of a system.

Consider two product platform models of the same platform. The platform consists of reusable, encapsulated parts and organs (like the moulding platform in Grundfos). The platform is modelled in a *Product Family Master Plan* with the Part_of and Kind_of structures. The platform is also modelled in a CAD model, consisting of a skeleton and parts with inherited geometry. There is a number of interesting similarities between the two modelling approaches:

1. The Part_of structure resembles the skeleton, in that it is a generic structure holding information about relations between variable entities.
2. The Kind_of structure resembles the collection of variable parts, which inherit some attributes from the skeleton, while other attributes are based on customisation.

The mindset of a Product Family Master Plan and a Top Down approach is somewhat similar. Both modelling approaches reflect an *object oriented view* on the system. In both cases, design engineers have to think about the totality of the system before delving into the details of the entities. This process also promotes an emphasis on generic and variable attributes, because generic attributes resides in the skeleton or Part_of, while the variable attributes resides in the entity parts, that is, in the Kind_of structure.

5.7 Aker Solutions

This case is included in order to give an example of use of the Product Family Master Plan in combination with a Top Down Design approach in the CAD system involving a skeleton model.

5.7.1 The role of the author

The author has been working as a researcher and as a consultant in Aker Solutions. The author has been involved in platform design initiatives with various products, and used the Product Family Master Plan tool together with colleagues during that work. In the following a CAD model and the use of skeleton models is discussed. The CAD models and the planning, preparation and design of the skeleton models, and the intellectual work related to that, are the works of two Aker Solutions design engineers. Thus, regarding the PFMP, the author has had an active role, and in the case of the skeleton models and CAD design only participated as an observer.

5.7.2 Introducing Aker Solutions

Aker Solutions is a part of the Norwegian based industrial conglomerate *Aker*. Aker spans various independent companies servicing a range of different engineering industries within emission reduction, energy solutions, oil and gas exploration and production, and shipbuilding employing some 26500 people worldwide with revenues of some 65 billion Norwegian Kroner in 2008.

The focus of Aker Solutions is worldwide engineering and construction services, technology products and integrated solutions for a variety of different customers mainly within the off shore oil and gas industries.

The research work has been carried out at an Aker Solutions subsidiary, based in Kristiansand, Norway. This part of Aker Solutions designs and manufactures various pieces of heavy duty handling equipment for drilling operations (i.e. drilling of oil and gas wells).

Drilling equipment

Drilling equipment is heavy duty machinery capable of operating in a harsh off shore environment, from tropical and hurricane prone waters in the Mexican Gulf to cold places with high waves such as the Arctic Sea. The environmental criteria imposed by wind, waves and temperature result in heavy mechanical loads on the machinery during operation and in various non operation modes, such as during a hurricane. Together with the high demands for explosion prevention on the oil rigs, the environmental criteria set some rather strict demands on the equipment.

Aker Solutions provide a wide range of machinery for the purpose of a drilling rig. For a conventional drilling rig Aker Solutions provides (depending on the level of detail when perceiving the rig) some 40 – 80 different machines operating in complex interplay. The interplay is characterised by complex spatial relations and *handshakes*, i.e. when one machine has to position itself relative to another machine in order for the two machines to be able to handle a piece of equipment (usually a drill pipe) in conjunction. Anti collision precautions are also important. Clearly, the control system is an important means to obtain the right interplay between different machines. However, the spatial layout of the rig and the environmental criteria (wind, waves, etc), has a large impact on how the *mechanical design* ensure a successful handshake between machines.

Drill pipes

The well is drilled by means of drill pipes. The tubes are made of steel and have threads in the ends, making it possible to screw the tubes together to form a so-called drill string. The drill string can be up to several kilometres long, and in the end of the string, the *drill bit* cuts through the ground to reach the reservoir. The overall purpose of the drilling equipment is to screw together sections of drill pipe in order to form the drill string, and to drill the hole by applying rotation to the drill string, thereby rotating the drill bit. For the purpose of this case, it is sufficient to know, that the equipment handles various types of drill pipe and other cylindrical items (called *tubulars*) which are used to drill the well and to seal the well from the surroundings in the ground.

5.7.3 The challenge

Aker Solutions has a long story of providing customised products to a variety of different applications and customers. Aker Solutions is mainly a *project* oriented business, meaning that the company engages in large scale drilling rig projects, in which it supplies various packages of machinery into a rig installation. Rigs are large and complex (mostly one off) installations with many stakeholders involved during the design process. The design process is characterised by a slowly progressing level of detail, and the fact that some criteria and specifications are determined late in the process through iterations between various stakeholders such as other suppliers, different shipyards etc. Therefore, each project – from an Aker Solutions standpoint - tends to result in a set of rather specific equipment even though many of the design criteria are constant from one project to the other. The project focus limits the reuse of design across projects. Documentation, drawings, user manuals, approvals etc. are also changed from project to project.

Complexity on several levels

Over a period of several years, the engagement in various rig projects has contributed to a significant complexity in the product range and within the organisation. This complexity is induced by variation on several levels;

- *Product complexity*
  The different products have for many years been tailor made for various purposes. Therefore, Aker Solutions now have a lot of past designs in their portfolio, many of which are overlapping in functionality and performance.
- *Product group complexity*
  There is a level one could call a product group level in which groups of some three to five machines interact in groups in order to solve a specific purpose, i.e. a subordinate function on the rig.
- *Rig complexity*
  On a higher level, each product (and product group) has been put together to form different rigs with different motion criteria, performance demands etc. Two cranes, which are seemingly alike from a functionality point of view, may be different if the two cranes are placed on two different rigs, and one rig is placed in higher waves than the other, thereby inducing greater forces on the equipment.

Thus, there is a complexity on several levels making it rather difficult to standardise the machinery. However, several internal analyses in Aker Solutions has pointed out that there is a potential for reuse across projects without compromising the performance of the products in each project.

5.7.4 Changing the state

In order to reduce non value adding product variation, different initiatives have been started. These initiatives have in common the desire to tailor make products without increasing the complexity, i.e. essentially to obtain variety and commonality at the same time.

Product focus and project focus

Aker Solutions has realised that there is a potential for improving the business by focusing more on *products* rather than strictly on the rig *projects* [Rudshaug, 2007]. An important aspect of the product focus is to *reuse* from one project to another project. That is, reuse of design principles, approvals, drawings, documents, parts, sub assemblies etc., to the extent possible.

Aker Solutions wants to change their focus and optimise products and be able to reuse across projects without losing the performance of products in different projects or the ability to customise products. In order to that, they have decided to build an overview of the present product portfolio as a first step, and from that overview, determine what to do.

The Eagle Light crane project

Out of the many different machines and initiatives, a specific machine has been chosen for the purpose of this research. It is a hydraulic operated crane called an *Eagle Light*. The reason to study this particular piece of machinery has to do mainly with the work of two design engineers who are improving the design of the crane, trying to standardise various designs out of a product platform like philosophy, while at the same time making a more efficient CAD model structure using Top Down Design principles. The project contains various interesting aspects in relation to this research;

- The starting point of the project was to “modularise” the crane, i.e. to standardise certain components without limiting the variation in the market place. Thus, the fundamental incentive was to *reuse by means of encapsulation* in order to obtain *variety* and *commonality* at the same time.
- The crane project team is experimenting with various Top-Down designs in the CAD system, i.e. they are working on generic structures and *skeletons*, serving as generic placeholders for references on designs, interfaces and motion patterns.
- The Product Family Master Plan tool is a visual analysis and modelling approach in the project.

Therefore, the case serves as an opportunity to report the combination of a visual modelling approach and a skeleton model in a CAD system.

The Eagle Light

Figure 5.64 depicts an Eagle Light. The Eagle Light is a crane which used to move drill pipes on a drilling rig. The crane can rotate (tilt) around a horizontal axis, thereby making it possible for the crane to elevate drill pipe from a horizontal position and pass them on to other types of equipment in a vertical position. The crane can also rotate (slew) around a horizontal axis, making it possible to the crane to delivery vertical drill pipes at different positions within the drilling rig. At the end of the crane a so-called Yoke is placed (see figure 5.64). The Yoke is used to hold the pipes during operation. Finally, the Yoke itself can rotate (tilt) relative to the Jib, thereby increasing the degrees of freedom for the pipe handling options.

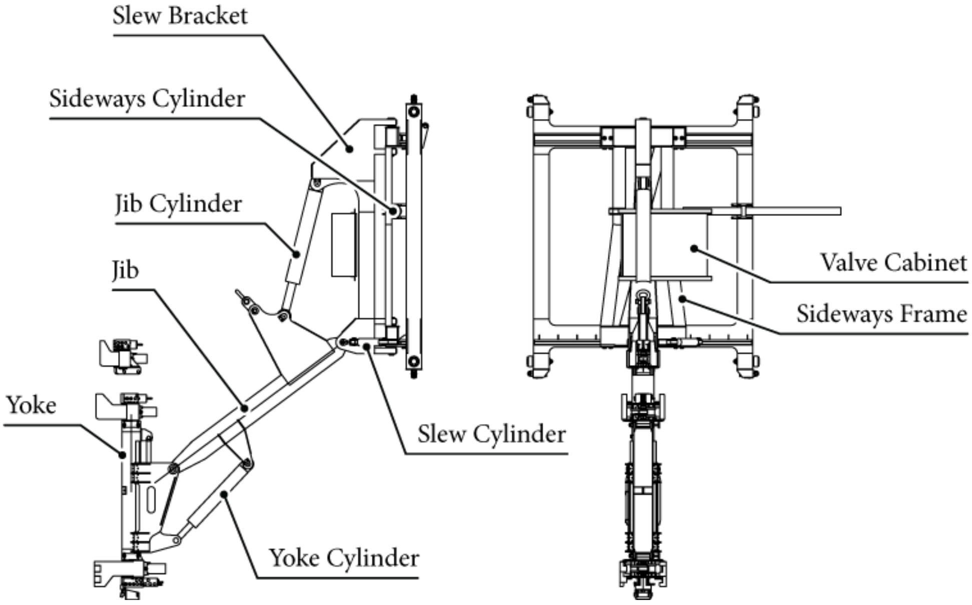


Figure 5.64: An Eagle Light, front view and side view. The crane is used to move various types of drill pipe on a drilling rig. (See figure 5.69 for a 3D view of the crane).

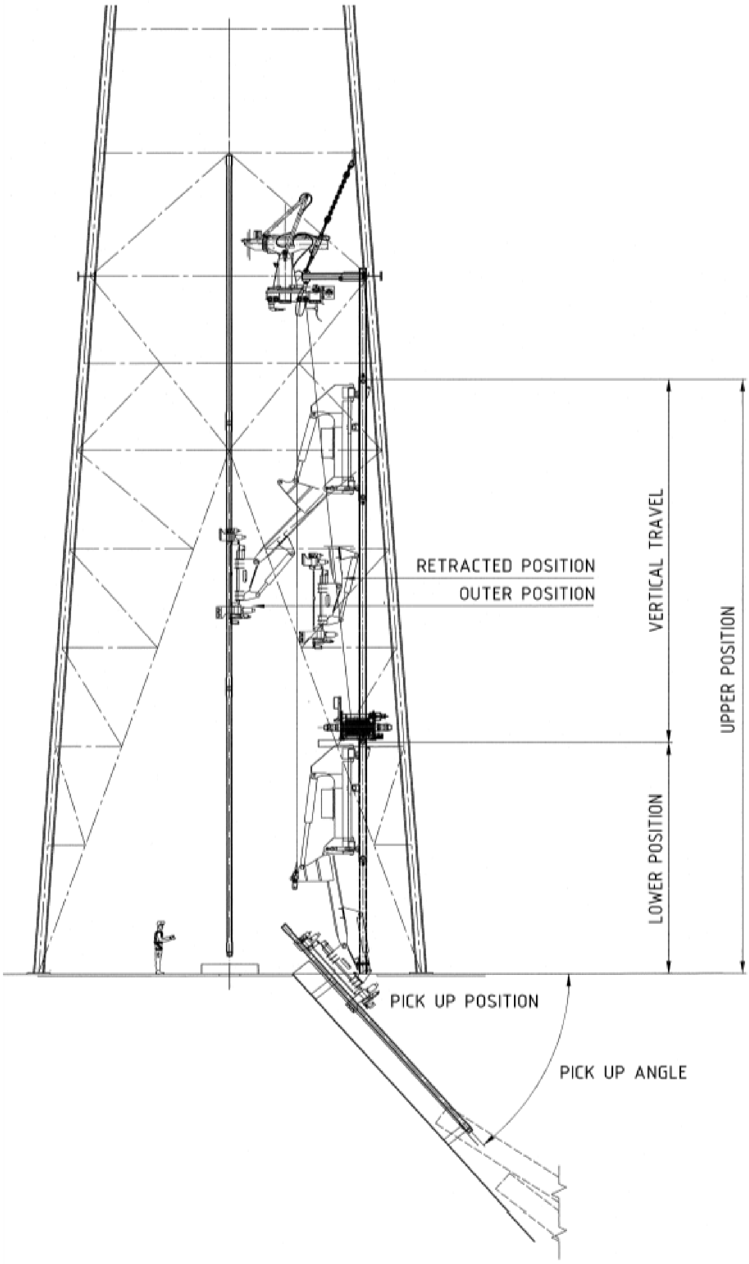


Figure 5.65: An Eagle Light inside a rig structure (a so-called derrick). The Eagle is shown in its two extreme positions, and in an intermediate position. This particular Eagle can take a drill pipe from the pickup position in the lower right of the figure, lift and rotate the pipe and hold the pipe in a vertical position in order for other machinery to take over the pipe. The person on the drill floor gives an impression of the size of the crane.

Figure 5.65 depicts an Eagle Light in various positions inside the rig structure. The rig structure is called a *derrick*. The derrick is a steel structure which stands above the so-called *drill floor*. The drill floor is the site of most of the operations during the drilling of a well. On figure 5.65 a person is standing on the drill floor, next to the centreline of the well, directly underneath the vertical pipe.

Product variation

The main attribute variation between various Eagle Lights is mainly found on a few attributes. The range of operation is limited by;

- *The reach*
  The reach is mostly determined by the length of the Jib, i.e. how far the Yoke can reach from the slew bracket.
- *The slew angle*
  Whether and to what extend the Jib and Yoke can slew around a horizontal axis.
- *The vertical travel*
  Whether and to what extend the Eagle can travel in a horizontal direction.
- *Horizontal travel*
  Whether the Eagle can travel in a horizontal direction (in- or outside of the paper plane in figure 5.65).
- *The possible pick up position*
  Which is mainly a function of the tilting of the Yoke relative to the Jib.

Except for the possible pickup position, all these dimensions of variety are mainly depending on a single or few attributes in one of a few parts in the Eagle. The reach for example, is more or less directly determined by the length of the Jib, if the other parts are held constant.

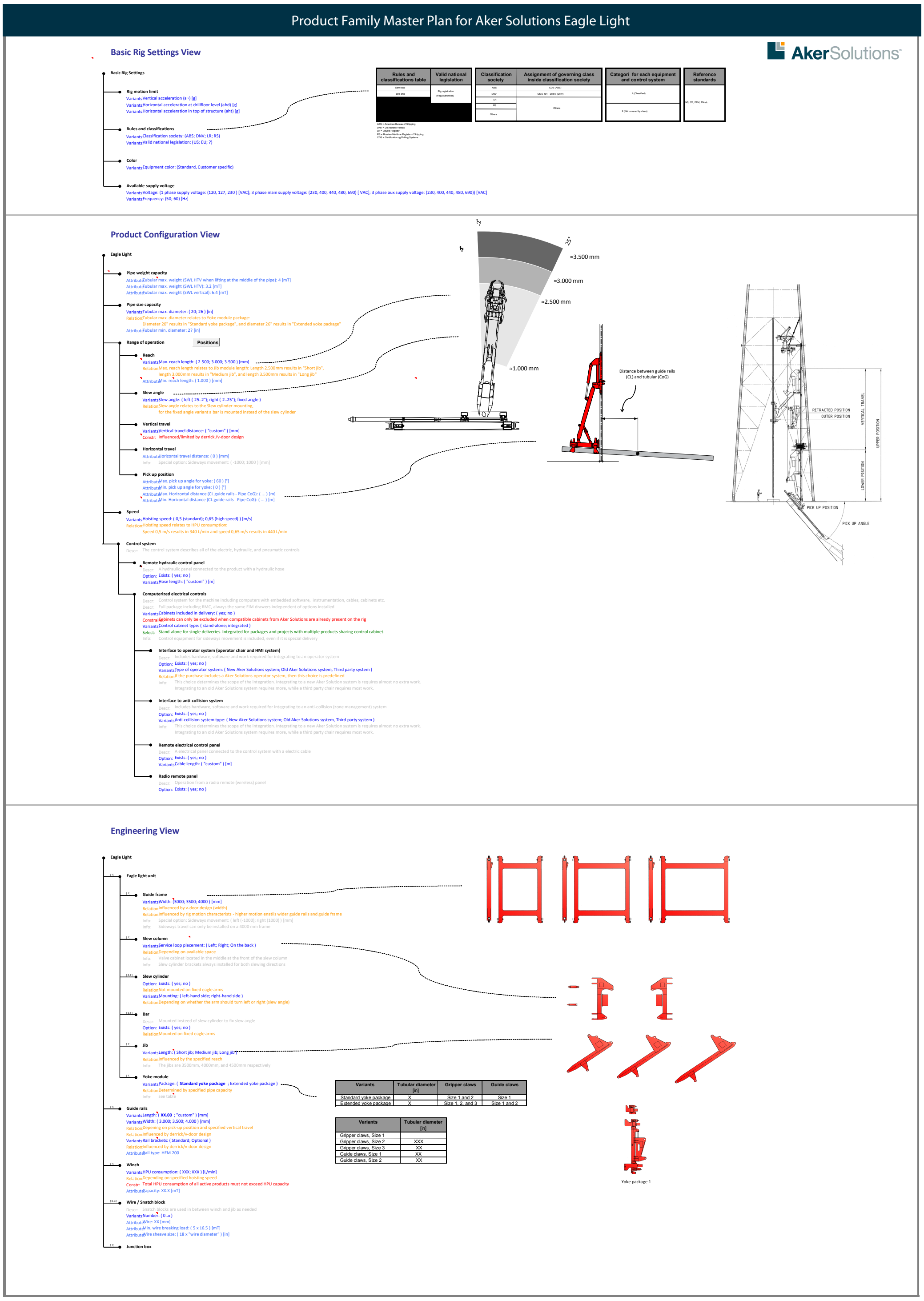
5.7.5 Modelling the Eagle Light

Past designs of the Eagle Light has been analysed using a Product Family Master Plan (PFMP). The PFMP depicts the variations of a selected and representative series of existing designs of Eagle Light cranes. On the basis of these historical designs, a new standardised series of Eagle Lights has been designed, and a new version of the PFMP has been made, in order to depict and communicate the new designs. This new PFMP constitutes one essential part of the modelling reported in this case, whereas the CAD models of the new Eagle Light constitutes another important part of the modelling.

The Product Family Master Plan

The Product Family Master Plan is a poster depicting a visual object oriented model of the Eagle Light. The PFMP of the Eagle is a slightly adapted version of the PFMP modelling principles described in chapter 5.3.4, and in Kvist [2009] and Harlou [2006]. Due to confidentiality reasons, only parts of the model are described in detail here.

The importance of the PFMP in this particular case lies in the match between the Part_of/Kind_of structure and the CAD model. The Part_of structure is made to fit a skeleton model in the CAD model. Thereby, the PFMP communicates the generic attributes, which are controlled by means of a skeleton model in the CAD system. The important things to visually model in the PFMP are the *variable attributes* and their *limitations*. In the PFMP there is a customer view and an engineering view. See figure 5.66. The top view (basic rig settings view) contains important design limitations imposed by overall design characteristics of the rig. The next view (Product Configuration View) corresponds to the Customer View in Harlou's [2006] definition. At the bottom there is an Engineering View.



Product Family Master Plan for Aker Solutions Eagle Light

Basic Rig Settings View

Basic Rig Settings

- **Rig motion limit**
  - Variants: Vertical acceleration (a ᵥ) [g]
  - Variants: Horizontal acceleration at drillfloor level (ahd) [g]
  - Variants: Horizontal acceleration in top of structure (aht) [g]
- **Rules and classifications**
  - Variants: Classification society: (ABS; DNV; LR; RS)
  - Variants: Valid national legislation: (US; EU; ?)
- **Color**
  - Variants: Equipment color: (Standard, Customer specific)
- **Available supply voltage**
  - Variants: Voltage: (1 phase supply voltage: (120, 127, 230) [VAC]; 3 phase main supply voltage: (230, 400, 440, 480, 690) [VAC]; 3 phase aux supply voltage: (230, 400, 440, 480, 690)) [VAC]
  - Variants: Frequency: (50; 60) [Hz]

Rules and classifications table	Valid national legislation
Semi-sub	Rig registration (Flag authorities)
Drill ship	
[redacted]	[redacted]

ABS = American Bureau of Shipping
DNV = Det Norske Veritas
LR = Lloyd's Register
RS = Russian Maritime Register of Shipping
CDS = Certification og Drilling Systems

Classification society	Assignment of governing class inside classification society
ABS	CDS (ABS)
DNV	OS E 101 - Drill N (DNV)
LR	Others
RS	
Others	

Categori for each equipment and control system
I (Classified)
II (Not covered by class)

Reference standards
NS, CE, FEM, EN etc.

Product Configuration View

Eagle Light

- **Pipe weight capacity**
  - Attribute: Tubular max. weight (SWL HTV when lifting at the middle of the pipe): 4 [mT]
  - Attribute: Tubular max. weight (SWL HTV): 3.2 [mT]
  - Attribute: Tubular max. weight (SWL vertical): 6.4 [mT]
- **Pipe size capacity**
  - Variants: Tubular max. diameter: (20; 26) [in]
  - Relation: Tubular max. diameter relates to Yoke module package: Diameter 20" results in "Standard yoke package", and diameter 26" results in "Extended yoke package"
  - Attribute: Tubular min. diameter: 2? [in]
- **Range of operation** Positions
  - **Reach**
    - Variants: Max. reach length: (2.500; 3.000; 3.500) [mm]
    - Relation: Max. reach length relates to Jib module length: Length 2.500mm results in "Short jib", length 3.000mm results in "Medium jib", and length 3.500mm results in "Long jib"
    - Attribute: Min. reach length: (1.000) [mm]
  - **Slew angle**
    - Variants: Slew angle: (left (-25..2°); right (-2..25°); fixed angle)
    - Relation: Slew angle relates to the Slew cylinder mounting, for the fixed angle variant a bar is mounted instead of the slew cylinder
  - **Vertical travel**
    - Variants: Vertical travel distance: ("custom") [mm]
    - Constr: Influenced/limited by derrick /v-door design
  - **Horizontal travel**
    - Attribute: Horizontal travel distance: (0) [mm]
    - Info: Special option: Sideways movement: (-1000; 1000) [mm]
  - **Pick up position**
    - Attribute: Max. pick up angle for yoke: (60) [°]
    - Attribute: Min. pick up angle for yoke: (0) [°]
    - Attribute: Max. Horizontal distance (CL guide rails - Pipe CoG): (...) [m]
    - Attribute: Min. Horizontal distance (CL guide rails - Pipe CoG): (...) [m]
- **Speed**
  - Variants: Hoisting speed: (0,5 (standard); 0,65 (high speed)) [m/s]
  - Relation: Hoisting speed relates to HPU consumption: Speed 0,5 m/s results in 340 L/min and speed 0,65 m/s results in 440 L/min
- **Control system**
  - Descr: The control system describes all of the electric, hydraulic, and pneumatic controls
  - **Remote hydraulic control panel**
    - Descr: A hydraulic panel connected to the product with a hydraulic hose
    - Option: Exists: (yes; no)
    - Variants: Hose length: ("custom") [m]
  - **Computerized electrical controls**
    - Descr: Control system for the machine including computers with embedded software, instrumentation, cables, cabinets etc.
    - Descr: Full package including RMC, always the same EIM drawers independent of options installed
    - Variants: Cabinets included in delivery: (yes; no)
    - Constraint: Cabinets can only be excluded when compatible cabinets from Aker Solutions are already present on the rig
    - Variants: Control cabinet type: (stand-alone; integrated)
    - Select: Stand-alone for single deliveries. Integrated for packages and projects with multiple products sharing control cabinet.
    - Info: Control equipment for sideways movement is included, even if it is special delivery
    - **Interface to operator system (operator chair and HMI system)**
      - Descr: Includes hardware, software and work required for integrating to an operator system
      - Option: Exists: (yes; no)
      - Variants: Type of operator system: (New Aker Solutions system; Old Aker Solutions system, Third party system)
      - Relation: If the purchase includes a Aker Solutions operator system, then this choice is predefined
      - Info: This choice determines the scope of the integration. Integrating to a new Aker Solution system is requires almost no extra work. Integrating to an old Aker Solutions system requires more, while a third party chair requires most work.
    - **Interface to anti-collision system**
      - Descr: Includes hardware, software and work required for integrating to an anti-collision (zone management) system
      - Option: Exists: (yes; no)
      - Variants: Anti-collision system type: (New Aker Solutions system; Old Aker Solutions system, Third party system)
      - Info: This choice determines the scope of the integration. Integrating to a new Aker Solution system is requires almost no extra work. Integrating to an old Aker Solutions system requires more, while a third party chair requires most work.
    - **Remote electrical control panel**
      - Descr: A electrical panel connected to the control system with a electric cable
      - Option: Exists: (yes; no)
      - Variants: Cable length: ("custom") [m]
    - **Radio remote panel**
      - Descr: Operation from a radio remote (wireless) panel
      - Option: Exists: (yes; no)

Engineering View

Eagle Light

- [1] **Eagle light unit**
  - [1] **Guide frame**
    - Variants: Width: (3000; 3500; 4000) [mm]
    - Relation: Influenced by v-door design (width)
    - Relation: Influenced by rig motion characterists - higher motion enatils wider guide rails and guide frame
    - Info: Special option: Sideways movement: (left (-1000); right (1000)) [mm]
    - Info: Sideways travel can only be installed on a 4000 mm frame
  - [1] **Slew column**
    - Variants: Service loop placement: (Left; Right; On the back)
    - Relation: Depending on available space
    - Info: Valve cabinet located in the middle at the front of the slew column
    - Info: Slew cylinder brackets always installed for both slewing directions
  - [0,1] **Slew cylinder**
    - Option: Exists: (yes; no)
    - Relation: Not mounted on fixed eagle arms
    - Variants: Mounting: (left-hand side; right-hand side)
    - Relation: Depending on whether the arm should turn left or right (slew angle)
  - [0,1] **Bar**
    - Descr: Mounted insteed of slew cylinder to fix slew angle
    - Option: Exists: (yes; no)
    - Relation: Mounted on fixed eagle arms
  - [1] **Jib**
    - Variants: Length: (Short jib; Medium jib; Long jib)
    - Relation: Influenced by the specified reach
    - Info: The jibs are 3500mm, 4000mm, and 4500mm respectively
  - [1] **Yoke module**
    - Variants: Package: (**Standard yoke package** ; Extended yoke package)
    - Relation: Determined by specified pipe capacity
    - Info: see table
- [1] **Guide rails**
  - Variants: Length: (**XX.00** ; "custom") [mm]
  - Variants: Width: (3.000; 3.500; 4.000) [mm]
  - Relation: Depening on pick-up position and specified vertical travel
  - Relation: Influenced by derrick/v-door design
  - Variants: Rail brackets: (Standard; Optional)
  - Relation: Influenced by derrick/v-door design
  - Attribute: Rail type: HEM 200
- [1] **Winch**
  - Variants: HPU consumption: (XXX; XXX) [L/min]
  - Relation: Depending on specified hoisting speed
  - Constr: Total HPU consumption of all active products must not exceed HPU capacity
  - Attribute: Capacity: XX.X [mT]
- [0..x] **Wire / Snatch block**
  - Descr: Snatch blocks are used in between winch and jib as needed
  - Variants: Number: (0..x)
  - Attribute: Wire: XX [mm]
  - Attribute: Min. wire breaking load: (5 x 16.5) [mT]
  - Attribute: Wire sheave size: (18 x "wire diameter") [in]
- [1] **Junction box**

Variants	Tubular diameter [in]	Gripper claws	Guide claws
Standard yoke package	X	Size 1 and 2	Size 1
Extended yoke package	X	Size 1, 2, and 3	Size 1 and 2

Variants	Tubular diameter [in]
Gripper claws, Size 1	
Gripper claws, Size 2	XXX
Gripper claws, Size 3	XX
Guide claws, Size 1	XX
Guide claws, Size 2	XX

Figure 5.66: A Product Family Master Plan of an Eagle Light.(Some information is hided or deleted for confidentiality reasons).

The customer/configuration view

The customer view is mainly a representation of the area of operation and important inputs about control system details. The customer view has a visual representation of the three standard areas of operation, by means of a top view of the crane. The top view is important, because it reflects the reachable area on the drill floor. Figure 5.67 is a sketch from the customer view;

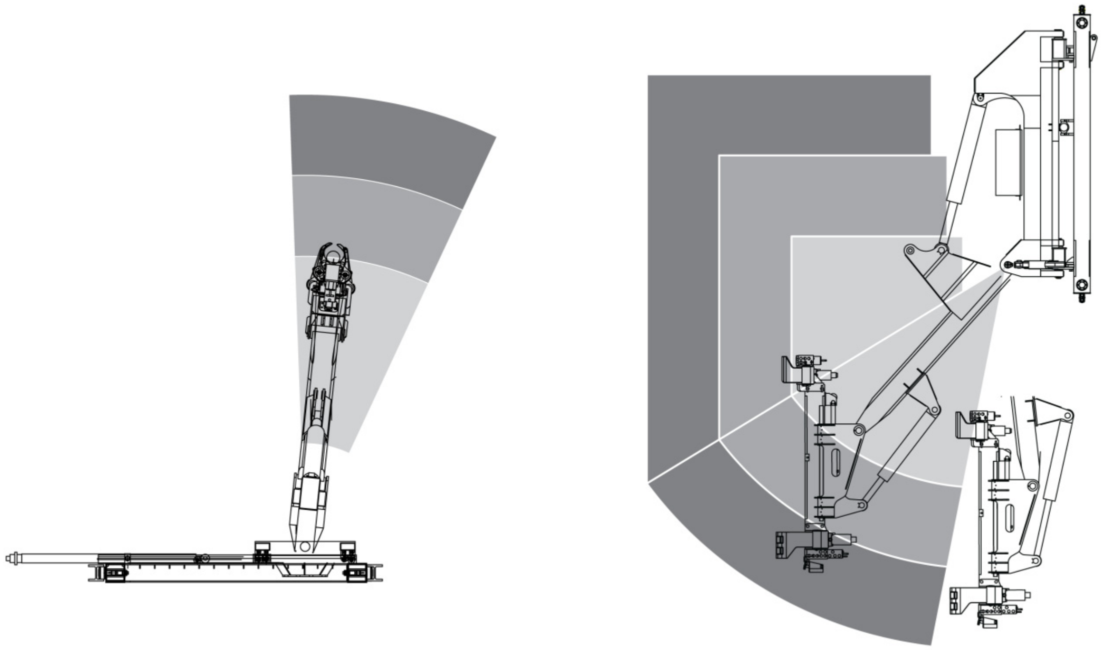


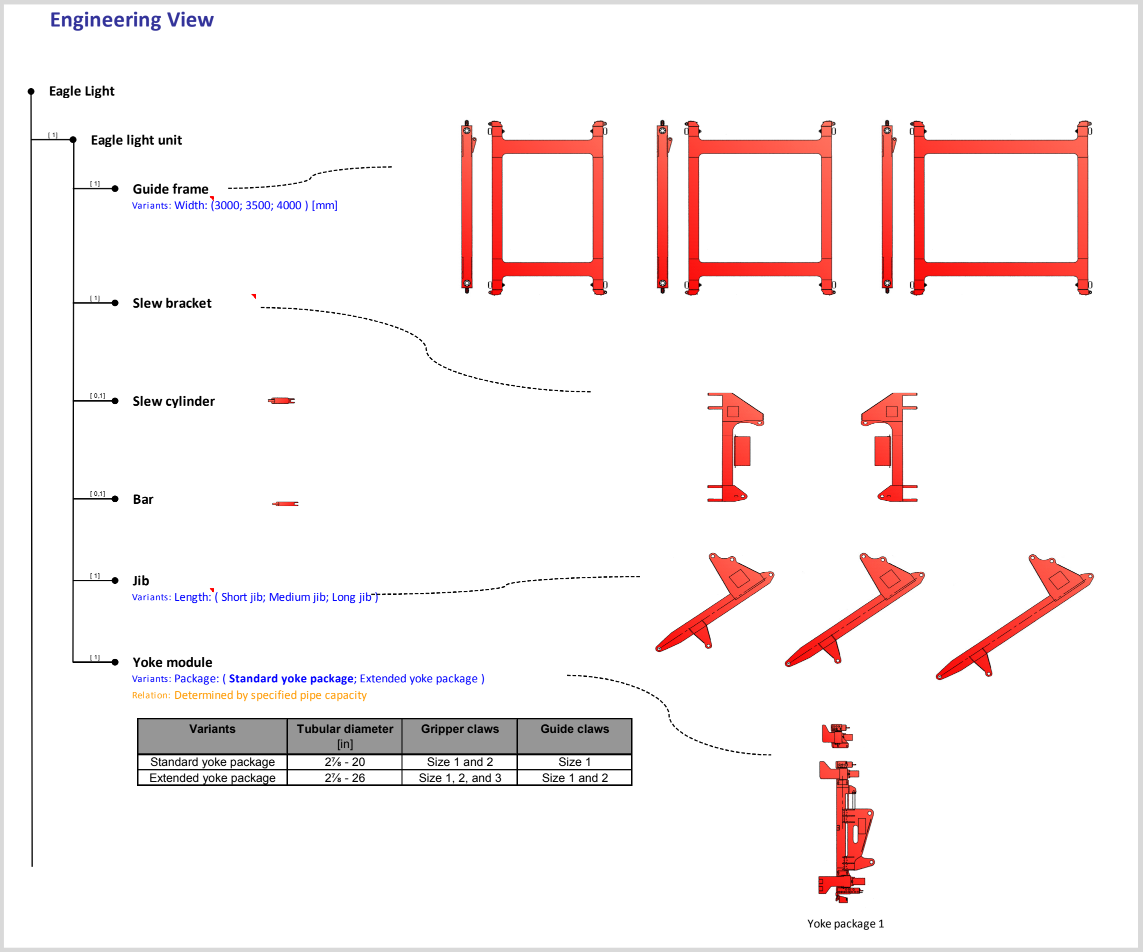
Figure 5.67: A principal representation of the three standard areas of operation for an Eagle Light. To the left a top view, to the right a side view.

Figure 5.67 is a top view of the eagle, in which the slew angle is shown. The slew angle is the same for all three variants, while the Jib comes in three standard lengths. These three areas of operation are shown as the three coloured areas. Notice that there is a minimum reach, i.e. that the coloured areas does not go all the way to the centre of rotation. This is a simple and visual way to represent the most important design limits of the Eagle Light platform.

The engineering view

The engineering view is a combination of the original engineering and part views from Harlou [2006]. Thus, the engineering view contains parts, yet they are formulated on a high level. Thus, the Part_of structure in the engineering view is not a bill of material in this case, but rather a representation of the physical *encapsulations of designs*.

A close-up of the engineering view reveals the different design encapsulations;



Variants	Tubular diameter [in]	Gripper claws	Guide claws
Standard yoke package	2⅞ - 20	Size 1 and 2	Size 1
Extended yoke package	2⅞ - 26	Size 1, 2, and 3	Size 1 and 2

Figure 5.68: A simplified version of the Eagle Light Engineering view. Constraints and design relations are deleted due to confidentiality. The three Jibs correspond to the three areas of operation in figure 5.67.

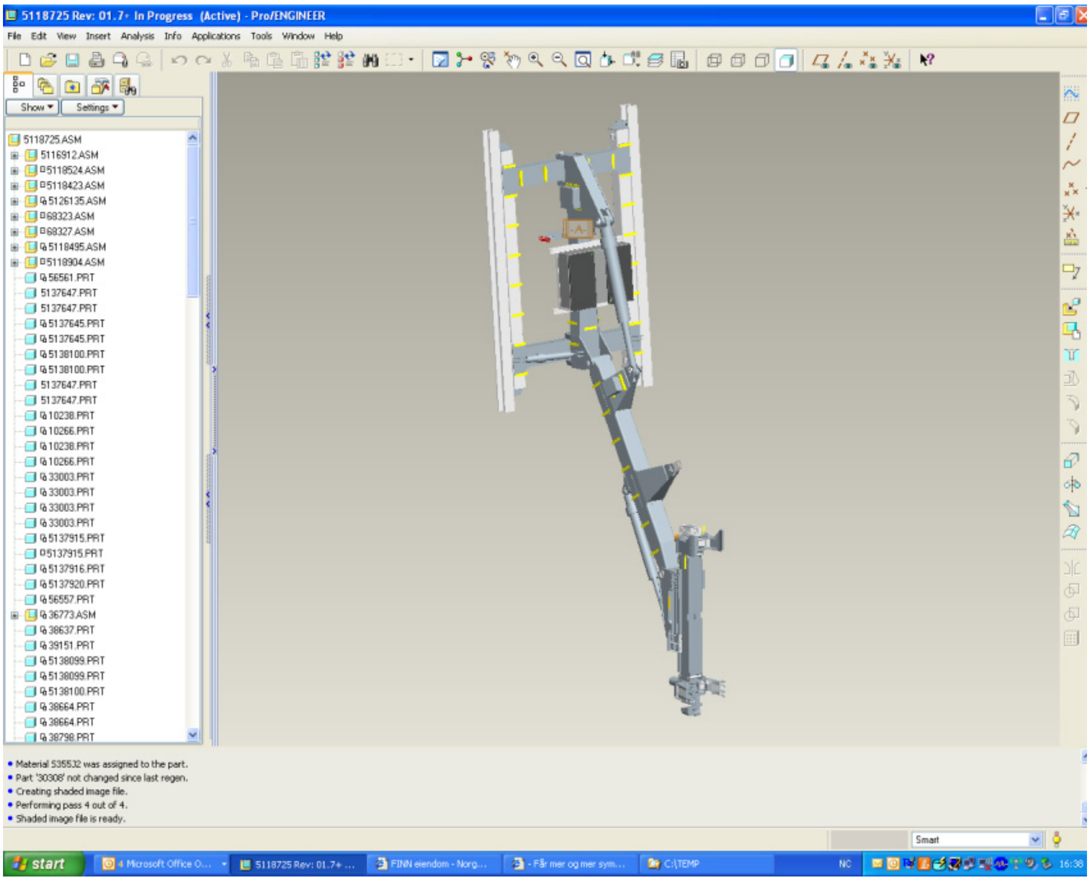
Figure 5.68 depicts a simplified version of the Eagle Light engineering view. Some of the details are left out due to confidentiality. However, the main concept in the engineering view is to depict the main design encapsulations, which corresponds to the main hierarchy of the skeleton models in the CAD system. In the figure, six main parts are shown in their main standard instantiations. These parts are the *Guide frame, Slew column, Slew bracket, Bar, Jib* and *Yoke*. The Kind_of structure is mainly a pictorial representation of different parts. Detailed information on the parts can be found in the attribute lists in the Part_of structure, someof which are deleted here for confidentiality reasons. The designers instantly recognise the different designs from the pictures. It gives them an overview of the different possibilities. Moreover, it makes it possible for non-designers – such as sales persons – to take part in discussions on how to change the designs in order to suit different customer needs.

In the older versions of the Eagle Light, these different parts have been designed in various different embodiments. Now, Aker Solutions, have decided to make (for now) three standard versions of the Guide frame, one standard version of the Slew bracket, three standard versions of the Jib and the two Yoke packages, all with standardised interfaces in between. From this set of standard designs, a large range of different Eagle Lights can be build. The Slew cylinder is used on either the left side or the right side of the Slew bracket in order to obtain a right hand or left hand side slew respectively. If a bar is placed instead of the cylinder, there is no slewing angle. This makes it possible to use the same slew bracket for Eagles with or without the slew possibility.

In order not to lose flexibility, Aker Solutions still maintains the ability to vary the dimensions on some of these parts outside the standard ranges. It is mainly the width of the guide frame and the length of the Jib. The width of the Guide Frame has to do with the design of the derrick and the transverse forces on the crane (the wider the Guide Frame, the larger possible moment). The length of the Jib has to do mainly with the reach, i.e. the range of operation. In the following chapter, an example of the variation of the Jib is given, during the explanation of the layout of the CAD models.

The Top Down CAD model

The Product Family Master Plan gives a rough overview of the various design encapsulations. The detailed design attributes are stored in various CAD models which are controlled by a series of *skeletons*. Figure 5.69 depicts an assembly instance of an Eagle Light.



- Material S355J2 was assigned to the part.
- Part '30308' not changed since last regen.
- Creating shaded image file.
- Performing pass 4 out of 4.
- Shaded image file is ready.

Figure 5.69: A CAD assembly of an Eagle Light in the CAD system (Pro/ENGINEER). The guide frames are attached to rails which are mounted on the derrick (the rig structure) .The Yoke is positioned in a near vertical position

Figure 5.69 depicts a base model from which different variants can be derived. The different parts and some of the attributes of the parts are inherited from a hierarchy of skeleton models. On a top level, a skeleton model controls the overall spatial relations between the main parts. Some of the parts have a skeleton of their own, in order to control variable and generic attributes.

The most important variable attributes are the sizes of grippers on the Yoke and the length of the Jib.

The Jib

Figure 5.70 gives an example of the Jib. The Jib is a single part in the CAD system.

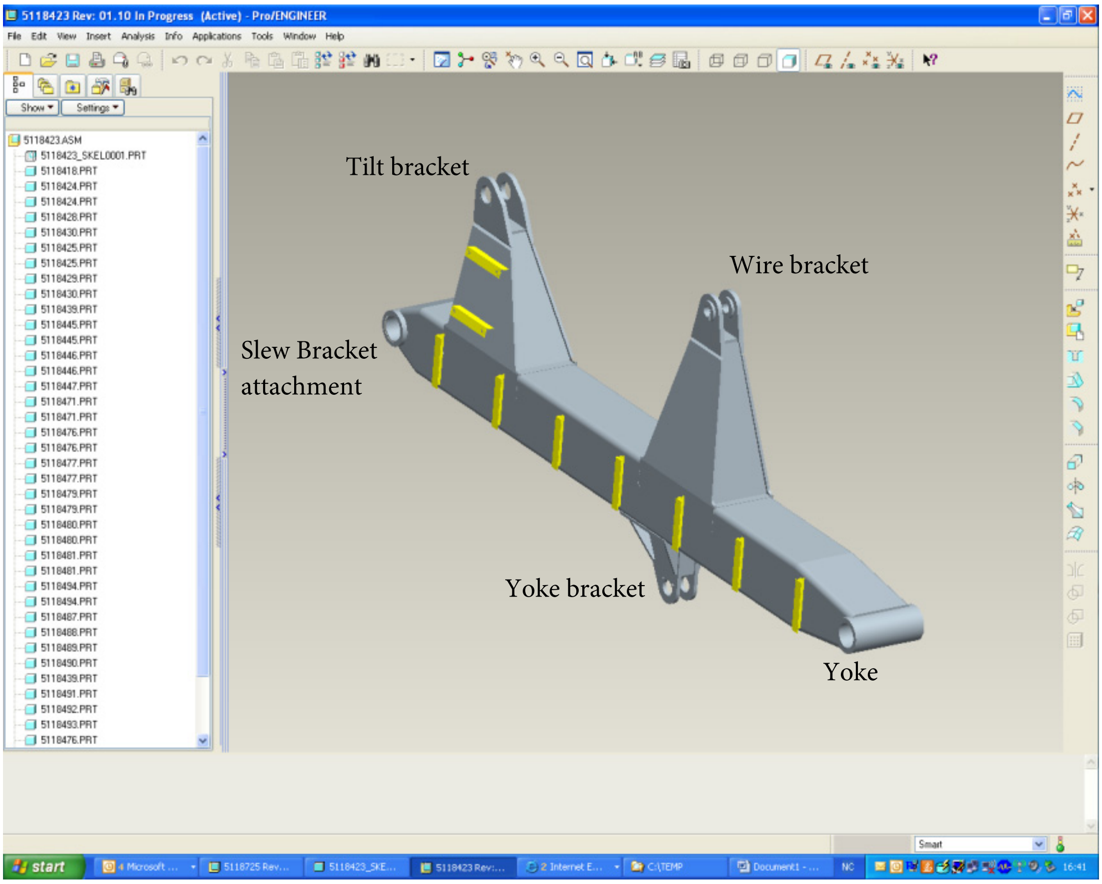
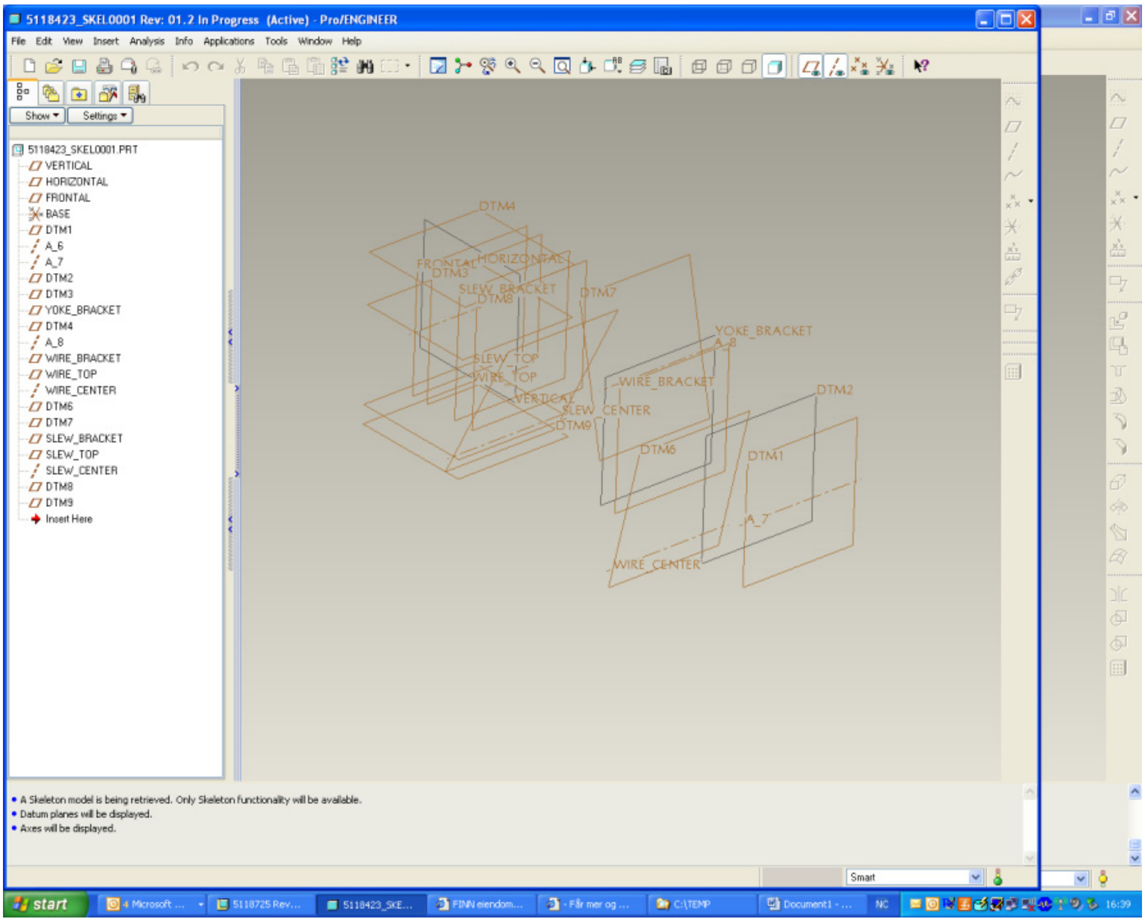


Figure 5.70: The Jib of an Eagle Light. The Jib is a part yet in the CAD system it is made up of various parts, which are controlled by a hierarchy of skeletons. The Part list is shown to the left. The Jib is characterised by various interfaces e.g. to the Yoke and Slew Bracket and to various hydraulic cylinders, and wires, which move the crane during operations.

The Jib in figure 5.70 is an important part in the Eagle Light. The length of the Jib has a major impact on the reach of the Eagle Light and thereby on the range of operation. Thus, the length of the Jib is often changed as a consequence of different customer requests. The Jib is designed as a CAD assembly of various parts. These parts represent different functional surfaces and features and their spatial relations and key attributes are controlled by the hierarchy of skeleton models. A view of the relations in a typical skeleton is shown in figure 5.71, in which a series of datum planes and axes, serves as the controlling relation between the functional features in the Jib. This particular skeleton controls the length of the jib, and the position of the wire bracket, yoke bracket and slew bracket relative to each other.



- A Skeleton model is being retrieved. Only Skeleton functionality will be available.
- Datum planes will be displayed.
- Axes will be displayed.

Figure 5.71: The skeleton which controls the position of the most important form features of the Jib. Notice that there are planes and axes.

Skeleton, family table and PFMP

A skeleton, a family table and a Product Family Master Plan are three different ways of modelling a product family. All of them have object oriented characteristics. The skeleton is a generic structure in which a series of alternative parts fit. The same applies for the family table, yet it is often on a part level rather than a parametric level. Finally, the PFMP itself, via the Part_of and Kind_of structures, is an object oriented approach.

In the Aker Solutions project, all three models have been used in interplay. The PFMP is the communication tool towards the organisation and internally in the project team, while the CAD models serve as the storage place for product details. It is in the CAD system the detailed attributes are varied and products are customised for certain customer needs.

5.7.6 Validating the work at Aker Solutions

In general, it is the impression of the management in Aker Solutions, that visual models have greatly improved the ability to gain and maintain an overview of the very complex products on a drilling rig. As of now, visual modelling and the Product Family Master Plan are used as a means to keep track on the product portfolio. Thus, from the reaction of both management and the stakeholders involved, they have clearly experienced an improved decision base.

The use of Product Family Master Plans in Aker Solutions has had a profound impact on the way product development is approached. It is an ongoing process to model all products in PFMPs in order to obtain a visual and easy accessible overview of the very complex product range. Over a period of two years, all important Aker Solutions products have been modelled in a Product Family Master Plan. The fit between CAD models and the PFMPs is also an ongoing process, yet the restructuring of thousands of CAD files is no easy task. However, Aker Solutions seem to benefit from some very professional CAD modellers and designers, during this process.

The visual modelling of design encapsulations has improved the ability to make decisions on the product portfolio and helped initiate a series of different standardisation project. It is now considered to be a strategically important part of the future trimming of the product portfolio.

Validating the decision base

As in the other two cases, the main source of validation comes from the reactions and statements of the employees in Aker Solutions, when they have been asked to assess the impact of visual modelling on their decision base. The general impression is that the visual models, i.e. the PFMPs have greatly improved the ability to make decisions about alternative design encapsulations in the totality of the product ranges. The fit between a CAD skeleton model and the PFMP has also made it possible to decide on characteristics that closely resemble that of both organ and part encapsulations. The skeleton is a generic structure, which makes it possible to reuse spatial relations and not just interfaces and parts. From a theoretical systems perspective, this resembles a reuse of the organ skeleton. From a practical viewpoint it is executed by means of a CAD skeleton (as long as the form features are closely linked to the functional wirk elements to the extent possible. See the discussion on form features and wirk elements in Part 4, chapter 4.5.3 and 4.5.4).

The employees at Aker Solutions have been relatively positive; however a true validation of the results is not possible to obtain under the limitation of the PhD project. The use of the PFMP has received extensive interest and funding by management in Aker Solutions and the methodologies are continued after the duration of this case project.

5.7.7 Concluding on the Aker Solutions case

Skeleton modelling

This case describes the use of a Product Family Master Plan as a visual model in interplay with a Top Down Design approach in a CAD system. The fact, that the PFMP gives a good overview of a product family is not a new finding. This has been reported extensively elsewhere [Harlou, 2006], [Kvist, 2009]. What is important to emphasise in this case, is the use of the PFMP together with the Top Down Design approach in the CAD system. The interesting finding here, is the ability to make the concept of an organ skeleton relatively concrete, by using a CAD skeleton. The CAD skeleton is used to manipulate form features, and the form features are designed to fit possible wirk elements. Thereby interfaces between parts and also important attributes of parts, can be controlled in a single generic hierarchy of product models.

> The use of skeletons has somewhat changed the perception of a product family in Aker Solutions from a set of discrete products, to a generic solution space from which entities can be derived.

The use of the Product Family Master Plan as a visual model has helped communicate the design limits of a product family, in order to avoid compromising the standards within the platform, when new designs are needed.

Decision making

The Product Family Master Plan now serves as an important means to support decision making in Aker Solutions. Over a period of two years, most of the important products in the product portfolio has been visualised in PFMPs. The posters are hanging on the wall in the office of a newly appointed portfolio manager, and are also found elsewhere in the organisation. These posters serve as a means of communication and a directory to more detailed information in various IT systems – and in particular in the CAD system.

It is the impression of the author, that the implementation of Product Family Master Plans has greatly supported the decision base in Aker Solutions. The company has a very complex product range with thousands of unknown factors in each drilling rig project. Still, it has been possible to visualise the most important attributes of the products and from this basis been able to reduce and manage product complexity.

5.8 Grundfos Technology Center

5.8.1 The role of the author

The author has participated in a joint research and consultancy project in Grundfos. Over a period of some eight months the author has been affiliated with the company. A part of the work has been published in a journal paper with colleagues [Mortensen et al, 2008b], and in a PhD thesis [Nielsen, 2009], yet with different emphasis on the empirical findings.

The author has been actively involved in a project team and with an active role in driving the changes in the company mainly together with two colleagues. The author has also taken part of the task of educating the employees in the project and providing a mindset of product platforms. Like in the case of Danfoss, this was considered necessary in order for the change process to occur, yet it is questionable from a research point of view, how this has influenced the validation of the work when asking the employees.

5.8.2 Introducing Grundfos Technology Center

Grundfos Technology Center is an internal provider of technical solutions and manufacturing equipment at *Grundfos*. Grundfos is a world leading pump manufacturer, with more than 10 million pump units sold on an annual basis. Grundfos employs some 13.000 people with revenues of roughly 13 billion Danish Kroner. Grundfos is renowned for its pump technology with circulator pumps, submersible pumps, and centrifugal pumps as the three major pump types. Grundfos is the world's largest manufacturer of circulator pumps with some 50 % of the world market.

Circulator pumps are used for heating, ventilation and air-conditioning in domestic houses, office buildings, hotels, etc. In industry, the pumps are used in different processes and for plant maintenance. In water supply and waste water applications, Grundfos offers a wide range of reliable pumps for irrigation, green houses and for municipal, private and industrial water supply, as well as sewage applications.

Grundfos Technology Center is an internal division within Grundfos. Grundfos Technology Center provides solutions and equipment to the factories of Grundfos, thus making manufacturing and testing equipment.

The injection moulding department

This project was carried out in the injection moulding department. Here, customised moulds for highly specialised heating pumps are designed and manufactured. Grundfos makes pumps for district heating purposes. The pump fit in a mainly gas driven heater unit for domestic purposes. These pumps are manufactured to OEMs (Original Equipment Manufacturer), i.e. customers, to whom Grundfos makes highly customised pumps and other pieces of equipment. These pieces are injection moulded using a certain composite compound.

5.8.3 The current challenges

Grundfos Technology Center manufactures injection moulding equipment for the factories in Grundfos. Changing demands and a pressure on price and lead time has forced the Technology Center to optimise their performance. They wish to cut down lead time and cost significantly in order to stay competitive towards the other divisions in Grundfos.

Thus, the current challenge is to develop and produce injection moulds faster and cheaper.

The moulds

It is difficult to show a picture of an injection mould, since the interesting part of a mould is in fact its cavities. Instead, the final products are good to take a look at, when looking at the functionalities of the injection moulds. In figure 5.72 three different typical products are shown. Each product has its own specific mould.

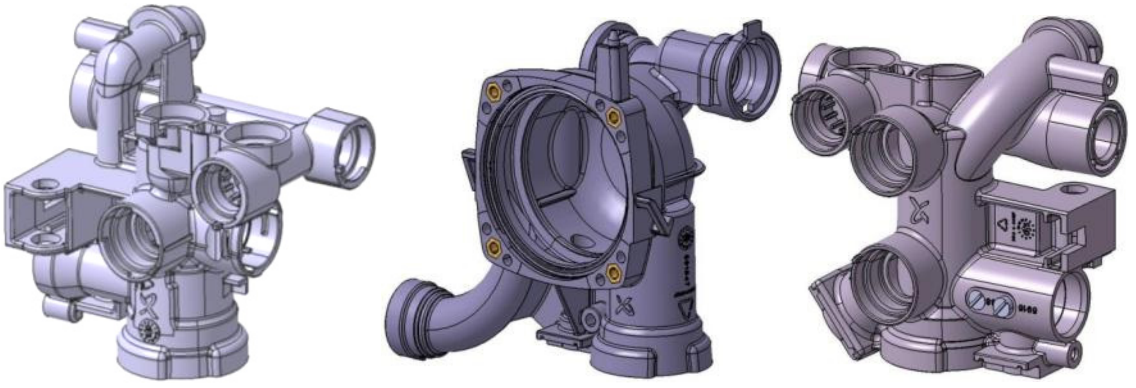


Figure 5.72: Three different moulding jobs for district heating applications. Only the middle one is for a pump. The other two are for various flow direction changes, and control applications within the heating unit.

Each of the products in figure 5.72 is moulded in one shot in a single mould (that is, one mould for each product). The injection moulds consist of two halves, which are pulled apart when the mould opens. In order to make the various connections and shapes in the products in figure 5.72, a series of retractable inserts are needed. The inserts are needed because the connections do not match the opening direction of the mould. Each connection on the products (the circular and cylindrical shapes) is more or less a standard connection like an M10 thread or a certain bayonet connection. However, the connections are placed in various different positions each time, and therefore the different mechanisms in the mould are different from variant to variant. Notice the bottom cylindrical geometry of each of the products in figure 5.72. That is the same type of connection on all three.

Grundfos has a desire to increase the level of design reuse in order to increase efficiency. Due to the highly specialised designs, features in the moulding equipment are somewhat *hand crafted* in the CAD system by different design engineers who, rather than searching for older designs, make their own designs, because they feel that it is safer, and more customised. When they do not trust the source, or know the design rationale behind an older version of a feature, it is safer to make a new one. Therefore, the design engineers spend a significant amount of time making almost identical geometries in different products.

This was basically the starting point of a platform project in Grundfos Technology Center. The challenge was to somehow bring down the resources spent on each mould, and reduce the lead time.

5.8.4 Changing the state of Grundfos

Clarifying the problem

In order to clarify the problems a series of subsystems in the moulds were analysed. The variation of the subsystems, the reasons for variations and the current design processes, along with the co-operation with the customers of the Technology Center (that is, other design departments within Grundfos) was analysed. As an example of this work, one of the subsystems is discussed in the following. It is the so-called collapsible core. The collapsible core is one of seven different subsystems that were part of the project. However, the challenges and changes are very similar in the seven cases. Therefore, only the collapsible core is used as an example in this thesis.

The collapsible core is used to mould the interior of a pump house. The pump house and the collapsible core are shown in figure 5.73;

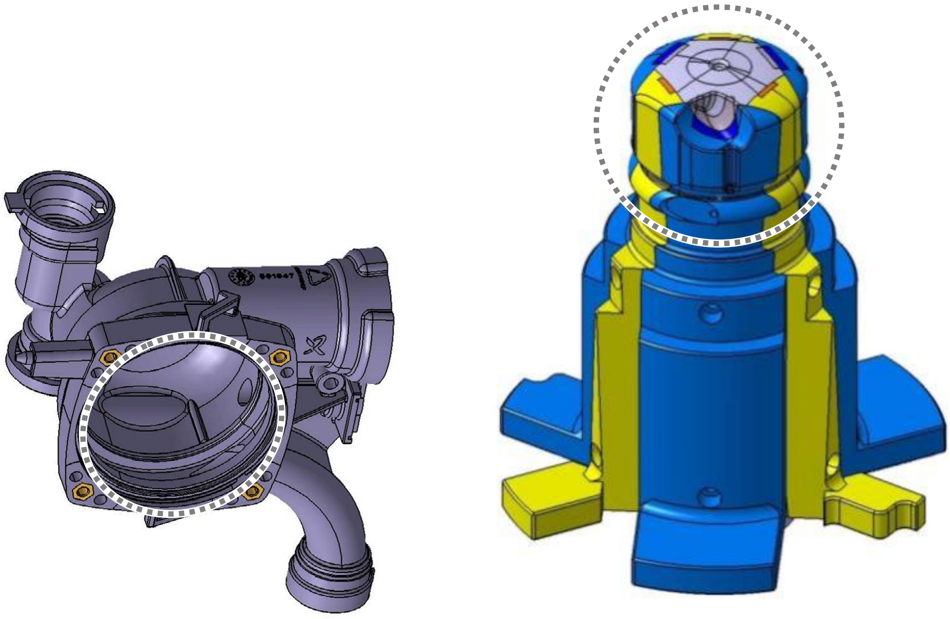


Figure 5.73: The inner geometry of the pump housing to the left is made by means of the collapsible core to the right. The top of the core serves as a mould insert.

Figure 5.74 depicts a cross section of a pump housing and a corresponding collapsible core. Notice the undercuts. They make it difficult to retract the moulding insert after moulding, because a smaller diameter is behind the insert in the pull direction.

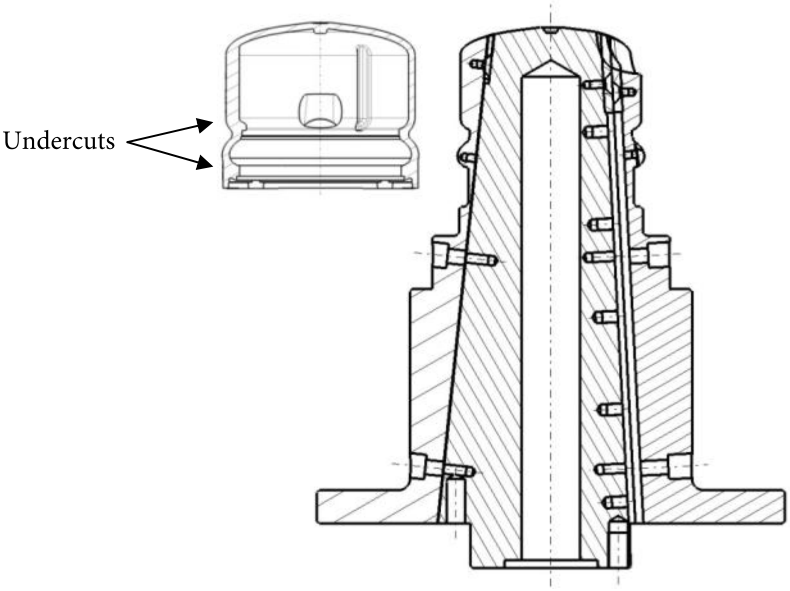


Figure 5.74: A cross section of a pump housing in the upper left and a cross section of the corresponding collapsible core. The collapsible core makes the inner geometry of the pump housing during the moulding process. Notice the undercuts in the pump housing. They make it difficult to retract the insert after moulding, which is why the collapsible principle is needed.

In order to be able to separate the mould without breaking apart the pump housing, the diameter of the collapsible core has to be decreased when the mould opens, so that the insert (the collapsible core) may pass the undercuts. This is the reasons for the *collapsible principle*. Figure 5.75 depicts the principle of collapse;

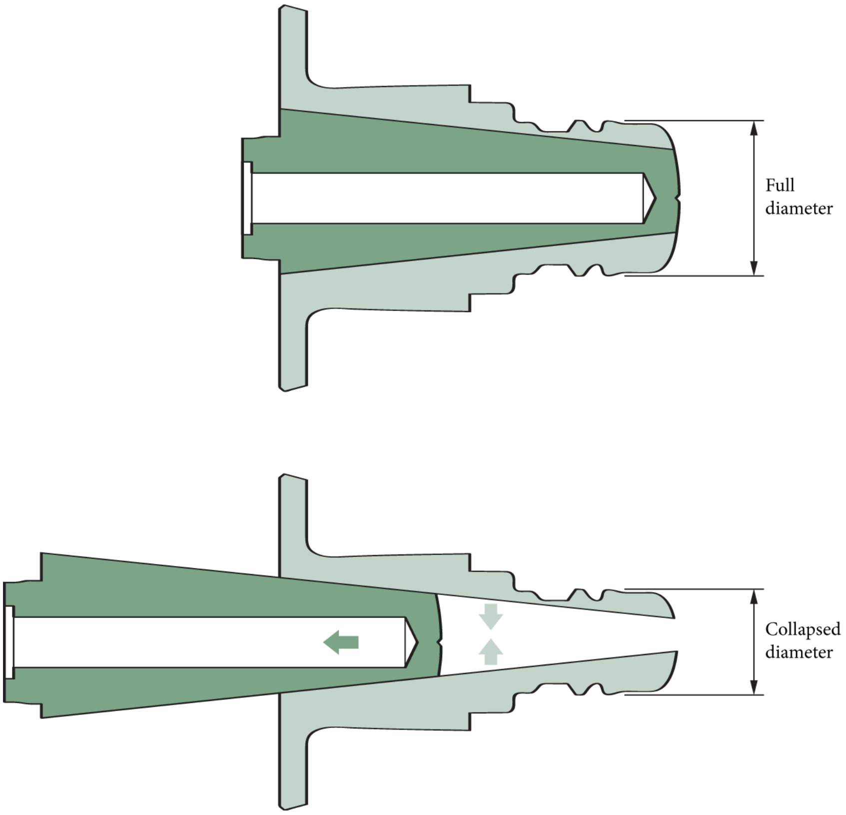
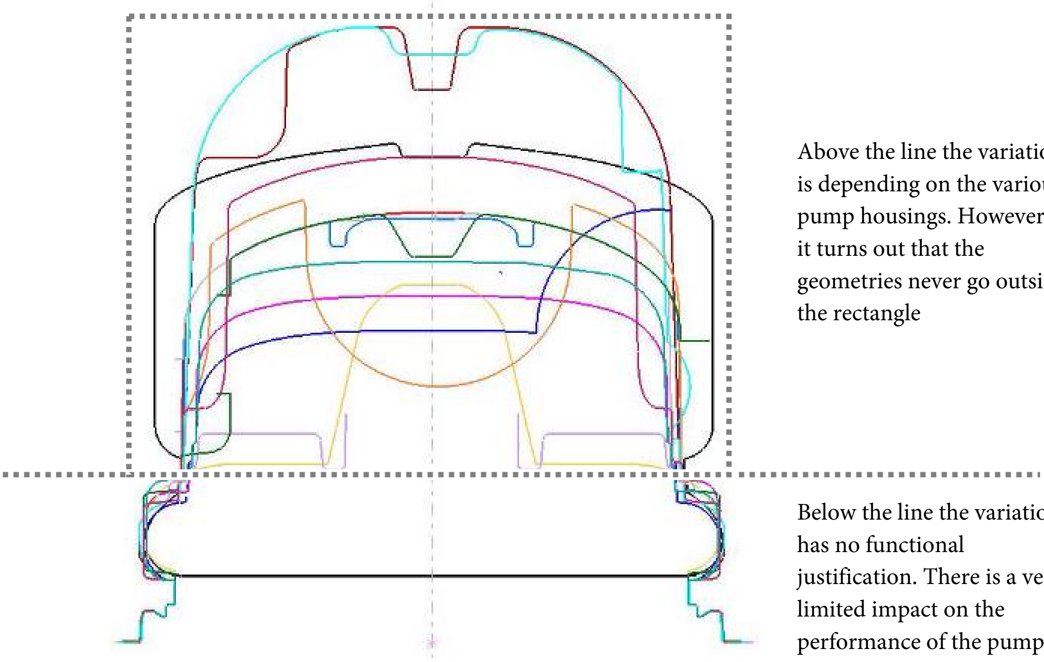


Figure 5.75: The principles of the collapsible core. A pyramid shaped centre part is retracted and the so-called segments are allowed to retract into each other thereby reducing the largest diameter of the core. Then, the core and segments can be retracted from the pump housing after the composite has hardened in the mould. The segments are inclined with two different angles, allowing them to slip underneath each other. Otherwise the periphery of the segments would collide.

The collapsible core principle is a well known way to allow undercuts to be moulded, and was introduced in the early 1980'ies, but has only recently received wide attention in industry [Jiao & Teo, 2004]. Before the collapsible principle was used in the injection moulding industry, a post process was often used to make the undercuts, as a fabrication process, such as a CNC lathe. Clearly, the one step process offered by the collapsible core is a major advantage.

Generic and variable properties

When analysing the past designs of collapsible cores, it turned out that many variations are present due to a lack of communication or design engineers sub optimising their designs, as discussed earlier. In order to highlight this, a very simple visual model was made. It depicts the cross section of collapsible cores from some ten representative designs. Figure 5.76 depicts the functional surfaces on the collapsible cores;



Above the line the variation is depending on the various pump housings. However, it turns out that the geometries never go outside the rectangle

Below the line the variation has no functional justification. There is a very limited impact on the performance of the pump.

Figure 5.76: A cross section of ten different collapsible cores. It is clear that beneath a certain line the variation is very limited, yet there is still variation. When the design engineers saw this visual model, they realised that there was a significant potential for standardisation of the geometry below the line.

Figure 5.76 is a very good example of the present challenges in Grundfos. All the ten collapsible cores are different, yet from the visual model above it became clear to the design engineers that the cores could have shared a large proportion of the geometry, and could have been made from the same basis. However, each collapsible core is different, and the variation below the line is enough to make a whole new chain of tolerances, new NC codes for the milling fabrication machines, new part IC numbers in the production etc.

Communicating with the customer

The customers of the Technology Center are in fact other divisions within Grundfos. The design of the mould is eventually decided by the design of the pump houses. The Technology Center delivers the moulds to the department in charge of designing the pump houses, and the moulds are then installed in the factories.

A lot of the variation below the line in figure 5.76 arose from the pump housing designers. Due to a high focus on customisation, the impact of the changes on the lead time and cost of the injection moulds were not clearly investigated and communicated in the organisation. During the project, the pump housing designers – i.e. the customers of the Technology Center – were asked whether it was possible to standardise the geometries slightly and stay within a certain set of parameters, and it turned out to be possible. Thus, by questioning the next step in the value chain, it turned out that some of the challenges in figure 5.76 were relatively easily overcome. Figure 5.76 was the main means of communication in this discussion, and despite the very simple layout it had a profound impact.

Small product changes to the pump housings becoming a large problem later in the value chain, turned out to be one of the core issues to solve in the project. In order to visualise this problem, another model was made in addition to the one above. It was deemed *The Snowball Effect* and was used to highlight the problem of small changes in the product creating large changes later on. It is in fact a visualisation of the Theory of Dispositions ([Olesen, 1992], see Part 3 chapter 3.2.4) in a Grundfos context. Figure 5.77 depicts the snowball effect;

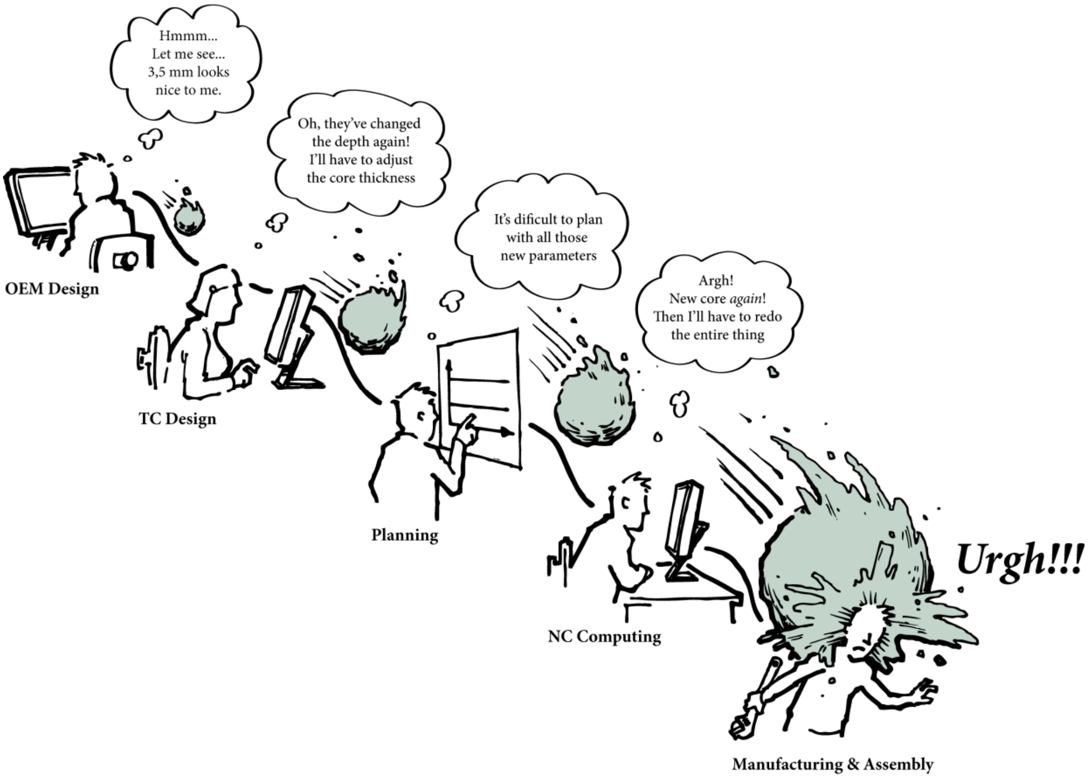


Figure 5.77: The Snowball Effect. The cartoon depicts the effects induced by a small and simple change in the CAD model of the pump. The pump designer (in OEM design) to the left makes a small change within a few seconds. The Technology Center designer (TC Design), has to change the collapsible core accordingly and spend some hours checking the design. The planner in the production has to take into account the risk of a new design and spend half a day's work on planning the mould. The programmer of the milling machine has to make a new program and spend a whole day on that. Finally the small change makes the staff in the factory spend weeks on manufacturing and assembling a new collapsible core.

Changing the state

It turned out that many of the above challenges could be overcome by deciding on certain parameters, lock the parameters within certain ranges, and then make these decisions propagate throughout the value chain in order to "stop the snowball from rolling". There was no real need for big design changes. The key was to let certain parts of the collapsible core vary and certain parts of the collapsible core stay constant, i.e. *grouping and decoupling into a generic and variable proportion*. Once that was done, it also became possible to separate the activities into a preparation and execution phase, i.e. encapsulation of activities.

These two processes are elaborated in the following.

Organ encapsulation

This grouping and decoupling was essentially – from a constitutive point of view – *organ encapsulation*. The primary function of the collapsible core is to create an inner surface in the mould cavity, comprising the inner geometries of the pump housing. The cavity of the mould may be seen as an organ made up of wirk surfaces and a wirk volume. From that perspective, the collapsible core hosts a wirk surface. Various wirk surfaces are represented by the 10 cross sections in figure 5.76. Thus, the wirk surfaces have to be grouped into *variable* and *generic* wirk surfaces, and somehow decoupled in order to easily change the variable surfaces and keep the generic surfaces unchanged. This decoupling was not taking place by means of classic modularisation. Using Ulrich's terminology [Ulrich, 1995], the collapsible core is a highly integrated product, and the wirk surface spans several parts within the collapsible core – see figure 5.78.

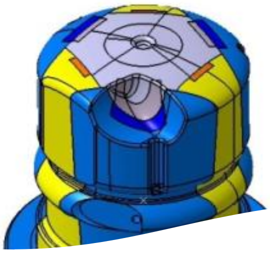


Figure 5.78: The top of the collapsible core is a wirk surface, which is part of the moulding organ, i.e. the cavity within the mould. The wirk surface is distributed over 14 different parts (including the guides between the pyramid and the segments, the ends of which are seen as the small rectangles on the top surface).The wirk surface is different in all moulds, however, constant below a certain level.

As it is discussed in Part 4, the decoupling of organs is mainly achieved by means of *process flexibility and not assembly flexibility*. The collapsible core is an example of this and as such equivalent to the key example in Part 4, chapter 4.5.3, figure 4.11. For the purpose of decoupling variable and generic surfaces on the top of the core, there is *no decoupling in the part domain*. Instead, if the cavity is seen as an organ and the top surface of the collapsible core is seen as a wirk surface, *the challenge is to decouple organs*. Due to the collapsible core design, it was out of the question to make a physical interface in the parts domain between the variable and generic part of the core. Therefore the decoupling had to take place mainly by means of process flexibility in the fabrication. It has been stressed (in Part 4) that *decoupling* of parts and organs is about being able to change attributes without the changes propagating to other areas (parts of organs).

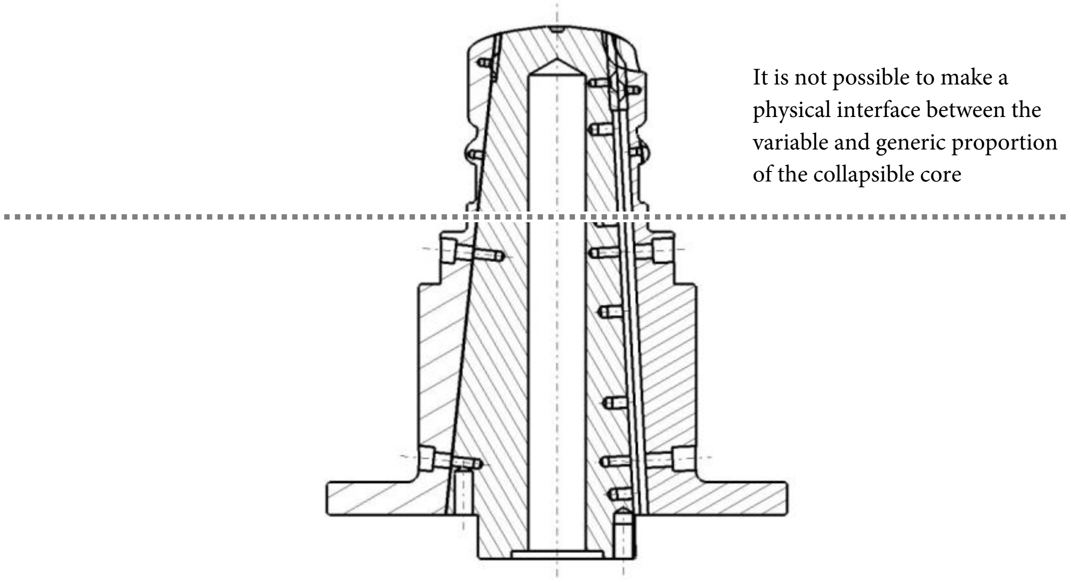

It is not possible to make a physical interface between the variable and generic proportion of the collapsible core

Figure 5.79: The generic and variable wirk surfaces on the collapsible core cannot be decoupled by means of a physical interface in the part domain along the line. Therefore decoupling has to take place in the organ domain by means of process flexibility, i.e. that one wirk surface can be changed while other wirk surfaces are held constant.

Part encapsulation and organ encapsulation

The example of organ encapsulation above was not the only structuring principle of in the Grundfos case. If the mould is seen as a whole, each subsystem may be perceived as physical modules, i.e. as encapsulated units in the part domain. Thus, a conclusion to draw from the Grundfos case is that platforms may be a combination of organ and part encapsulation and that these different structuring principles may be found on several levels of decomposition.

Activity encapsulation

The clear splits between variable and generic attributes of the collapsible core also opened the opportunity for encapsulating activities – both in development, fabrication and assembly – and make a split between preparation and execution tasks.

In the original setup, a large part of the mould design and manufacturing processes were awaiting the final design of the pump house. However, with a clear split between generic and variable attributes, and with the confidence that the collapsible cores rarely went outside the rectangle marked in figure 5.76, it was eventually possible to initiate some of the demanding process steps before the last details of the design were known.

The fundamental concept was to make a semi-manufactured part, i.e. a basis part almost finished, yet without the last customised details. This part is independent of the final pump design, as long as the pump design stays within a set of known design rules (represented by the rectangle in figure 5.76). The standard collapsible core is then put on the shelf until the final geometry is known, and then it is possible to make the final execution steps.

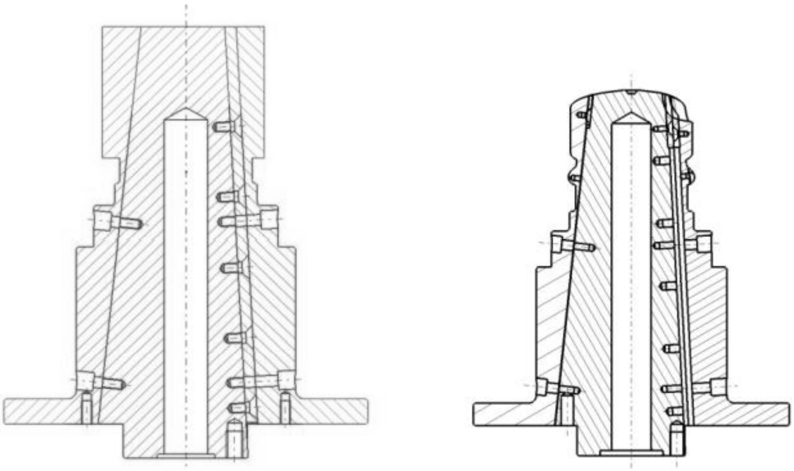


Figure 5.80: The semi-manufactured result of the preparation phase to the left, and a finished collapsible core to the right. The part to the left was called the platform by the employees in Grundfos. Notice that the standard part to the left has excess material making it possible to manufacture all the different cross sections in figure 5.76 - and expected future designs, which are even taller.

This process setup makes it possible to encapsulate a whole series of activities into a preparation phase, and to postpone another set of activities until the final geometries are known. This is essentially postponement, and the points of variegation are sought to be postponed until the final details are known, i.e. until the final order decoupling point (see Part 4, Chapter 4.6.2 for more on postponement). The postponement of activities and the preparation – execution split is shown in figure 5.81, which is a visual model used during the project to depict the activities as a part of the platform.

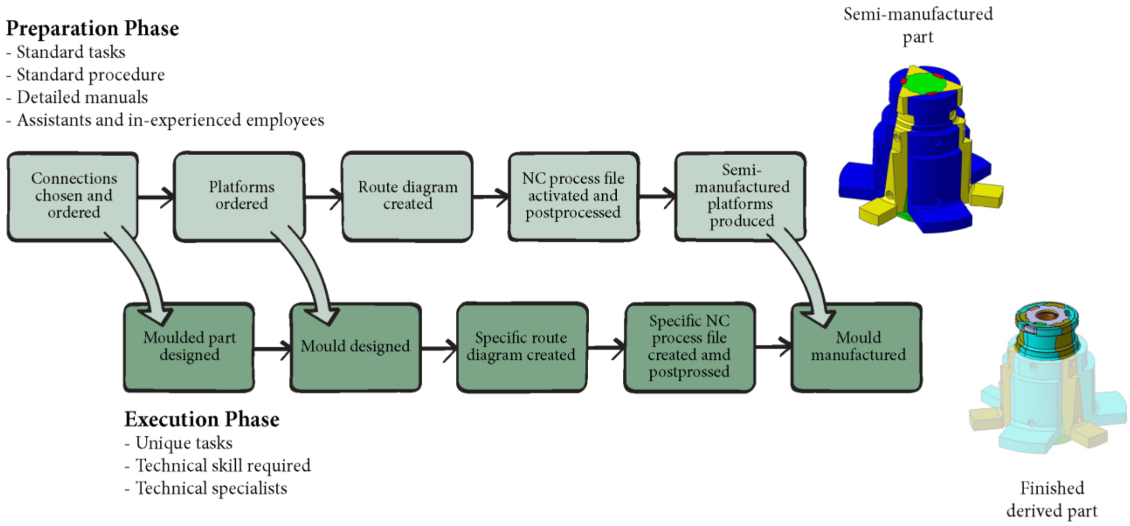


Figure 5.81: A visual model of the activities in developing and producing a collapsible core. The activities are separated into a preparation and an execution phase.

Changing the critical path

One of the main drivers for the encapsulation of activities was to decouple some of the process steps with a long lead time from the critical path. This essentially reduced reduce the bottle necks in the overall lead time. Some of the processes used to manufacture the collapsible core were independent of the final geometry, and in the old setup on the critical path. By encapsulating the generic design and making a corresponding encapsulation of process steps, these long lasting processes were removed from the critical path.

In order to visualise the opportunities with a more prepared setup, a visual model of the activities in the development and production of the pump housing and moulds were setup. Figure 5.82 depicts the old and the new process from order to delivery of the mould, with an indication of the reduction in lead time. The proportions match the actual lead time reductions for the collapsible core. Notice that some of it has to do with shorter steps due to reuse (of well known solutions, tools, and software codes) while some of the reduction has to do with paralleled activities. Hence the two grey arrows represent the lead time and resource allocation differences respectively.

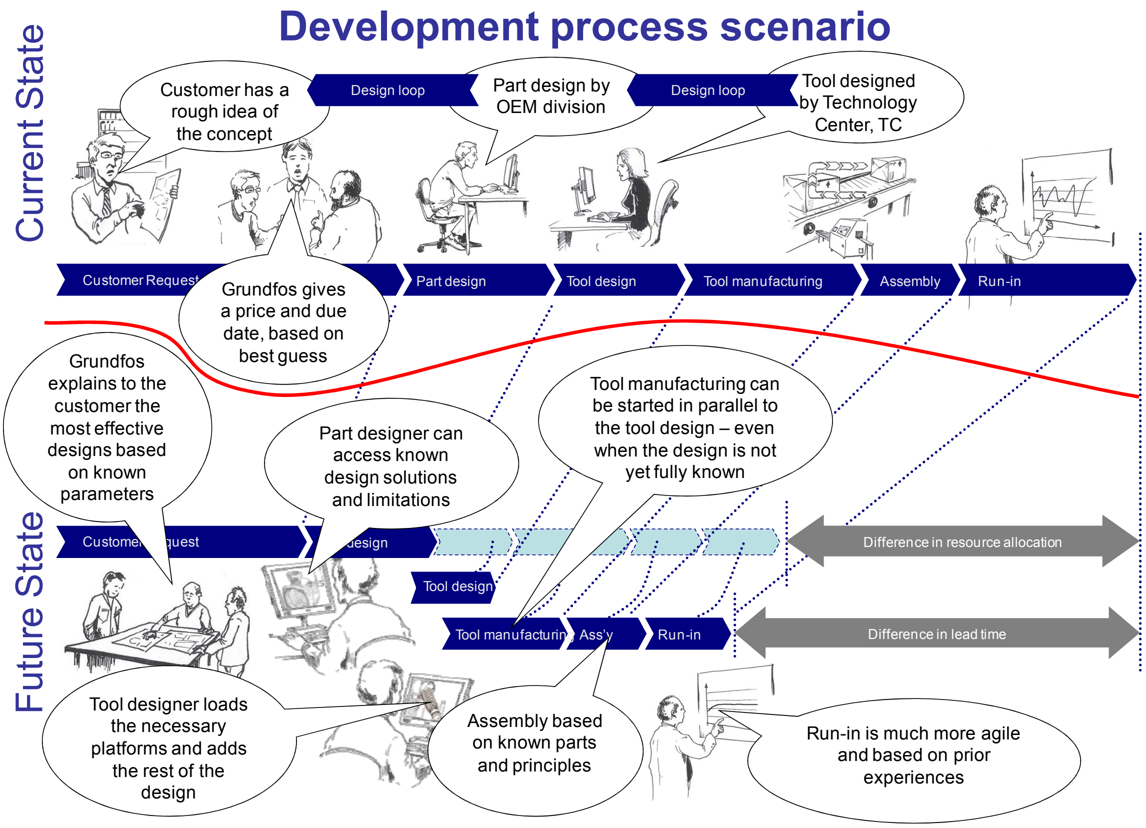


Figure 5.82: A scenario for the improvement in lead time, based on reductions in lead time of the single phases and the fact that some of the phases can be paralleled due to reuse and preparation.

5.8.5 Modelling the platform

The Product Family Master Plan

The Product Family Master Plan (PFMP) was chosen as the main media to model the platform. The PFMP format was chosen because of the ability to make an object oriented model, i.e. the possibility to map generic and variable attributes in the same visual model. During the project, the PFMP evolved to include more information than just on the physical parts and components, and the format had to be changed accordingly. This change is a consequence of perceiving the *software* and *activities* as a part of the platform. These different parts of the model are elaborated in the following.

A copy of the whole Product Family Master Plan is shown in figure 5.83. The original poster is 1,5 metres tall and some 3 metres wide. The collapsible core is modelled in the area marked with a rectangle.

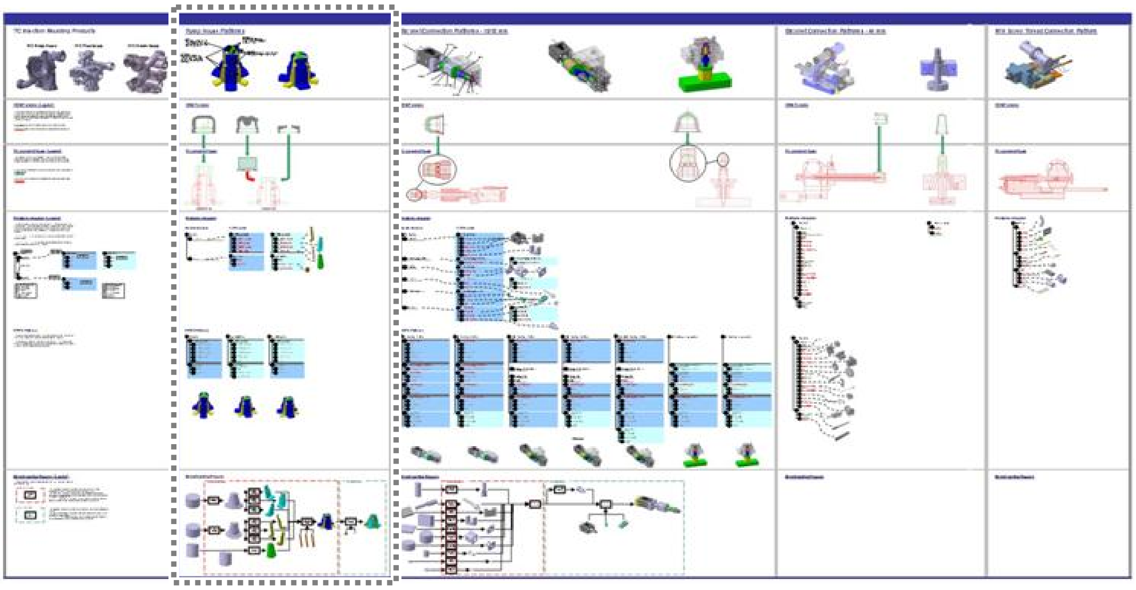


Figure 5.83: The Product Family Master Plan from Grundfos Technology Center. A series of seven sub systems in the mould were modelled visually in the PFMP. The dashed area is enlarged in the following figure (5.84).

Each column in the PFMP represents a sub system, that is, a connection type of certain geometry. In figure 5.83 the collapsible core is shown with subsystems for bayonet connections and thread connections in different diameters. These subsystems were eventually called *platforms* in Grundfos, and the PMFP includes a visual model of the required geometry, a cross section of the subsystems representing generic and variable attributes, a model of the ERP information on the subsystem, a model of the PDM system bill of materials and finally a model of the process activities in the manufacturing setup.

The marked column in figure 5.83 is the model of the collapsible core. This part of the PFMP is explained in the following and is used as an example of how the PFMP is built.

Modelling the collapsible core

The model of the collapsible core is shown in figure5.84. The different parts of the model (1 through 6) are explained in the following.

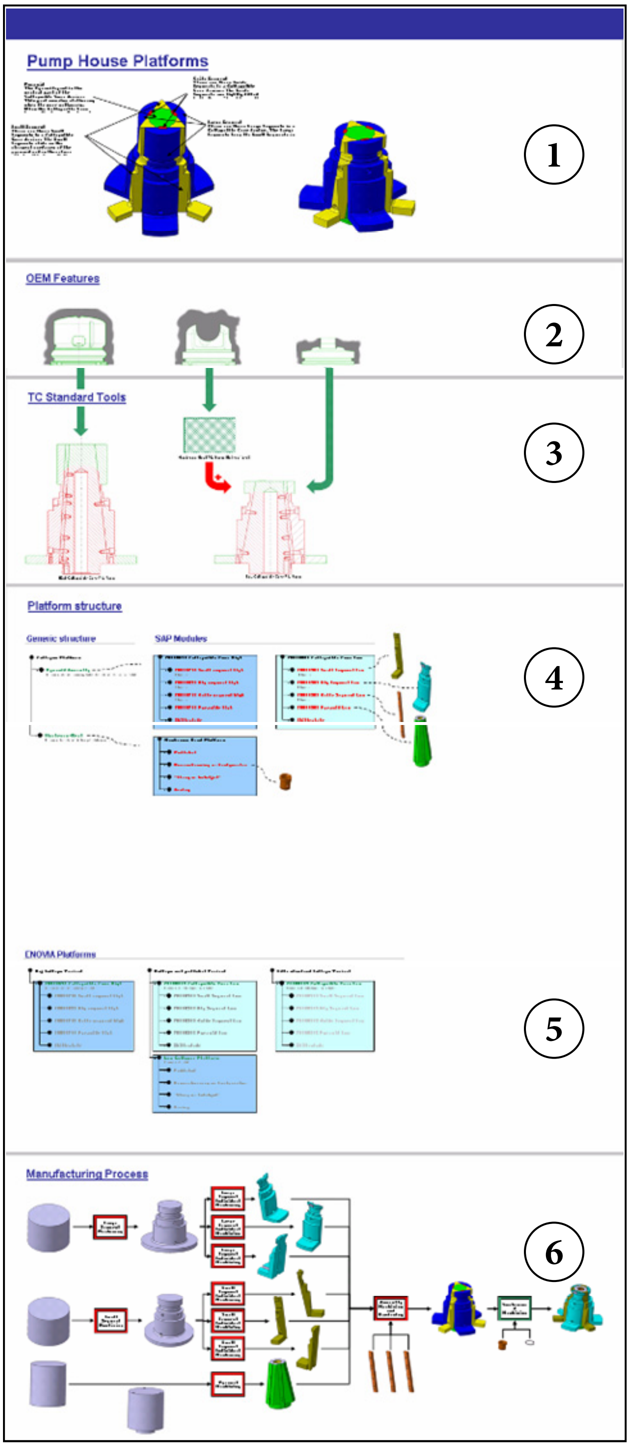


Figure 5.84: The platform model of a collapsible core; (1) A general description of the collapsible core, (2) a cross section of the inner geometry of the pump house, called the OEM Feature because the OEM design department makes the pump design, (3) a cross section of the standardised semi-manufactured collapsible core, (4) a visual representation of the standardised Bills of material in the ERP system, (5) a visual representation of the Bills of material in the PDM system (ENOVIA) (6) a visual representation of the manufacturing process.(Parts of this model has been published in the Int. J. of Mass Customization, [Mortensen et al., 2008b]).

(1) General description of the collapsible core

This section is basically an illustration explaining the most important design principles by word and by means of a drawing. The drawing may seem obvious for most of the design engineers involved in the project. However, it proved useful as a communicative tool towards external stakeholders in the organisation, to whom the details of the collapsible core were not necessarily well known.

Due to confidentiality the picture and the description is not further elaborated.

(2) OEM features and the standard collapsible core

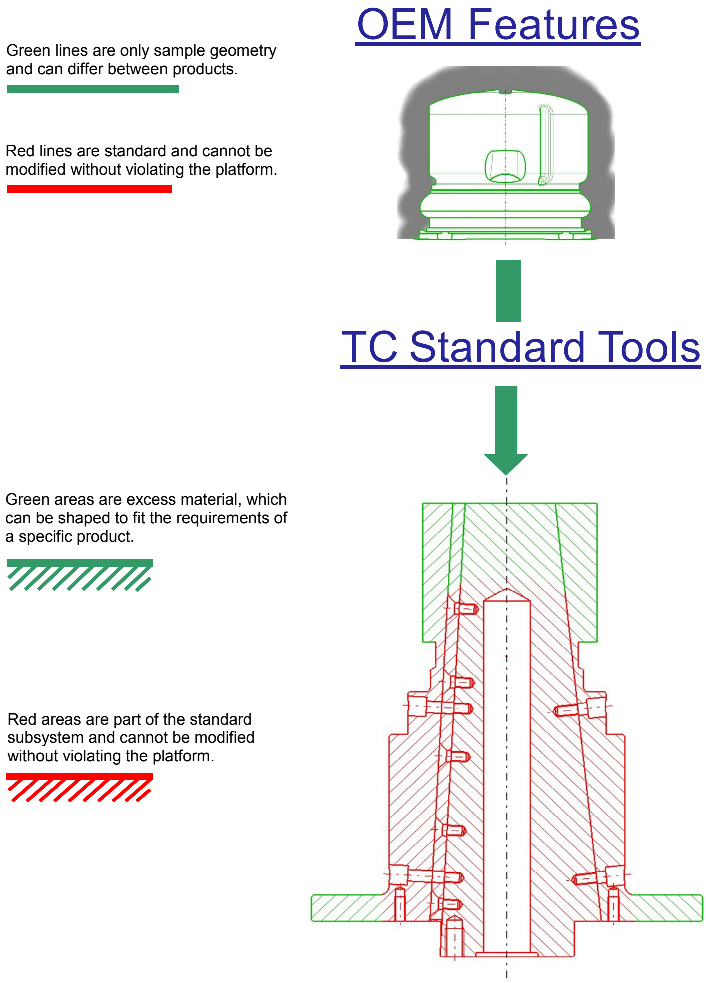


Figure 5.85: Detail from the PFMP; An illustration of the semi-manufactured collapsible core and the design degrees of freedom. Notice the red and green areas of the cross sections. They represent the generic and variable surfaces.

Figure 5.85 depicts the middle part of the PFMP in which two cross sections are shown. Like in the Danfoss case, the cross sections are used as simple yet informative visualisations of the design requirements. In this case, the desired functional surface (wirk surface) is shown as the *OEM Feature*, represented by the inner geometry of a pump house. The semi-manufactured collapsible core is shown underneath.

Using colours to visualise generic and variable attributes

Notice the colour codes, and the legend to the left. Using a traffic light analogy, green colours are the attributes/surfaces that the designers may change freely, while red areas depict standardised surfaces that are kept constant in the platform. The whole shape of the inner geometry is free for the designer to change and is therefore green. (The reason to have the red line legend in the top left is that some of the other connections and subsystems in the PFMP had designs that were partially locked, and their illustrations are red and green, and not just green.

The corresponding collapsible core underneath has both generic and variable attributes. The illustration in figure 5.85 shows the areas in which the designers are free to change the functional surfaces and the areas (or rather volumes) in which the designers are not allowed to freely change the geometry.

This particular drawing and the concept of *red and green areas*, turned out to become an important part of the platform perception in Grundfos. It is very simple yet with a profound impact. The concept of generic and variable attributes was coined by the expression *red & green areas,* and this became the paraphrase of choice when the designers communicated about the platform during the project.

(4) ERP system bills of material

The ERP system (Enterprise Resource Planning) is used to keep track on processes and the orders of parts in various production steps. The ERP system is a production planning system. When the designers in the pump design department (OEM) know that a new pump housing is on the way, they can order a collapsible core platform, as seen in the preparation/execution model in figure 5.81. When ordering the platform, the SAP ID code is activated and a set of routines is started. These routines are assigned to a SAP bill of material. Each collapsible core was therefore assigned to a standard bill of material in SAP, and this bill of material was modelled visually in the PFMP in order for the designers and planners to have an overview and a common understanding of the information in the ERP system.

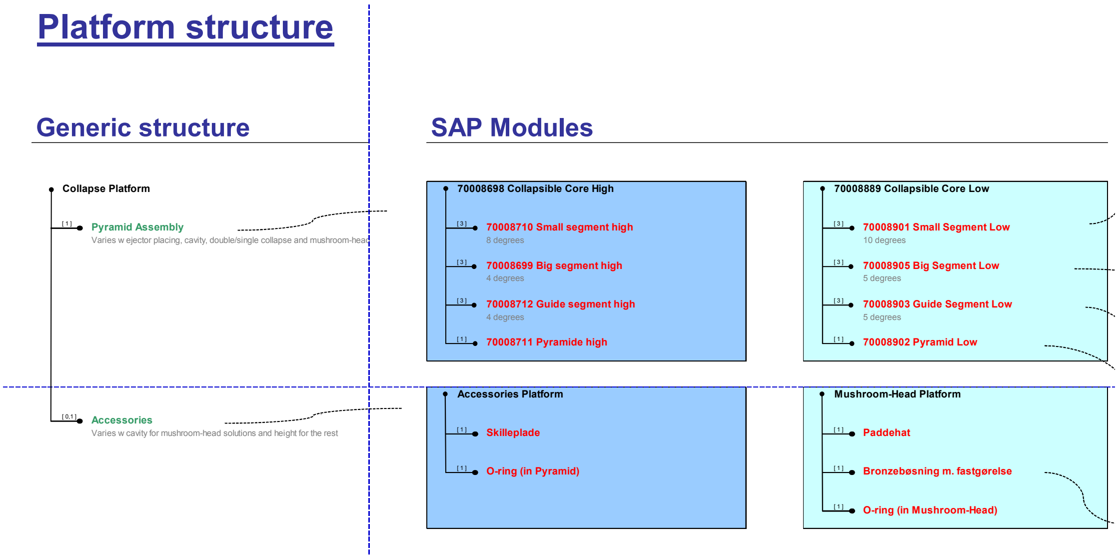


Figure 5.86: A detail from the PFMP; A visual model of the bill of material for the ERP system (SAP). Each part is written with a description and a code ID making it possible to search for that particular part in SAP.

Figure 5.86 depicts the visual model of the generic bill of material in SAP. The mode contains the *high* and *low* collapsible cores as two variants of the same structure. The PFMP notation (see chapter 5.3.4) is used with the Part_of (to the left) and Kind_of (to the right) structures. The modelling object here is not the actual parts but the SAP-ID's. It means that figure 5.86 is a model the order bundles in SAP. If a *70008698 Collapsible Core High* is ordered, a group of parts is ordered including the right amount of segments, pyramids, etc. The colour codes red and green are also used in this model. The letters in the two kind_if structures in the right part of the figure are red to illustrate, that they are standard and cannot be changed. Each ID code represents a standard part of the platform. However, once, the standard part is used in the execution phase, the whole assembly is changed and therefore the Part_of structure is green, since the *Pyramid assembly* as a whole unit is changed in the execution phase (see the process in step 6 in the following).

The visual model also helps to communicate the naming convention. There had been a problem earlier with classification of components and names. Some part names are in Danish, some in English, some of them were written in CamelCase, (InWhichTheSentenceIsSubtractedLikeThis), some were written in abbreviations (Like this; *Collpsbl. core H* meaning *Collapsible Core High*) etc., making searching and reuse of design solutions very difficult. The PFMP helps to establish a naming convention for components. Moreover, the parts are no longer classified by their name, but by their place in the Part_of structure.

(5) PDM system bills of material

The PDM system (ENOVIA) is used to control the information about the products, such as various documents and also the location of CAD files. In the PDM system there were also bills of material. New bills of material for the platforms were made in ENOVIA. They are based on the parts in SAP and are directly linked to the parts depicted in figure 5.86. Thus, updating takes place in SAP and the changes are inherited to ENOVIA.

This is shown by shading the letters in the ENOVIA model, see figure 5.87

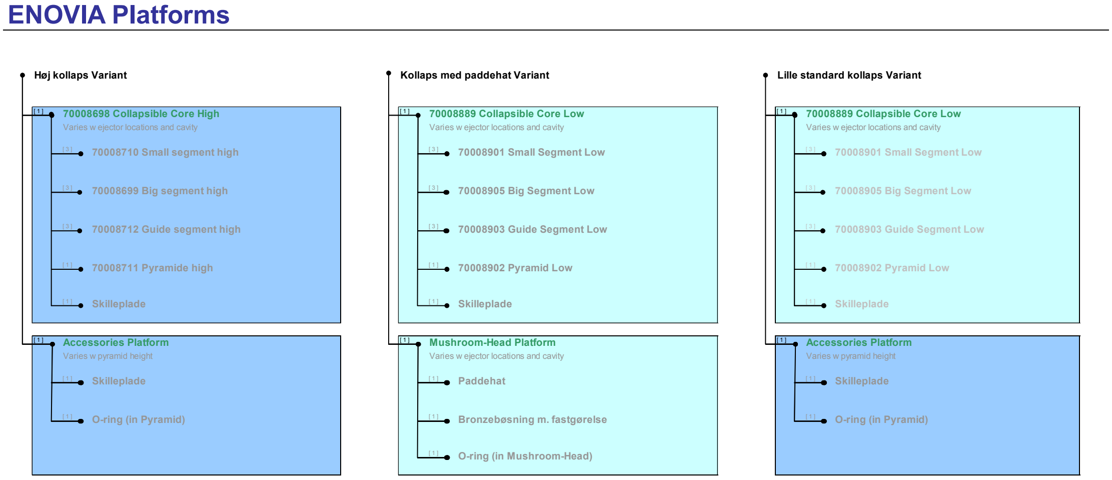
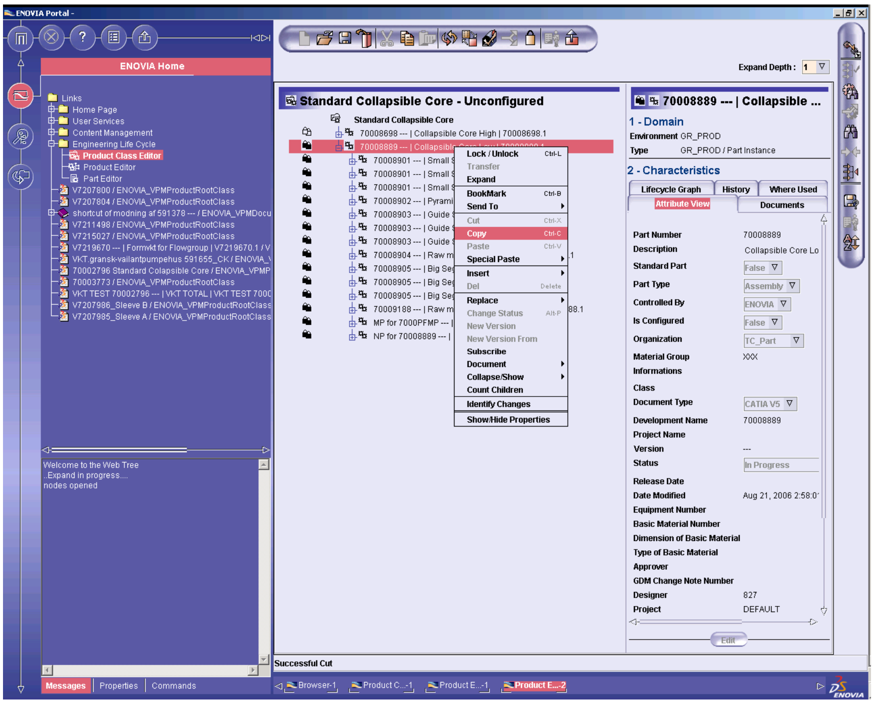


Figure 5.87: Detail from the PFMP; A visual illustration of the PDM system (ENOVIA) bill of material. The letters are shaded in light grey to depict that they are reflections of the parts in the SAP structure. Changes made to the SAP structure will propagate to this structure.

The structures in figure 5.87 are three different standard configurations based on the parts in the SAP structure. These assemblies are used as master copies when a new project is started. Figure 5.88 is a screen shot from ENOVIA, in which the detailed product model is found.



V7207800 / ENOVIA_VPMProductRootClass
V7207804 / ENOVIA_VPMProductRootClass
shortcut of modning af 591378 --- / ENOVIA_VPMDocu
V7211498 / ENOVIA_VPMProductRootClass
V7215027 / ENOVIA_VPMProductRootClass
V7219670 --- | Formvkt for Flowgroup | V7219670.1 / V
VKT.gransk-vailantpumpehus 591655_CK / ENOVIA_\
70002796 Standard Colapsible Core / ENOVIA_VPMP
70003773 / ENOVIA_VPMProductRootClass
VKT TEST 70002796 --- | VKT TOTAL | VKT TEST 7000
V7207986_Sleeve B / ENOVIA_VPMProductRootClass
V7207985_Sleeve A / ENOVIA_VPMProductRootClass

Welcome to the Web Tree
..Expand in progress....
nodes opened

Standard Collapsible Core - Unconfigured

Standard Collapsible Core
70008698 --- | Collapsible Core High | 70008698.1
70008889 --- | Collapsible Core Low | 70008889.1
70008901 --- | Small S
70008901 --- | Small S
70008901 --- | Small S
70008902 --- | Pyrami
70008903 --- | Guide S
70008903 --- | Guide S
70008903 --- | Guide S
70008904 --- | Raw m .1
70008905 --- | Big Seg
70008905 --- | Big Seg
70008905 --- | Big Seg
70009188 --- | Raw m 88.1
MP for 7000PFMP --- |
NP for 70008889 --- |

70008889 --- | Collapsible ...

1 - Domain

Environment GR_PROD
Type GR_PROD / Part Instance

2 - Characteristics

Part Number	70008889
Description	Collapsible Core Lo
Standard Part	False
Part Type	Assembly
Controlled By	ENOVIA
Is Configured	False
Organization	TC_Part
Material Group	XXX
Informations	
Class	
Document Type	CATIA V5
Development Name	70008889
Project Name	
Version	---
Status	In Progress
Release Date	
Date Modified	Aug 21, 2006 2:58:0
Equipment Number	
Basic Material Number	
Dimension of Basic Material	
Type of Basic Material	
Approver	
GDM Change Note Number	
Designer	827
Project	DEFAULT

Successful Cut

Figure 5.88: A screen shot from ENOVIA. The collapsible core is modelled in the PDM system. From the Product Family Master Plan the designers can gain an overview, while more details are obtained in the PDM system. (This screen shot has been published in the Int. J. of Mass Customization, [Mortensen et al., 2008b]).

(6) Manufacturing process

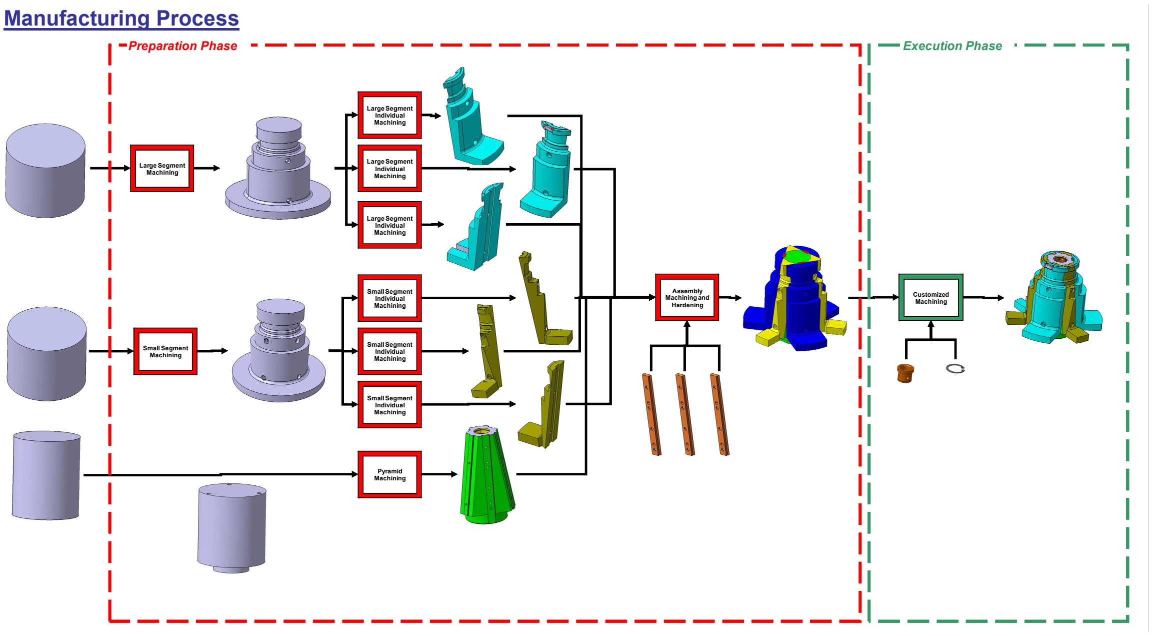
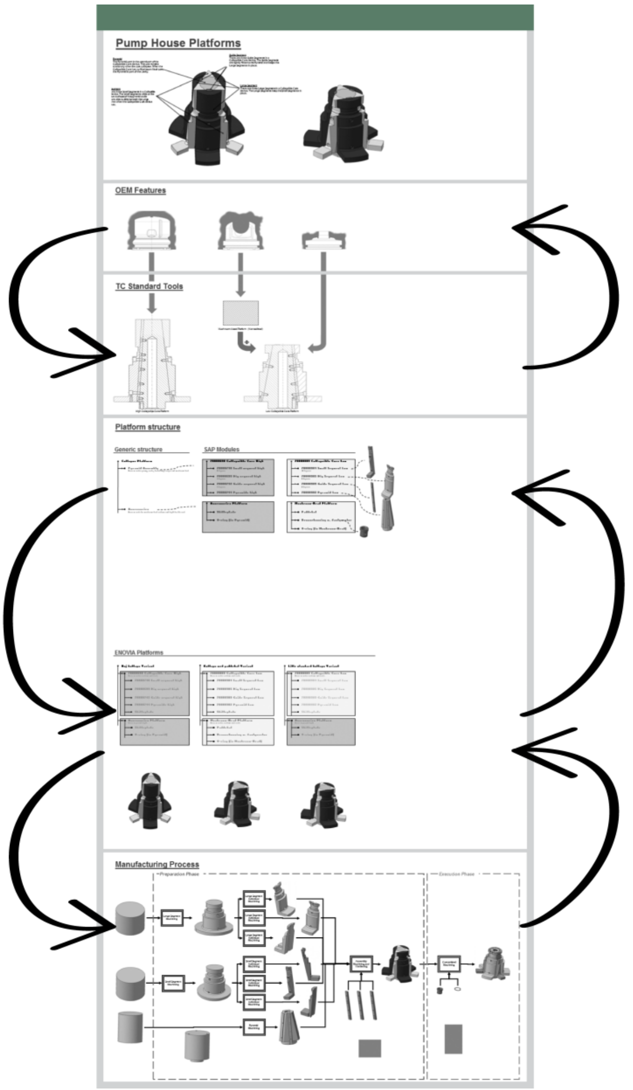


Figure 5.89: A detail from the PFMP; The manufacturing steps of the collapsible core. The red and green colours are again used to visualise the preparation (generic) and execution (variable) steps. (Earlier published in the Int. J. of Mass Customization, [Mortensen et al., 2008b]).

The manufacturing (in fact manufacturing and assembly) processes are shown in figure 5.89. There is a split in preparation and execution activities. All processes the preparation activities in the red rectangle are independent of the final geometry as long as that geometry is within the limits shown further up the in PFMP in the cross section of the collapsible core (see figure 5.85). The activities in the red square are standardised and initiated once a SAP code is activated (figure 5.86). These standardised activities were considered to be a part of the platform.

The PFMP as a platform model

In the above sections, the various views of the Product Family Master Plan are explained. These different view form a visualisation of the product platform, see figure 5.90



Molded part form features match platform capabilities

Value-added platforms are introduced

The platform consists of standardized assemblies of parts with variable feature/wirk surfaces, and standard ERP, PDM and NC models

Value-added parts are introduced

The collapsible core is produced in a two-step sequence

Value-added processes are introduced

Figure 5.90: The principle of the Product Family Master Plan as a model of the Platform. The poster depicts several different platform elements, and gives the designers and decision makers an impression of the links from customer demands to manufacturing processes.

Figure 5.90 depicts the “flow” of information from the different demands of the customers (i.e. the designers of the moulded parts). The form features of the moulded parts match the capabilities of the platform and no surprises arise, because the limitations are communicated to the designers. The platforms are made of standardised assemblies of parts with variable feature surfaces. From a functional perspective, the surfaces are in fact wirk surfaces. The platform also consists of standardised models of ERP and PDM data and the NC code for the manufacturing. Finally, the activities in the production are encapsulated into a preparation and execution sequence.

A picture of the PFMP as a poster on the wall is seen in figure 5.91. The picture is taken during a project meeting, and in fact the picture illustrates how the visual platform model serves as a decision base. During the discussions on different alternatives, the poster was constantly used as the basis.

Figure 5.91: Three participants from the project in a discussion in front of the PFMP. The PFMP is hanging on the wall in the mould department. In the picture, the three persons are discussing the SAP structure of the collapsible core. (This photo has been published earlier in the Int. J. of Mass Customization, [Mortensen et al., 2008b]).

NC codes is a part of the platform

The NC codes for the machining of the collapsible core was standardised in groups and assigned to the SAP codes in figure 5.86. (The NC, *Numerical Control*, codes are used to control the trajectory and tools during machining of the parts for the collapsible core). Thus, each time a platform is ordered, a set of standardised NC codes are also activated. Parts of the customised NC code are also built upon the standard NC code. The NC codes are modelled in the CAD system (CATIA) on the basis of the CAD models of the collapsible core.

Making the PFMP

The Product Family Master Plan is made using Microsoft Excel. Excel is not a graphical tool, yet it is very flexible when it comes to import and export of data. Therefore, excel was chosen. Excel has the ability to serve as a database, while at the same time being able to generate large posters and include pictures and illustrations. Another advantage of Excel is the fact that all the stakeholders in Grundfos had Excel installed and could review and edit the PFMP and eventually take over the editing responsibility.

The CAD models

On the collapsible core, the top surface can be considered as a wirk surface in a moulding organ, comprising the cavity inside the mould. When making the CAD model, the features (surfaces and solid geometries) can resemble this functional wirk surface, and the form features and wirk features become coincident. This was done in the CAD models of the collapsible core and the Pump housing. The inner geometries of the Pump housing were inherited to the CAD models of the mould and then again to the CAD models making up the Collapsible Core assemblies.

This hierarchy of attributes inheritance was controlled by means of skeleton models. Unfortunately, due to confidentiality, these models cannot be shown here. However, the concept of the models is to have a generic set of skeleton models in which spatial relations and important form features are controlled and inherited to instance models. Thus, the important surface on the top of the collapsible core is linked to the inner geometry of the pump house. The pump house file cannot go beyond the boundaries of the moulding platform. Thereby wasteful complexity is eliminated, and the updating of instance CAD files is made simpler.

It is somewhat difficult to better describe the hierarchies of CAD models, because it is not possible to show figures and screen shots of the models. The Aker Solutions case gives a more thorough introduction to the use of a PFMP in interplay with a Top Down Approach and a skeleton model in CAD.

A physical mock up

The final visual model used in the project, was an SLA-model of the collapsible core (SLA is a rapid prototyping method based on stereolithography). The model was used as a very tangible display of the design limits and was spray painted in red and green, and placed in the mould design department. This is an example of a physical platform model – unfortunately there are no photos of this model to include in the thesis.

Simulating the activities

The PFMP is a visual model printed on paper and hanging on the wall, and therefore a rather passive media for the message to come through. In order to test the new working procedures, a series of workshops were set up. The purpose of these workshops was to make the stakeholders in Grundfos (in fact those departments on the Snowball effect illustration in figure 5.77) work together on a design problem, as if they had the platform already implemented. This workshop is thereby a kind of *activity model* resembling the Design Game from the Danfoss case (see chapter 5.5). This time however, the design media were real world problems. An existing design specification was used as a case. All stakeholders were gathered in one large conference room with intranet facilities and their own computers. Then a workflow was simulated using a combination of real data files (such as the SAP structures and CAD files) and paper based representations of orders, emails and communication.

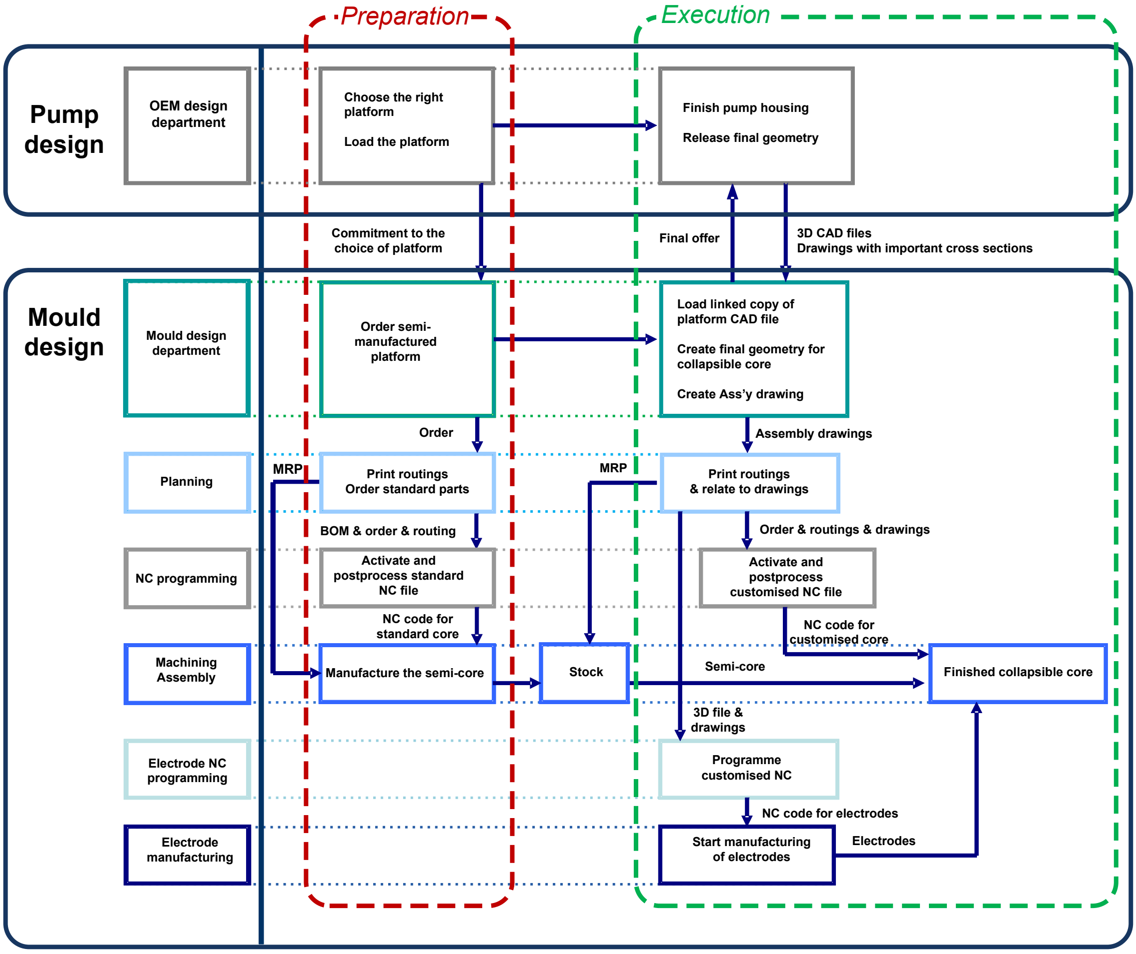


Figure 5.92: A visual activity model of the role of various departments in the preparation and execution phases of a mould design process. The model was used as the basic sequence in the workshops. The most important thing to understand in the model is the split between the preparation of generic activities in the preparation phase, and the variable activities in the execution phase.

Figure 5.92 is a visual model of the activities in various departments in a preparation/execution context. I served as the basis of a series of two consecutive workshops in which people from the different departments played their respective roles in the development process. Clearly, the manufacturing steps had to be omitted, as they are difficult to simulate during a single day. The workflow however, in both design and production activities, was simulated.

5.8.6 Validating the results in the Grundfos case

Based on the reactions from the stakeholders involved in the case project, they experienced a greatly improved ability to perform decisions on a product family level by means of visual modelling.

Validating the results at Grundfos cannot directly include an increased performance. Instead, the validation has to do with the decision base. However, the models of the collapsible core indirectly lead to a significant reduction of the lead time of a mould design and production process. However, it is not possible to state that it was due to the models alone.

In general, the decision makers in Grundfos expressed a clear improvement of the decision base, when important challenges were visualised. Without the models, they would have been more difficult to achieve, given the reactions from the involved employees. A simple example is the illustration of ten cross sections in figure 5.76. This is a very simple model of ten different functional surfaces, yet it achieved quite a lot of attention in the organisation and served as a means of communication between the mould designers and the pump designers.

Below is a collection of reactions from the stakeholders involved in the project and in the workshops in which the future design activities were modelled;

"The platform we are defining is closely linked to both customers, OEM design and production. We will therefore have much higher benefits than previously achieved".

"I like the visual approach of the PFMP – we can have a more structured and professional dialogue concerning the platform content and scoping".

"I feel confident in the platforms – we know that they will be working when we start manufacturing – meaning that we can focus our attention on other part of the moulds".

"Platform makes it possible to optimize our solutions".

"Platform application will make it possible to balance our effort in production and design in a much better way".

The word "platform" was used to denote the columns in the Product Family Master Plan, such as the one shown in figure 5.84.

Like in the Danfoss case it is hard to claim a fully validated and unbiased study. The involvement of the researcher biases the expressions of the employees in the company, and so the reactions from the audience are questionable.

Parts of the models (only the ones in the PFMP) have been published in a journal paper [Mortensen et al., 2008b] and thus received some acknowledgement regarding the usefulness and the internal consistency of the models, by means of a peer review.

Effects of the project

The case project actually resulted in a significant reduction in the overall time to market for a collapsible core. It is however, from a research point of view, not possible to identify to what extent the visual models made the difference. The impression from the reactions from the project team members in Grundfos, is, that for example the very simple illustration of functional surfaces in figure 5.76, had a large impact in the way people started to think in encapsulation. Decoupling variable from generic attributes became important, and the following encapsulation of activities in the design, fabrication and assembly phases, made way for the reduction in lead time. However, from a research point of view, the links between the visual model and the reduction in lead time are not strong enough to claim that there is in fact an impact. This is one of the reasons, why the measurable criterion is the *decision base* rather than other quantifiable criteria such as profit and lead time.

5.8.7 Concluding the Grundfos case

The Grundfos platform is constituted by reuse and encapsulation of a mix of parts, organs, software, knowledge and activities. During the project some of these platform elements have been visually modelled in various ways in order to support decision making;

The visual models

The Product Family Master Plan

- *Visualising variation in the part and organ domains.*
  - The parts and organs were modelled using simple cross sections of the products. A colour code of red and green is used to visualise whether a certain region of a product is generic (i.e. *red* representing that the design is locked for editing) or variable (i.e. green representing that the design is open for editing).
  - Visualising the space in which functional surfaces may vary, thereby depicting
- *Representing wirk surface encapsulation on the top of the collapsible core*
  - Visualising PDM and ERP product models, i.e. software
  - The Product Family Master Plan is used to also visually model the product models in the ERP and PDM system. The PFMP depicts the bills of material, and by use of the product ID numbers more information is accessible for the decision makers in the IT systems. The overview is kept in the PFMP while the details are kept in the ERP and PDM systems. Through the ID codes to the PDM system, the necessary CAD files can also be accessed.
- *Visualising postponement in fabrication and assembly, i.e. activities*
  - Some of the activity models focus on postponement and the sequence of customising and non customising processes, i.e. the *points of variegation*. The colour code of green and red is used also here to denote generic (preparation) and variable (execution) activities.

Activity models

Apart from the postponement of activities modelled in the Product Family Master Plan, the Grundfos platform also consists of a series of standardised workflows. The activities are generally split into a preparation and execution phase, and there is a standardised way for various stakeholders to engage in these activities. Several visual models are made to depict these activities. A combination of simple work flows and more graphical scenarios are used to communicate how the activities are supposed to be carried out and what their effects are (mainly on the lead time).

Modelling the skeleton and wirk elements

Using a Top Down Approach with skeleton models to control generic and variable attributes in the CAD system makes it possible to make a very tangible model of the sometimes rather intangible concept of wirk elements. Wirk surfaces were modelled in the CAD system and published to single parts. A so-called skeleton is used as a generic structure in the CAD system in order to control the spatial relations between functional surfaces in the CAD model.

For a more illustrative example of a skeleton model in a CAD system, see the Aker Solutions case.

Decision making

Various visual models were used to improve the decision base during the project. The Grundfos case was mainly a project of *decision making* rather than *product design changes*. The embodiment design of the finished moulds did not change significantly. The project had more to do with establishing a common consensus on various parameters and ranges of these parameters within the already existing designs. In order to establish these various decisions, a number of different visual models were used.

It is a clear impression from the project, that the visual models were major drivers for improved decision making. They provided an overview on a complex set of different design variables, in order for decision makers to base their decisions on.

5.9 Mapping the cases

This chapter will compare the three cases using the phenomenological framework proposed in Part 4, and map the cases in the space of meetings. The three cases from Danfoss, Aker Solutions and Grundfos are quite different. The solenoid valves in Danfoss are relatively simple, yet the total product family is quite complex. The drilling equipment of Aker Solutions is quite complex both in variation and in the totality of the installations on a drilling rig (yet the Eagle Light crane is only a subset of that complexity). The injection moulds at Grundfos have been improved through a better communication with customers, and a decision on how to standardise attributes.

What do these rather different product platform initiatives have in common? From a fundamental viewpoint, they all share the challenge of *reuse* and *encapsulation*. The platform elements however are different. They range from organs to parts, from standardised pieces of software NC code and PDM bills of material, to spatial relations in skeletons, i.e. elements in the organ domain. All of these platform elements are reused and/or encapsulated.

Due to the different platform elements in the three cases, the *modelling objects* are also different. The models are also representing different phases in a platform development project, from the very conceptual models in the puzzle piece at Danfoss, to the finished implemented Product Family Master Plans and related CAD models at Aker Solutions.

Despite the differences, the three platform projects represent various modelling objects and phenomena which all fit in the framework proposed in Part 4.

5.9.1 Mapping the meetings of the three cases

Mapping the three platforms into the phenomenological framework in Part 4 may help illustrate the different phenomena and modelling objects within the three platforms. The framework spans 66 different meetings between platform elements and life phase systems. In each of these meetings one may ask *how, what* and *why encapsulation* and *reuse* takes place.

An example of platform elements, phenomena and the related modelling objects is seen in the Danfoss case. Here, postponement is modelled as an effect of encapsulation by means of the production puzzle. The related platform elements are the *activities* in the life phase systems of fabrication and assembly. Thus, in a platform context, encapsulation and reuse of activities in different life phases becomes the interesting modelling object. Figure 5.93 illustrates how the production puzzle from the Danfoss case fits in the framework. The puzzle can help answer the question: "*How, what and why, are activities reused and* *encapsulated in the fabrication and assembly life phases?*". That is essentially the knowledge, which the production puzzle has to provide to the decision makers.

	Parts	Organs	Software	Activities	Knowledge	People
Platform preparation						
Platform execution						
Purchasing						
Fabrication				●		
Assembly				●		
Testing						
Transport						
Sales						
Operating						
Service						
Recycling						

Figure 5.93: An example of the mapping in the phenomenological framework. Encapsulation and reuse of activities in the meeting with the fabrication and assembly life phase systems are important phenomena in the Danfoss cases, and it is modelled by means of the production puzzle.

Figure 5.93 is an example of the two meetings which are chosen as means to model the postponement of activities in the Danfoss case. Postponement - as a phenomenon – is modelled by means of the production puzzle, and the model depicts the activities which happen in the fabrication and assembly life phase systems, i.e. in particular *meetings* between activities – as a platform element class – and life phase systems.

The difference between modelling objects and platform elements

Each of the three platform cases is characterised by a number of different *platform elements and phenomena*, and only a subset of these are covered by the models. Therefore, one can view the framework from two perspectives:

1. As a map of platform elements and phenomena
2. As a map of those of the platform elements, which are covered by the platform models

In the following, only the *modelled* aspects are put into the framework.

The three cases

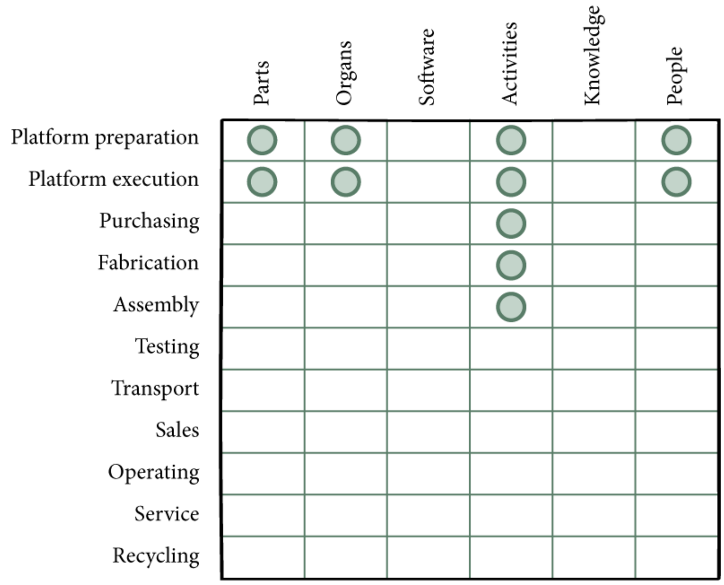
In the following, the three cases are mapped into the framework in order to give a visual comparison of the different modelling objects in the various cases.

Solenoid valves at Danfoss

In the Danfoss project there are various models. Each of these models covers different phenomena by means of different modelling objects. The models in the case mainly cover the following platform elements and life phases (see the conclusion of the Danfoss case (chapter 5.5.10) for an elaboration of the bullets);

- *The product puzzle*
  - Reuse and encapsulation of organ and parts for the use of platform designers in the preparation and execution phases.
- *The production puzzle*
  Reuse and encapsulation of organs and parts and the effects in the fabrication and assembly.
- *Building block poster*
  - Keeping track on people (design responsible) during the later preparation and early execution phases
  - Keep track on the status of the different platform constituents, by expressing the design status of various parts
- *The Design Game*
  The design game served two main purposes;
  - Serving as an activity model expressing the preparation and execution phases
  - Representing the purchasing challenges.

Figure 5.94 depict the relevant meetings in the above list.



	Parts	Organs	Software	Activities	Knowledge	People
Platform preparation	●	●		●		●
Platform execution	●	●		●		●
Purchasing				●		
Fabrication				●		
Assembly				●		
Testing						
Transport						
Sales						
Operating						
Service						
Recycling						

Figure 5.94: The models of the Danfoss case mapped into the framework. This illustration both represents the phenomena in the platform and the objects of the platform model.

Drilling equipment at Aker Solutions

The platform at Aker Solutions is a set of reusable designs. The designs are reused on a part level and on an attribute level. The platform models consist of a Product family Master Plan and a set of CAD models in a Top Down hierarchy. The related meetings are depicted in figure 5.95;

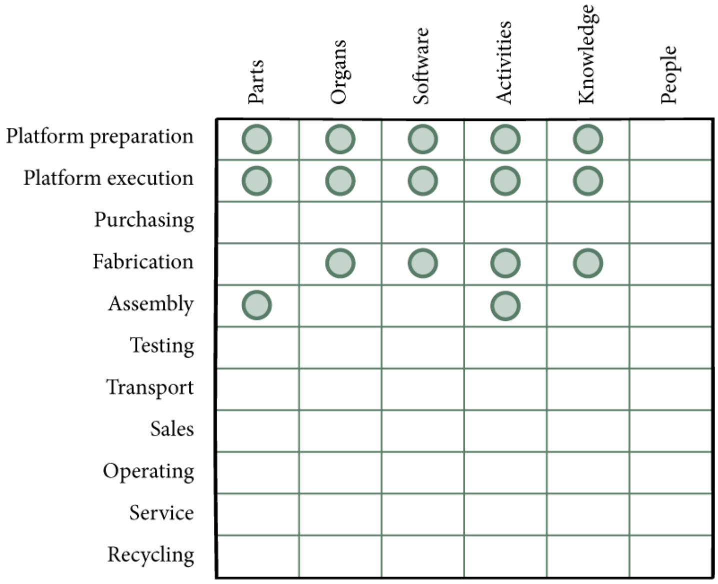
	Parts	Organs	Software	Activities	Knowledge	People
Platform preparation	○	○	○			
Platform execution	○	○	○			
Purchasing						
Fabrication		○				
Assembly	○					
Testing						
Transport						
Sales						
Operating						
Service						
Recycling						

Figure 5.95: The models of the Aker Solutions case mapped into the framework.

Figure 5.95 gives an impression of the meetings in which the various models are relevant. Starting from the top right, the part encapsulations are modelled in the Product Family Master Plan by means of illustrations of the different parts, from which a product variant can be combined. This is used in the preparation and execution of the platform. The encapsulation and reuse in the organ domain is somewhat – yet not fully - represented by the skeleton model in the CAD system. As it is pointed out in chapter 5.6, the coincidence of *form element* and *functional elements* is a prerequisite for a CAD system to be able to control wirk elements. Thus, it is a matter of viewpoints of the designer, when building the CAD model, whether to perceive the features of the CAD system as strictly geometrical or whether to also allow for a functional perception to take place. In the latter case, wirk surfaces and skeletons, can be visualised and modelled by a Top Down approach in the CAD system, which is why the organ domain is included in the map in figure 5.95.

Moulding equipment at Grundfos

Figure 5.96 depicts the map of the models in the Grundfos case. The Product Family Master Plan, with its models of the various types of software, includes software in the models. Software is a modelling object in the PFMP while also being a media for product models, though the ERP, PDM and CAD systems. Indirectly – through the code numbers written in the Product Family Master Plan – the NC code is also a platform element, and thereby a piece of reusable software. The Product Family Master Plan also depicts a visual model of repeated fabrication and assembly activities in an encapsulated setup (due to the split between preparation and execution). These standardised sets of activities are reused. Thereby, this model depicts activities as a platform element in the fabrication and assembly life phase systems.



	Parts	Organs	Software	Activities	Knowledge	People
Platform preparation	○	○	○	○	○	
Platform execution	○	○	○	○	○	
Purchasing						
Fabrication		○	○	○	○	
Assembly	○			○		
Testing						
Transport						
Sales						
Operating						
Service						
Recycling						

Figure 5.96: The models of the Grundfos case mapped into the framework. These are the meetings covered by the models.

The cross sections in the PFMP and the models in the CAD system represent the wirk surfaces and the parts, used in the preparation and execution phases respectively. Finally, the encapsulation of wirk surfaces in the organ domain has effects in the fabrication life phase system, while the parts have to be assembled, and thereby dispose certain effects in the assembly life phase systems. This phenomenon is accounted for in part 4, chapter 4.5.3. This is why the meetings parts+assembly and organs+fabrication are marked in the framework.

5.10 Concluding the cases

This chapter gives a brief conclusion on the cases, their differences and similarities, the impact of the work in the cases and the limitations of the findings.

5.10.1 The purpose of the cases

The cases serve two main purposes in the response to the research questions;

1. *Modelling indications*
   The cases give indications on how to model various phenomena related to the reuse and encapsulation of different platform elements in the meeting with different life phase systems. They thereby serve as an answer to Research Question 2.
2. *Validity*
   They somewhat add concreteness and validity to the usefulness of the phenomena identified in the work on Research Question 1. The cases thus serve as an empirical addition to the validation of the work in Research Question 1, in particular the practical applicability of the concept of encapsulation in the organ domain (of organs and wirk elements).

An important question is then to what extend these two purposes have been met by the cases. This is discussed under the following two headlines.

Providing indications on modelling approaches

The cases provide several different approaches to visually model phenomena related to reuse and encapsulation in a product platform context. The models are very different; however they all fit in the same context of meetings, as shown in the mapping of the cases, by means of the phenomenological framework (see chapter 4.8). The three case descriptions can be seen as a contribution to the tool box of decision makers in industrial product development projects. The models are based on certain theoretical understandings of a system, a product and a product family, of which the Theory of Domains is the most important one. Based on this theory, and on the research approach, hopefully a satisfactory level of *confidence in usefulness* has been met, and thereby new knowledge built. Knowledge that will enable and/or inspire decision makers in product platform projects to be able to build visual models in various phases of a product and of various platform elements, depending on the type of industry, product, and platform approach.

Adding validity to the concept of organ encapsulation

The first research question initiates an investigation of various phenomena related to the reuse and encapsulation of various types of so-called platform elements, the effects of reuse and encapsulation in various meetings, and the activities leading to these effects. Part 4 is an attempt to answer this question from a relatively theoretical standpoint, based on a review of literature. The visual models proposed in the three cases, somewhat bring some of these phenomena into a practical setting, and report on the use of these. The chief phenomenon listed in Part 4 is the concept of encapsulation in the organ domain. The reason to grant encapsulation in the organ domain particular interest is that a successful function to form mapping does not necessarily have to imply *physical interfaces*. This again implies that part encapsulation has strong dispositions to the assembly life phase system, while organ encapsulation has strong dispositions to the fabrication life phase system, (see the key example in chapter 4.5.3, figure 4.11). Thus, encapsulation in the organ domain and encapsulation in the part domain have to take place in interplay, and a platform is likely to have some degree of both encapsulation types – a platform is not solely based on one or the other of these encapsulation types.

All three cases have degrees of organ encapsulation and degrees of part encapsulation, and this phenomenon has received particular interest in the work on the models. The puzzle piece in Danfoss gives the opportunity to build concepts with changing organ and parts encapsulations (see the example with orifice in chapter 1.5.5). The Lego Design Game gives the participants a feeling for the impact of various part encapsulations. The Building Block Poster gives an overview of different types of part encapsulations. In the Grundfos case, the Product Family Master Plan, with the colour coded cross sections gives an opportunity for design engineers and other stakeholders, to see the functional space in which they can design a wirk surface for the moulding organ inside the cavity of the mould. The skeleton models in the Aker Solutions case is a representation of the spatial relations between functional surfaces and entities, i.e. wirk elements, and the split in generic and variable attributes.

From this perspective, the cases help to add validity and applicability to the concept of encapsulation of organs and wirk elements. On a first glance, it may seem as a rather theoretical system perception, but the impression from the cases is, that encapsulation – when instantiated and visualised in the right models –

can be a very handy way for design engineers to manipulate the layout of a product platform, and thereby the effects, which decision makers strive for.

5.10.2 From concept to implementation

The three cases are not fully covering the framework. Rather, they give indications on how to model specific phenomena in specific industrial cases. Nevertheless, the three cases span the typical phases of a product platform project. The Danfoss puzzles are used in the early stages of conceptualisation, to build qualitative models of product families and the related production setup. The Building Block Poster is used to represent part encapsulations during the design and implementation of a platform. The Grundfos PFMP is used to reflect the designs, when implemented in the ERP and PDM systems, and finally the Aker Solutions case is an example of a PFMP which, in interplay with skeleton models in a CAD system, serves as a fully implemented product platform, useful as a design template in the operational execution phases in the future.

Thus, the three cases provide indications on how the concepts of reuse and encapsulation can be modelled throughout the duration of a platform project from conceptualisation to implementation.

5.10.3 Fitting the platform and the model

From the cases, a certain pattern emerges. The nature of the platform should have an impact on the nature of the modelling efforts. Two important approaches to platform system perceptions have been pointed out many times in the thesis;

- Parts encapsulation
- Organ encapsulation

From literature, two different platform variation approaches have been identified (see Part 4, chapter 4.5.3);

- Combinatorial approach
- Attribute quantification approach

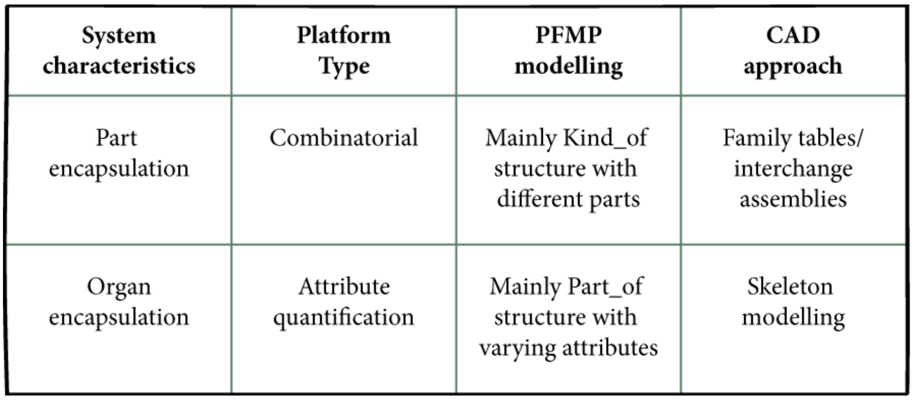
The Product Family Master Plan holds information in two different structures;

- The Part_of structure
- The Kind_of structure

In a CAD system, a Top Down Design approach can be done in many different ways, of which two have been pointed out here;

- The CAD skeleton
- The Family Table

From the three cases, it seems fair to claim that there is a fit between these different characteristics and modelling dimensions. Figure 5.97 is an illustration of this fit;



System characteristics	Platform Type	PFMP modelling	CAD approach
Part encapsulation	Combinatorial	Mainly Kind_of structure with different parts	Family tables/ interchange assemblies
Organ encapsulation	Attribute quantification	Mainly Part_of structure with varying attributes	Skeleton modelling

Figure 5.97: A proposal for a fit between the system characteristics in a product platform and feasible modelling strategies.

Unlike many of the references in literature, it is not the intention here to claim, that the above two rows reflect to different platform types. Rather, the two rows reflect different characteristics which may very well be part of the same platform. Thus, decision makers have to choose their different modelling techniques based on the nature of the platform and the “mix” of system characteristics.

5.10.4 Limitations

While reporting the results of the cases, one must take the limitations to the case studies and in particular to the validation of the studies into account.

Validating on the basis of feed back

The empirical validation of the three cases is mainly based on feedback from employees and an observation of the way the models were used. Clearly the observations are highly biased, as there are no statistical tools or other such alternatives used to rule out preconceptions or other biases. There is little or no quantitative empirical input to analyse. In this case, the observations are of a rather qualitative nature and are made on a daily basis as a part of the action and participatory research approach, in which the researcher has taken an active part in the projects. An alternative could have been to set up more formal interviews, and then analysed the inputs from the stakeholders. This was in fact done as a part of the Lego Design Game and the Platform Thinking Seminars in Danfoss, however, the approach was abandoned for the following reasons;

1. It was the impression of the author that a lot of unspoken feedback was lost, when asking questions – the stakeholders answered only the questions asked, and not the questions that should have been asked. From that perspective, an interview is as biased as an observation (depending of course on the nature of this observation and what the observed are told before the study).
2. The employees were not able to fill in a questionnaire during work and meetings, and after the meetings, it was not feasible to make them spent a lot of time writing down their own thoughts about the of a model of the decision made during a steering committee meeting for example.

Instead of a formal series of interviews, the input from various stakeholders has arisen from the participation of the researcher in the three case projects.

This is a limitation of the study and of the validation.

The stakeholders are also biased

The researcher is not the only factor inducing biases to the study. All the cases have in common the fact that the visual models were a fairly new approach in the company. Most of the design engineers and other stakeholders had a natural interest in new methods and models. Thus, a use of the models on a daily basis and as part of a routine in the departments has not been tested out thoroughly, and the feedback from the stakeholders is biased by their own curiosity and eager to take part of the project. There were also several stakeholders who were critical towards the approach, yet the general impression is that the idea of visual models and the concept of encapsulation were accepted as a sound way to go about design and product development. The quotes, which are written as examples of the reactions from stakeholders, are included to give an impression of the improvement of the decision base.

6

Conclusion

In Part 6 the results of the thesis are outlined, the general limitations of the conclusions discussed, the implications on further research accounted for and some final perspectives provided.

6.1 Introduction

The work presented in this thesis seeks to clarify various phenomena related to product platforms, and the challenge of modelling these phenomena. Apart from being a research project, the PhD study is also a research education. Part 6 concludes on the research project, the findings and the research education aspects.

The structure of Part 6

Part 6 has the following structure;

Chapter 6.2: Research motivation

A short discussion of the research motivation and the background of the project.

Chapter 6.3: Research contributions

- *Chapter 6.3.1: Clarifying platform phenomena – Research Question 1*

  This chapter gives a discussion of the findings in the work on Research Question 1. The aim of the work is a clarification of various phenomena related to product platforms. The main contribution from this work is the introduction of the concept of encapsulation in the organ domain. The concept makes it possible to explain reuse effects in platforms that do not necessarily have a modular design.
- *Chapter 6.3.2: Visual modelling – Research Question 2*

  This chapter lists the findings from the work on Research Question 2. The aim of the work is to explore whether different visual modelling approaches are perceived as an improvement of the decision base by decision makers and practitioners in companies. The main contribution from this work is a range of different modelling techniques and – based on feedback from the involved case companies - the confidence that a visual modelling approach is in fact experienced as an improved foundation to base decisions on by industrial practitioners in the field.

- *Chapter 6.3.3: The research approach*

  In this chapter the implications from the research approach on the findings are discussed and some limitations are listed.

Chapter 6.4: Future research

This chapter indicates how some of the findings can be taken one step further

Chapter 6.5: Concluding on the PhD project

This chapter concludes on the PhD project as a study and education of the author.

Chapter 6.6: Perspectives

This chapter gives some final remarks on the implications of the thesis and the topic of product platforms.

6.2 Research motivation

A product platform approach is different from a traditional single product development approach for a number of different reasons. One of the primary reasons is that a platform often serves as a foundation for a *product family*. This means that several products are developed in a united approach and that *something* is reused between this set of products. One of the fundamental reasons to reuse is a desire to be able to utilise resources more efficient, in order to satisfy the needs of customers more effectively. Figure 6.1 depicts a metaphor of this fundamental compromise between internal efficiency and external effectiveness.

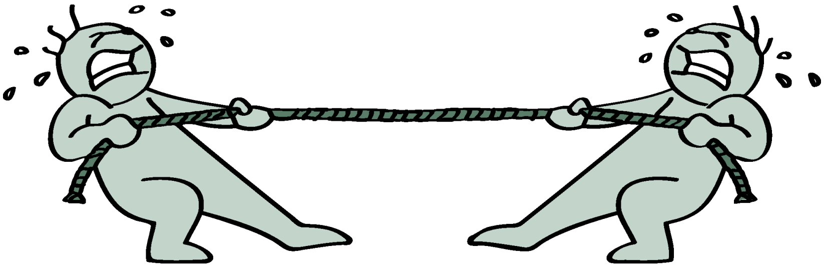


Figure 6.1: The fundamental driver for any platform approach is to achieve an optimal compromise between external performance and internal resource utilisation.

The fact that more products are developed based on the same reused assets makes way for some characteristic phenomena within the topic of product platforms. A primary driver for this research has been to clarify and visually model some of these phenomena, in order to improve the ability to perform successful decision making in product platform projects based on knowledge on these different phenomena.

6.3 Research contributions

The *clarification* and *modelling* of platform phenomena are the essential subjects of this thesis. The two subjects are reflected in two research questions, and the results of the work on the two research questions are discussed in the following.

The *clarification of phenomena* is mainly done by means of a literature review and a discussion on various theories and present contributions. As a part of this discussion, the concepts of organ and part encapsulation is introduced. This is described in Part 4.

The *modelling of phenomena* is described in Part 5. The main contents of this work is a review of existing modelling approaches and – using three industrial cases as a starting point – contributions to new modelling approaches, which can help visualise and instantiate the phenomena, which are discussed in the work in Part 4, and a contribution to the confidence in the use of visual modelling as a decision base in product platform projects.

The two research questions and the corresponding contributions are listed in the following chapters.

6.3.1 Clarifying platform phenomena - Research Question 1

> ***Research question 1***
>
> What phenomena are related to the encapsulation and reuse of *constitutive elements in a product platform,* the expectable *behavioural effects* arising from reuse and encapsulation, and the *activities* leading to reuse and encapsulation effects?

The research question implies several objects of study. First of all, the concepts of *reuse* and *encapsulation* are claimed to be fundamental aspects of the system formed by a product platform. The *carefully planned and deliberate reuse and encapsulation* are seen as two fundamental system characteristics, which make a platform approach different from a traditional single product development approach (chapter 1.3.1, chapter 4.1, 4.3 and 4.4). This particular way of describing product platforms is not seen in literature as of today.

On that basis, the research question seeks to clarify *what* a platform consists of (constitutive elements), *why* the platform is implemented (the effects), and finally *how* a successful platform may be obtained (the activities). The basic idea is to be able to provide decision makers with an improved know-how, know-why and know-what, about these phenomena in order to perform better decision making in platform projects.

The answers to the research question are elaborated in the following. First the justification of reuse and encapsulation as platform fundamentals is shortly concluded.

Encapsulation

In this thesis, *encapsulation* is considered as the *grouping* and *decoupling* of platform elements;

Encapsulation = grouping & decoupling;

1. *Grouping*
   Grouping is the process of deciding which elements that fit together as a unit. The grouping can be

done from several viewpoints, in order to achieve several different effects, and the elements which are grouped may be different as well. These different elements are discussed in Chapter 4.5.

2. *Decoupling*

   Decoupling is the process of finding means to decouple the groups from each other. Depending on the nature of the grouped elements, the means can be different. In the case of parts, the decoupling is often taking place by means of a physical interface, i.e. a certain design solution. If an activity or production step is grouped, the decoupling is of another kind.

It is encapsulation that makes it possible to change some parts of a product family while keeping other parts constant, i.e. reusing. Thus, encapsulation is often a prerequisite for reuse.

Encapsulation versus modularisation

The word encapsulation is used as a close synonym to the word *modularisation*. However, the word modularisation is considered to be unsuitable as a fundamental describer of platforms. Instead, the word encapsulation is used to describe the process of grouping and decoupling, due to two main reasons;

1. *Modularisation implies a physical split between parts*

   Some of the most widely cited definitions of modularity have to do with grouping and decoupling of physical elements, i.e. what is often called *modular products*. Thus, modularisation often implies that modules are perceived as physical sub assemblies and that physical interfaces are used as a means to obtain decoupling. One of the aims of Research Question 1 is to highlight that this is not always the case, and that there are in fact other ways to achieve reuse benefits.

2. *A lack of consensus*

   There are many different understandings and definitions of modularisation, thus the word is difficult to use in a *fundamental* description of various phenomena. Encapsulation however, covers a more fundamental systems understanding.

Modular product architecture

A large body of research within product platforms has deemed the *mapping from function to form* as a very important driver for the ability to gain reuse effects in a product family. This mapping is often referred to as the product architecture:

- *The form*

  A typical (mechanical) product consists of subsystems which consist of parts. These parts and subsystems interact in a certain hierarchy.

- *The function*

  Likewise, the main function of a product can be broken down into sub functions (provided that the design principles of the subsystems and parts are known). The sub functions also interact in a certain hierarchy.

- *Function to form mapping*

  The match between these two hierarchies is essentially the function to form mapping, and it has a great impact on the ability to gain reuse effects.

Encapsulation does not imply part interfaces

The vast majority of research on the concept of *modularisation* and *modular product architectures* implies a certain function to form mapping, in which parts are physically decoupled by means of interfaces. Often, standardised interfaces are reported as a prerequisite for obtaining reuse benefits. This thesis provides examples of the contrary, i.e. cases in which reuse effects are obtained without decoupling between parts (see chapter 4.5.3 and figure 4.11). The concept of encapsulation has the ability to explain the system characteristics of a product platform in which reuse benefits takes place without necessarily having a decoupling between parts, as a prerequisite for obtaining the reuse effects. This is explained by means of the Theory of Domains, and is deemed *organ encapsulation*. (Organ encapsulation is further described later in this conclusion).

Reuse and sharing

Reuse and sharing are simply denoted *reuse* in this thesis. A hypothesis implied by Research Question 1 is that reuse is a fundamental characteristic of product platforms. One of the main drivers of a product family and platform based approach is to be able to tailor make products without losing internal efficiency. Several authors report that a product family without a deliberate and careful reuse strategy is likely to be characterised by more efficiency than a case without. Some also stress that reuse can happen between different product generations, that is, in a time dimension, and within the same generation, i.e. across different product variants.

The constitutive platform elements

In Part 4 various *platform elements* are discussed. Platform elements are considered to be the constituents of the platform. It is the elements, which are reused and/or encapsulated in order to gain the platform benefits. Based on a review of existing literature it is stated that platform elements can be divided in (but not limited) to the following classes; Parts, Organs, Software, Activities, Knowledge, People. These are considered as fundamentally different classes of platform constituents, and in these classes various elements are subject to both reuse and encapsulation.

Two of these classes are emphasised in the answer to Research Question 1, both taken from the Theory of Domains, and used to describe certain types of reuse and encapsulation;

The part domain

The part domain constitutes a point of view on the products, in which the parts, components, machine elements and other physical constituents of the product is the object of study. Parts constitute the physical embodiment of the product. Parts are considered to be subject to reuse and encapsulation.

Form feature elements

In the thesis, the level of resolution is taken a step further by introducing form feature elements as constitutive platform elements. Form feature elements are considered to be surfaces, solid volumes and other features of parts, i.e. reusable geometry. Form features are extensively used in feature based CAD design, and have the potential to be design elements in a product platform. Form feature elements are also considered to be subject to reuse and encapsulation.

Part skeleton

Form features are related in part skeletons. A part skeleton is considered to be the spatial relations between the entities of parts, i.e. between form feature elements.

Encapsulation

Encapsulation in the part domain is the grouping and decoupling of parts. It is somewhat equivalent to the traditional perception of modularisation. It is the process of grouping design solutions and then decoupling them from each other by means of standardised interfaces. This phenomenon has been extensively described in literature.

The organ domain

The organ domain constitutes a point of view in which *function carriers* are the objects of study. The concept of organs is taken from the Theory of Domains (chapter 3.2.2, [Andresen, 1980]). Organs are function carriers, thus they are physical but their boundaries are not determined solely by geometry. Thus, organs are physical abstractions which depend on a certain functional viewpoint. An organ may be a subset of a part or be distributed into several parts. Organs are – like parts – considered to be subject to reuse and encapsulation.

Wirk elements

Organs can be further elaborated into wirk elements. Wirk elements are considered to be the entities of organs (The concept of wirk elements is described in chapter 3.2.3). Wirk elements are considered to be constitutive platform elements and subject to reuse and encapsulation.

Encapsulation in the organ domain

The encapsulation of organs and wirk elements is a phenomena not yet covered by literature. The abstraction of wirk element encapsulation makes it possible to describe – from a systems perspective – how encapsulation can take place without a decoupling taking place in the part domain, i.e. without necessarily having physical interfaces to ensure decoupling. The two best examples of this phenomenon are found in chapter 4.5.3 (and figure 4.11), and in the Grundfos case in chapter 5.8.

This research contribution makes it possible to phrase what many existing platform definitions fail to address, namely the concept of design flexibility without implying a modular product design. Many product platforms in fact benefit from designs, which are not modular in the classic sense. The concept of encapsulation in the organ domain can serve as a description of a product platform – from a systems perspective – in which it is possible to gain reuse effects in non-modular products (often referred to as integral products). Thus, a modular design is not a prerequisite for reuse effects and increased efficiency, and an integral product design (architecture) is not necessarily inflexible.

Encapsulation in the organ domain

Encapsulation in the organ domain – of organs and wirk elements - provides a concept, with which it is possible to explain the system characteristics of a product platform with reuse benefits and without being based on a modular design

Encapsulation of assets which are not part of the product

Some of the platform element classes in the list above (Activities, Knowledge, and People) are not directly part of a product. Thus, they are of a different kind than parts and organs. Software does not have to be either. But these classes are still considered to be able to describe elements in a platform which are subject to encapsulation and reuse. Activities and knowledge elements can be grouped and decoupled and reused. Some of the cases in Part 5 (the Danfoss and Grundfos cases) discuss how activities can be modelled as platform elements, and how activities are standardised and reused.

The behavioural effects

The behaviour of the platform is considered to be the *effects*, which happen in the meetings between the platform and its life phase systems. Reuse and encapsulation of the above mentioned constitutive platform elements result in various effects. The following effects and related phenomena are considered to be the most important ones in this thesis;

Preparation and execution activities

The concept of encapsulation can be used to explain another of the fundamental characteristics of a product platform approach. It is the ability to clearly separate the development of a product family into a preparation and an execution phase, and thereby an *effect* of the meeting between the activities as a platform element, and the development system. Encapsulation in this case is the grouping and decoupling of various development activities.

Dispositional relations arising from encapsulation

Extending on the discussion on encapsulation in the part and organ domain, a specific effect is noteworthy. It is the difference in the nature of the effects of encapsulation of parts and organs respectively in the production;

> ***Dispositional effects from part encapsulation***
>
> *Part encapsulation (modularisation) has strong dispositional effects in the* ***assembly*** *system*
>
> ***Dispositional effects from organ encapsulation***
>
> *Organ encapsulation has strong dispositional effects in the* ***fabrication*** *system*

It means that the effect of a successful part encapsulation can make the assembly task easier. On the other hand, the assembly system is a prerequisite for a successful decoupling of parts. The effects occur in a meeting.

Likewise, a certain encapsulation in the organ domain can make it possible to vary some wirk elements on the same part without changing other wirk elements on that part. This effect has an impact on the process flexibility, and the capabilities of the fabrication life phase system are an important driver for success. Again the effects occur in a meeting. These viewpoints are described in Part 4, chapter 4.5.3.

Activities leading to reuse and encapsulation

Based on a review of various product platform development methods, it is stated that the following fundamental sequence is recognised in the vast majority of platform development approaches;

Platform preparation

- Scoping the platform
  - Often as a trade-off between customer needs and design capabilities
- Designing the platform
  - Grouping and decoupling of reused and variable attributes in the platform
  - Inducing the highest possible variety in the product family
  - Inducing the highest possible commonality in various life phase systems

Platform execution

- Creating derivative products from the platform based on customer requests

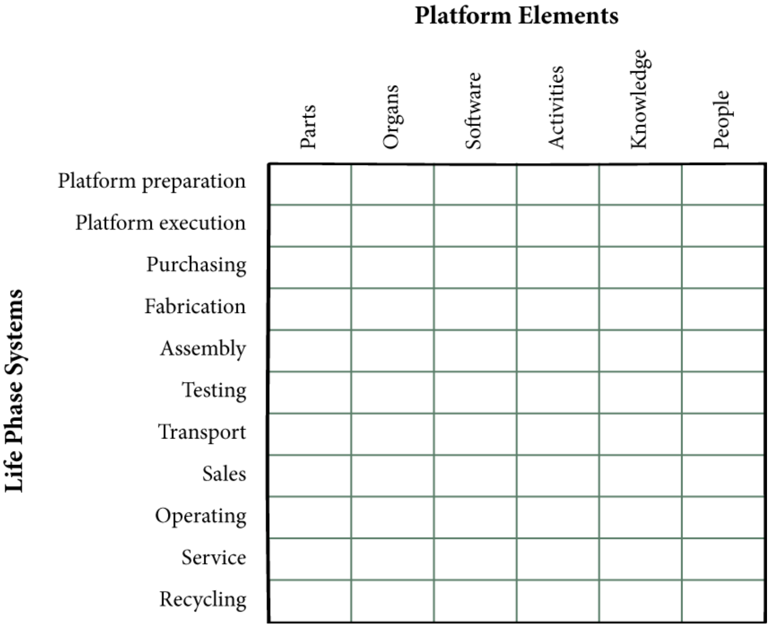
Maintenance

- Apart from the strict preparation/execution, the platform also have to be maintained and upgraded

This is not considered to be a research contribution. It is a context in which reuse and encapsulation fits, and also the context in which the modelling work in Research Question 2 has to fit.

Phenomena occurring in meetings

In the thesis, there is a review of product platform perceptions and definitions (mainly chapter 4.2 and 4.5). On the basis of the findings in this review, *reuse effects by means of encapsulation in certain meetings* is considered to be a fundamental driver in all platform projects. These meetings occur when the platform elements meet a certain life phase system. In the end of the discussion on platform phenomena (in Part 4), a framework is proposed as a visualisation of these meetings (chapter 4.8). Figure 6.2 depicts the framework.



Platform Elements

Life Phase Systems

	Parts	Organs	Software	Activities	Knowledge	People
Platform preparation						
Platform execution						
Purchasing						
Fabrication						
Assembly						
Testing						
Transport						
Sales						
Operating						
Service						
Recycling						

Figure 6.2: The phenomena identified in the work on Research Question 1 are all possible to map into a phenomenological framework, visualising a space of meetings spanned by the platform elements and the life phase systems.

The framework in figure 6.2 depicts a space of meetings spanned by the platform elements and the life phase systems. It is not an exhaustive space, as more life phases and more platform element classes could be added, depending on viewpoint and purpose. However, it is evident that all platform perceptions reviewed in this thesis fits into the framework, and it can thus serve as a tool to map various different platforms into the same context. When deciding on what to model, and which phenomena to study in a particular platform project, decision makers can ask themselves the following three questions to all the 66 meetings listed in figure 6.2:

1. How is reuse and encapsulation obtained in this meeting?
2. What is reused and encapsulated in this meeting?
3. Why is reuse and encapsulation used in this meeting?

The final viewpoint to bring forward from Part 4 is that decision makers, in the search for an understanding of phenomena related to reuse and encapsulation in a particular platform, can go through figure 6.2, asking the three questions to each meeting. This will provide a stepwise way to clarify what modelling dimensions the platform should be supported by. See chapter 4.8.5 and figure 4.42 for an elaboration on the above framework.

The question of how to model the phenomena is the topic of Research Question 2.

6.3.2 Visual modelling – Research Question 2

The second research question is an extension of the first research question. The assumption is that decision makers and other stakeholders in a company (such as the design engineers) have to be able to see the phenomena in order to manage them – they have to be able to see the platform in order to manage it. Assuming that a visual model is an efficient means to solve that issue, the second research question is;

> ***Research question 2***
>
> What possible ways exists to visually *model* the phenomena related to reuse and encapsulation of *constitutive platform elements*, inside as well as outside of the part domain - in order for decision makers to experience an improved decision base in platform projects? Ideally, such models should provide decision makers with knowledge on potential *behavioural effects* arising from the meetings between platform elements and life phase systems.

A review of existing modelling approaches

In the thesis, a review of existing modelling approaches is provided (chapter 5.3). From this review it is evident that the encapsulation of elements that are not directly related to product parts, is not modelled in any of the existing product and product platform modelling methods. Few even incorporate the function to form mapping, and few models provide the users with a visual representation of the product. Mostly, the models are schematic and abstract representations, and not easily recognisable from a product design point of view.

Contributing with different modelling approaches

The answering of Research Question 2 is done by means of different phenomenon and information models developed to suit the industrial context in the three case companies. The cases cover a rather wide range of models, which are used for different purposes to model different phenomena and effects in different stages of a product platform development project. A more extensive conclusion on the different models is given in chapter 5.10.

The cases provide a set of different visual modelling approaches with the following purposes:

- Conceptualising different organ and part encapsulations and modelling the dispositional effects in the product life phase systems using a puzzle piece approach (see the Danfoss case chapter 5.5.5).
- Representing activity encapsulation by means of a game enabling stakeholders in the company to experience the design activities during a platform development process and the possible split between

preparation and execution, and the relations to the corresponding encapsulation of design solutions into generic and variable parts (see the Lego Design Game in the Danfoss case in chapter 5.5.8).

- Visualising the overview of part encapsulations in a product family, while keeping track of the responsible people and the design status of the parts. The model gives an overview, while at the same time providing details on each part, and serving as a visual directory to the data in the ERP system and CAD systems (The building block poster in the Danfoss case, chapter 5.5.6)
- Visualising generic product structures and related part and organ encapsulations together with a CAD skeleton, (see the Aker Solutions case, chapter 5.7).
- Visualising variation in the organ and part domains, wirk surfaces, software PDM and ERP product models and postponement and the points of variegation as a part of a Product Family Master Plan (see the Grundfos case, chapter 5.8.5).
- Visualising the encapsulation of activities after the implementation of a product platform approach (See the visual activity model in the Grundfos case, chapter 5.8.5).
- Visualising the effects of a lack of reuse in order to communicate the potential benefits of reuse (see the “Snowball effect” in the Grundfos case, chapter 5.8.4, figure 5.77).

These different models indicate how various phenomena can be concretised and visualised in order for decision makers to experience an improved decision base while managing the platform.

Many of the stakeholders involved during the three cases expressed their acceptance of the visual models as a means to perform better decision making, mainly due to the overview provided by the models and an improved knowledge on the phenomena visualised by the models. In some cases a rather theoretical and abstract phenomenon was instantiated in a visual model, thereby becoming useful as a design object. The prime example of such intangible phenomena suddenly becoming a design object is the *encapsulation of wirk elements* (which is constituted be two phenomena of encapsulation and wirk elements). By means of various models, design engineers were able to work on alternative wirk element encapsulations and thereby gaining different effects of platforms – effects that were not always a result of modularisation in the classical sense. An example of this is shown in the Danfoss case – see chapter 5.5.5 and figure 5.38.

Thereby, the cases also serve as a validation of the usefulness of wirk element encapsulation, i.e. encapsulation in the organ domain.

End-to-end modelling

The various models described in Part 5 cover different phases of a product platform project from the early conceptual phases to the final implementation and use stages of a platform. The puzzles in Danfoss (chapter 5.5) are used to conceptualise the platform, i.e. as a part of the preparation phases. The Product Family Master Plan is used together with a CAD skeleton model in Aker Solutions during the use of the platform, i.e. during the execution phases. The different models give an impression of the various different ways, in which a visual modelling approach can be utilised throughout a platform project from end to end.

The concept of a skeleton

In order to explain some of the phenomena related to reuse and encapsulation, the concept of skeletons is emphasised in the theoretical basis of the thesis and in two of the three cases (Aker Solutions and Grundfos). The skeleton is a placeholder for spatial relations of the features of system elements, and the concept is found both in systems theory (from a functional viewpoint) and in modern CAD systems (from a form feature viewpoint).

Modelling skeletons in a CAD system

Form feature skeletons are used in CAD systems in a Top Down Design approach. The Top Down Design approach is an approach in which spatial relations and important interfaces and features are designed before the detailed embodiment design of the parts are known. It is also a way to control constraints in assemblies in a common model, instead of constraining parts or each other successively. (see chapter 5.6).

The skeleton in a CAD model hierarchy makes way for an efficient way to control generic and variable attributes in a product family. It is – to some extent - possible to model the form features in the CAD system from a functional viewpoint. Thereby, the CAD skeleton become close to the wirk element skeleton and the CAD skeleton can be used to control wirk element encapsulation.

6.3.3 The research approach

The research approach is a mix of several research strategies.

Research Question 1

The clarification of phenomena is mainly dealt with by means of a literature review and discussions based on logical inference out of existing findings. The validation of these findings (such as the concept of encapsulation in the organ domain), is mainly based on the (hopefully) internal consistency of the argumentation of the concepts and indirectly by observing how the models of these phenomena are used and received by industrial practitioners (such as the product and production puzzles in the Danfoss case, chapter 5.5.5).

Research Question 2

The identification of models resembles more the discipline of an engineering design research approach with the development of a “support” according to the terminology of Blessing & Chakrabarti [2002]. Action research is also used as a part of the case studies in the sense that the author has taken an active part in all three case projects.

Limitations

Influencing the object of the study

The close collaboration with industry and the active involvement in cases is perhaps one of the strengths of the research. However, it also make the studies somewhat biased by the influence of the author. Strictly speaking, the author induces some changes in a company and then report on the effects of these changes. This creates a scientific contradiction in the sense that is not possible to state what the effects would have been without the presence of the author and what long term effects there will be in the companies after the projects are stopped. Will the companies continue with the models? Will the effects (if any) prevail?

This is of course a very classic research challenge. Hopefully, the setup of the study (discussed in Part 2), has helped limit the bias of the findings.

Research depth

It was chosen in the beginning of the project to try to encompass more than one company for the case study, to study different products and projects and to study different stages of a platform development project. Therefore, the study involves three companies. This somewhat limits the resources spent in each company and limits the resources spent on validation.

6.4 Future research

There are several topics to go for, should someone wish to continue this work;

- *Validating the use of the models*
  A more thorough validation of some of the models would be an interesting subject for future work. In particular the effects of the two jig saw puzzles from the Danfoss case (chapter 5.5.5). Do they in fact result in better decision making or is it just a perception in the minds of the users?
- *The Design Game as a laboratory*
  Testing the Lego Design Game as a laboratory for engineering design research would also constitute an interesting research project. It is sometimes difficult to make large scale tests of design methods. However, the Lego Design Game might be able to serve the purpose as a laboratory in which several design processes can be simulated, and thereby new design methods and tools tested. This is not necessarily limited to a platform study – single product development and engineering design disciplines might also benefit from such a test laboratory.
- *Encapsulation of wirk elements*
  A further clarification of the encapsulation in the organ domain, and the effects and nature of wirk element encapsulation needs further clarification. This thesis has scratched the surface of a very profound discussion.
- *The skeleton as a reusable element*
  The concept of a skeleton is not included as a platform element, but perhaps it should have been. Skeletons can also be reused and skeletons can also be encapsulated.
- *CAD Top Down Design as a means to control product platforms*
  In this thesis two Top Down Design approaches (the skeleton and the family table) are related to product platforms. It is the impression of the author that most modern CAD systems, with the concept of skeletons, provides a readily available means to control generic and variable attributes in a product platform. However, there very few – if any – academic reports on the use of skeletons and Top Down Design for product platform and product family design.

6.5 Concluding the PhD project

The PhD project has two overall purposes. One thing is the research work itself. Another thing is the fact, that the project serves as an education, i.e. a training to become a researcher. In this part of the conclusion, the training/educational aspect is concluded upon.

The project setup

The PhD project has been carried out by a single author yet in close collaboration with a research group at the Technical University of Denmark, consisting of four colleagues. The project was started in 2004 and ended in 2008. The thesis is published in 2009.

Much of the work has been done in collaboration with three industrial companies, in which the author has taken an active part as a project resource and as a researcher. The three companies are Danfoss Automatic Controls, (Denmark), Grundfos, (Denmark) and Aker Solutions, (Norway). These three companies have willingly taken part in the research and provided the empirical input. These cases have served as a frame for the formulation of the research questions and as a means to add validity to the findings.

When assessing the results of the work, it is noteworthy that Danfoss has covered some 60% of the expenses of the project. However, it is the impression of the author that the company did not impose any limiting restrictions on the research, nor did it direct the studies in a certain way.

Research education

The author has participated in different PhD courses, of which the Summer School on Engineering Design Research (in 2005) provided by the Design Society, is probably the most important one, when it comes to the education in the discipline of conducting research.

Participating in conferences

The author has participated in the following conferences:

Attending without presentation a paper

- IDETC/DTM 2004, ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Salt Lake City, Utah, USA, September 28-October 2, 2004
- 12th International Product Development Management Conference, Copenhagen Business School, Denmark, June 12 – 14, 2005
- The 2007 World Conference on Mass Customization & Personalisation (MCPC), MIT, Cambridge, USA, October 7 – 11, 2007

Attending and presenting a paper

- Product Development Day, Industrial seminar at the Technical University of Denmark, December 2004.
- Product Development and Management Association 2005 International Conference: Innovation in Global Product Development, "Driving Sustainable Growth and Productivity across the Value Chain", October 22 - 26, 2005, San Diego, California
- International Conference on Engineering Design, ICED'05, 15 - 18 August, 2005, Melbourne, Australia
- 9th International Design Conference, DESIGN 2006, Dubrovnik, Croatia, 2006

From attending the conferences, the author has gained a general insight in the research field, while also gaining experience in the process of writing and getting accepted papers through peer reviews. Moreover, the author has gained experience on how to present a scientific topic during a conference session to an academic audience.

Publishing in a journal

During the PhD work, the author has participated in the process of writing and publishing two articles in the International Journal of Mass Customization. The papers are listed in the reference list, [Mortensen, 2008a & 2008b].

Teaching at the university

The author has taken part in several teaching activities at the Technical University of Denmark. One of them was a basic course in engineering design. The other was partly developed and planned from scratch with two research colleagues. The topic of the course is product platform development and modelling and the course is – at the time of writing – still running for the third time with good student feedback.

Teaching in industry

As a part of the project – mainly in the company Danfoss – a lot of training and education was planned and conducted by the author. A total of some 200 employees (mainly white collar workers from R&D, marketing and operations) have been the audience of presentations and assignments made by the author. The Lego Design Game (see chapter 5.5.8) was developed in collaboration with a research colleague (Morten Kvist, also reported in Kvist [2009]), and it was a major success based on the feedback from the participants in Danfoss (and also from students at the Technical University of Denmark).

6.6 Perspectives

With this thesis I have investigated the topic of product platforms, and reported concrete ways to visually model product platforms in industrial projects. As I have written in the introduction, the incentives for many companies to pursue a product platform approach, is to be able to master the balance between external performance and internal efficiency, in order to become a stronger player in global competition. Hopefully, the description of phenomena in Part 4 and the modelling techniques described in Part 5 can inspire stakeholders and decision makers in companies to take up the challenge of global competition in their own way and develop a platform and set up models that will fit their particular organisation, market, and product opportunities.

However, it might be of use to give a few thoughts on how product platforms will evolve as a strategy of choice in the future. Over the past decade, an increasingly personalised consumerism has evolved and it has had an increasing impact on the global economy. During the final stages of this research project, the global economy experienced the worst financial crisis seen since the 1930'ies, and at the time of writing this thesis, the end and the outcome of this crisis is yet unknown. The – until then - ever increasing demands for customised products have apparently been slowed down significantly. In the same period, the environmental impact from this ever growing consumerism has reached a higher stage of awareness in the minds of consumers around the world, and it is very likely to have an impact on consumer habits. Some say that the basic driver for a product platform project is the desire to *do more with less*. Maybe companies in the future will have to utilise product platforms in order to *do less with even less*.

Publications

Peer reviewed papers and articles published during the project

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This PhD thesis describes various phenomena related to product platforms and investigates how some of these phenomena can be visually modelled in order to support decision making in industrial platform projects.

The investigation of platform phenomena is based on the notion that *reuse* and *encapsulation of platform elements* are fundamental characteristics of a product platform. *Reuse covers* the desire to reuse and share certain assets across a family of products and/or across generations of products. *Encapsulation* is seen as a process in which the different elements of a platform are *grouped* into well defined and self-contained units which are *decoupled* from each other. Based on the Theory of Domains, the concept of *encapsulation in the organ domain* is introduced, and organs are formulated as platform elements. Unlike most present perceptions of platforms and modularity, the concept of organ encapsulation makes it possible to describe the system characteristics of a product platform which is not characterised by standardised physical interfaces between the varying elements.

By means of three industrial cases, it is discussed and exemplified how some of the phenomena and effects related to reuse and encapsulation can be visually modelled during product platform projects.

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