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Brownfield Process

A Method for the Rationalisation of Existing Product Variety towards a Modular Product Family

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ABSTRACT

The purpose of the research is to define what kind of design information is needed when existing non-modular product elements are designed towards a modular product family that enables product configuration — and what kinds of steps facilitate this kind of design. Thus this thesis poses two research questions:

RQ1. How to structure the design information needed in the designing of modular product families?

RQ2. How to create the design information needed in the rationalisation of existing product variety towards a modular product family?

The research approach includes application of Design Research Methodology (DRM) as originated by Blessing & Chakrabarti (2009). This research includes four main stages (Research Clarification, Descriptive Study I, Prescriptive Study and Descriptive Study II), all focusing on the defining of influencing factors and their impacts, as DRM suggests.

This thesis considers that design reuse, product variety, standardisation, modularisation, product platforms, product families and product configuration are all main product structuring topics when an existing product assortment should be rationalised. Consideration of these topics makes up an effective tactic for the enabling of product variants to be provided for customers, without forgetting the benefits of design reuse and commonality in an industrial environment.

The contribution of the research suggests that there are five key factors from a design information perspective that are essential in modular product family development aimed at product configuration. These elements are also the answer to RQ1:

- **Partitioning logic** defines viewpoints that affect product structuring decisions from both a business and customer perspective.
- **A set of modules** includes building blocks of product variants of a product family.
- **Interfaces** (standardised) enable efficient defining of product variants in the order/sales-delivery process.
- **Architecture** describes how modules and their interfaces are related to each other. Architecture also considers layout issues such as space reservations.
- **Configuration knowledge** describes the relations between product family elements and customer needs that create a need for variety. Configuration knowledge can also present compatibilities of product elements or customer needs.

The thesis also suggests a design process known as the **Brownfield Process** (the **BfP**), and includes ten steps in which design information related to the above key factors is defined. This is the suggested answer to RQ2.

- Step 1: **Target setting based on business environment**
- Step 2: **Generic element model of the Module System**
- Step 3: **Architecture: generic elements and interfaces**
- Step 4: **Target setting based on customer environment**
- Step 5: **Preliminary product family description**
- Step 6: **Configuration knowledge: generic elements and customer needs**

- Step 7: **Modular architecture: modules and interfaces**
- Step 8: **Configuration knowledge: module variants and customer needs**
- Step 9: **Product family documentation**
- Step 10: **Business impact analysis**

The role of the BfP within the context of design research is discussed. From an academic viewpoint, there is a lack of these kinds of modularisation methods that aim at configurable products, although single aspects and key factors of the proposed method have been often discussed and their benefits and importance are emphasised separately in the literature. From an industrial viewpoint, the steps of the method can be applied in a real life environment based on the case studies. Thus contribution of the thesis can be considered worthwhile and an important addition in this research field.

PREFACE

After completing my Master of Science of Technology studies about product development and mechanical engineering in the Tampere University of Technology (TUT) in the year 2007, opportunity opened for me to start a career as a researcher and doctoral student in the research group of integrated product and production development led by Professor (emeritus) Asko Riitahuhta and therefore I want to thank him first for all his patience and support as a supervisor towards my doctoral studies.

During the past years I have had great opportunity also to work with several other intelligent people in both academia and industry and to witness different kinds of projects. I want to thank all of you including all my past and present colleagues in the Department of Production Engineering and the Department of Mechanical Engineering and Industrial Systems of TUT and all industry partners I have worked with.

I wish to express my special gratitude to Dr. Timo Lehtonen and Dr. Tero Juuti from TUT for countless numbers of inspiring and challenging discussions and all kind of support related and unrelated to my and our research. Without this possibility, this thesis would have probably never seen the daylight. I would like to thank Mr. Petri Huhtala, Mr. Mikko Vanhatalo, Mrs. Leena Ryynänen and Mr. Nillo Halonen as well as Dr. Antti Pulkkinen and Dr. Mikko Koho about early and present days in the university. I have tried to learn from you as much as my limited capabilities enable.

I am grateful to Industrial Research Fund of the Tampere University of Technology and the testament foundation of K.F. and Maria Dunderberg for the scholarships I have received. These scholarships have been in very critical role in enabling finishing this Doctor of Technology thesis. Research projects mostly funded by Tekes, the Finnish Funding Agency for Technology and Innovation, have been great help in testing and implementing the contribution of this thesis in real life industrial cases.

I want to thank external evaluators Professor Hans Petter Hildre from Aalesund University College, Norway and Professor Niels Henrik Mortensen from Technical University of Denmark, Denmark for their encouraging comments about the work.

I would like to thank consulting company Nordic Element Oy for supporting my career.

Finally, I want to thank my family and friends about the support and providing also something else to do and think about than only the research.

Tampere, April 2015

Jarkko Pakkanen

ABBREVIATIONS AND ACRONYMS

4C	Customer needs, cost to satisfy the need, communication and convenience to buy the product
4P	Product, price, promotion and place
ATO	Assembled-to-order
BfP	Brownfield Process
BOM	Bill of materials
CE	Concurrent Engineering
CSL	Company Strategic Landscape
CTO	Configured-to-order
DS I	Descriptive Study I
DS II	Descriptive Study II
DFX	Design for X
DMSM	Design Method Selection Matrix
DRM	Design Research Methodology
DSM	Design Structure Matrix
Dymo	Dynamic Modularisation
ERP	Enterprise Resource Planning
ETO	Engineered-to-order
FCA	Function-component allocation
ICD	Interface Control Document
IPD	Integrated Product Development
IT	Information technology
MFD	Modular Function Deployment
MIM	Module-Indication-Matrix
MTO	Made-to-order
MTS	Made-to-stock
Od1	Operand in state 1 (transformation process)
Od2	Operand in state 2 (transformation process)
PDD	Property Driven Development
PMPP	Post Mass Production Paradigm
PFMP	Product family master plan
PS	Prescriptive Study

PSBP	Product Structure Blue Print
PS-FEM	Product Structuring Finite Element Method
QCD&F	Quality, cost, delivery and flexibility
QFD	Quality Function Deployment
RC	Research Clarification
R&D	Research and development
RQ1	Research question 1
RQ2	Research question 2
SE	Simultaneous Engineering
TDesP	Theory of Design Processes
TTS	Theory of Technical Systems
VAM	Variety Allocation Model

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1 INTRODUCTION

This research is about modular product family development in an engineering design context. There are companies which are competing for the share of a single or several customer segments. When a company is trying to fulfil the needs of several customer segments, one challenge is the cost effectiveness of offering product variety. Randall & Ulrich (2001) define product variety as the number of different versions of a product offered by a firm at a single point in time. The company should have the capability to answer to a number of customer requirements in a way in which the operations of the company would be profitable enough.

Based on observations performed in research projects, such as the one discussed in this thesis, one phenomenon in the product manufacturing industry is that the number of items has become high during the time when the company has offered products for different customer segments. In the worst case, there can be different solutions to the same customer needs without any good reason. Yeh (1991) explains that although the broadening of product variety increases the marketing competitive power of the company, it also causes the company to lose cost advantages. Forza & Salvador (2002) add that the greater product variety can also create information management issues. Information to be used in the order-delivery process can be incomplete, incorrect or lost.

In this thesis, the differences between new product development, redesigning and incremental designing are also discussed. Challenges exist to industrial companies in designing completely new products as, for instance, Oja (2010) explains. Taking evolved market segments that would facilitate the making of optimal product structure choices into consideration and drafting a new product family by forgetting the existing product solutions is often impossible. Based on the literature review, the main reason for this is the scarcity of resources and the different kinds of risks. Abandoning the existing product solutions might, for instance, be difficult because of the current customer portfolio. Customers might need long-term service for the products whose life cycle is long, and new product development includes, for example, risks related to time, cost and technology maturity perspectives. Thus incremental designing and partial redesigning are more common.

Standardisation, modularisation, product platforms, product families and product configuration are considered as a means for the effective defining of products for changing customer needs in product delivery projects by reusing technical solutions which are developed outside the order-delivery process. In the long run, these strategies of product development are typically considered to be more profitable than fully projecting procedures in which each customer delivery is designed from scratch. Different definitions have been presented for these means of product development. Standardisation of components and processes is considered as a key enabler of effective and high-quality operations such as product development and production. Modularisation is discussed often to include the designing of modules, which are typically considered as interchangeable building blocks of the product variants and their interfaces, and thus the defining of the modular architecture of products. Product platform is often understood as a reusable standard section of a product family which remains the same no matter what product variant of a specific product family is studied. Thus a product family consists of different product variants (sometimes the terms product instance and product configuration are also used) and the aim of the product family is to correspond to a specific group of recognised customer requirements against which the product family is designed. The aim of product configuration as an activity is to define a customer specific solution by utilising the product family structure.

According to the literature review, modularisation, product platforms, product families and product configuration are typically related to the production paradigm of mass customisation. Practice has proven though that it is not always possible to modularise the product perfectly in a way that it would consist only of standardised elements in order to satisfy all of the customer orders. This means that there might also be a need to design customer-specific sections for the products in order-delivery projects. Structure of these kinds of products is considered as partly configurable (Juuti 2008) consisting of standardised and configurable sections and also of unique sections.

Thus at the beginning of this thesis, production paradigms are explored. The aim is to clarify what these paradigms mean and what kinds of properties typical products have within each paradigm. The main reference is the publication by Victor & Boynton (1998), but other views are also considered. In addition to paradigms, in order to piece together a broader view of the research area, the main approaches, models and processes of design sciences and product development are studied. These include, for example, publications by Hubby & Eder (1988, 1996), Pahl & Beitz (1996), Ulrich & Eppinger (2008) and Andreasen (2011). Several basic principles and viewpoints, as well as design methods, have been presented related to the enabling of standardisation, modularisation, product platforms, product families and configuration. In this work, the properties of these design strategies are also studied. The study reveals that generic design processes and models do not consider in deep detail these strategies, but that more specific publications are more comprehensive regarding these aspects. Research on the methods reveals the main categories of these design strategies, which are discussed later on in this chapter.

Essential design information elements, which relate to modularisation, the designing of product platforms and product families and the defining of customer specific product configurations, can be recognised from the literature. This thesis suggests, as a principle result based on findings from the literature, that there exist five main design information elements, including partitioning logic (reasoning for the modular structure/product family), set of modules, interfaces, architecture and configuration knowledge. It is stated that consideration of these elements facilitates the designing of a modular product family and affects the risks, which Forza & Salvador (2002) discussed earlier in this chapter.

As has been discussed, a number of different design methods have been presented for the rationalisation of product variety. Approaches can be categorised as, for example, function-oriented approaches, scale-based approaches, module-based approaches, indices, mathematical optimisation models with algorithms and matrix approaches. These methods include several interesting viewpoints. In spite of this, based on the literature review done in this thesis, a method that would explicitly consider the previously mentioned five design information elements and suggest steps that would support the defining of design information related to these elements is missing, although these information elements are considered important.

For this reason, the main objective and also the main contribution is to define a design method that would consider the above-mentioned design information elements of partitioning logic, set of modules, interfaces, architecture and configuration knowledge in the designing of a modular product family whose aim is to rationalise an existing product assortment. Thus the method is not primarily meant for the designing of a completely new product family, but rather presumes that aspects related to existing solutions and the customer and business environment are available and usable in the rationalisation work of the product variety. The suggested method is analysed and the results suggest that the presented approach has method-like characteristics. An industrial case, from the sheet metal handling industry, is used for validating the main aspects of the method.

The Design Research Methodology (DRM) of Blessing & Chakrabarti (2009) is applied to this thesis. This research method includes four main steps, which are Research Clarification, Descriptive Study I, Prescriptive Study and Descriptive Study II. Research questions and research method are discussed in Chapter 2 in more detail. Chapter 2 also includes a presentation of the structure of this thesis.

2 RESEARCH DESCRIPTION

This chapter presents research objectives and questions and research method. An outline of the thesis is also presented in this chapter.

2.1 Research objective and research questions

The objective of this research can be divided into the viewpoints of the three stakeholders alphabetically: academy, author and industry. The main contribution of the thesis is in the context of methods for the rationalisation of the existing product variety towards a modular product family.

The academy, a community of practitioners mainly consisting of other researchers in the same research field, is a very important target group for the thesis. Academic objectives include a) studying the existing literature in the research area and discussing its advantages and disadvantages, b) presenting a design method for the designing of modular product families that could facilitate the design situation and c) analysing the contribution of the thesis as regards the trajectory of design research in modularisation, product platform and a product family development context.

The author of the thesis aims to increase and develop skills needed in a scientific research approach and to improve his knowledge of the topic, with the aid of this dissertation process. The assumption of the author of this thesis is that an extensive literature review will facilitate the achieving of this objective.

The industry also has a significant role in this thesis because the aim is that the contribution of the thesis would be beneficial to industrial companies with certain properties. One of the most important of these properties, and one that would describe which companies the contribution of the thesis would benefit from, is that a) a company needs to have product variants in their product offering in order to stay competitive in the markets but b) the company also understands that the existing products could include more standardisation and commonalities and that current products have potential from a redesign perspective in order to increase competitiveness and c) the company also wants to invest in product development. These aspects define the core of the industrial situation at which the contribution of the thesis is aimed. Thus one objective in this thesis is to explain the contribution for rationalising the existing product variety of a company towards a modular product family, including what kind of design information needs to be designed step by step.

Based on the research objectives, two research questions were formulated:

RQ1. How to structure the design information needed in the designing of modular product families?

RQ2. How to create the design information needed in the rationalisation of existing product variety towards a modular product family?

Based on these research questions, the expected contribution to RQ1 improves an understanding of modular product family development, especially from an academic perspective, whereas the expected contribution to RQ2 aims to present a process that is targeted at the manufacturing industry.

Eskola & Suoranta (2001) discuss, in their book about qualitative research, that observations by someone are always built upon his/her earlier experiences. In this research, a forecast that would restrict research actions is not set, but the possibility for surprise or learning is enabled, as Eskola & Suoranta describe. Thus hypotheses are not presented in this qualitative research.

2.2 Research methodology

At a higher level, this thesis is about engineering design. According to Hubka & Eder (1988), **engineering design** is a process done by humans. They state that this process is helped by technical means that facilitate the changing of requirements (information) to specifications (information) of a technical system so that the technical system would fulfil the needs of humankind. There exist also definitions about designing. Blessing and Chakrabarti (2009) defines designing as follows: "***designing** includes activities that generate and develop a product from a need, product idea or technology to the documentation needed in realising the product and to fulfilling the needs of the user and other stakeholders*".

Science has been characterised as a systematic way for the pursuit of new knowledge (Niiniluoto 1997). A research discipline of science for and about engineering design has been presented. **Design science,** according to Hubka & Eder (1988, 1996) includes a collection (a system) of logically connected knowledge in the domain of designing. They explain that design science contains scientific research on design activities and the concept of design methodology and technical information. It focuses on the problem of recognising all occurrences and classifications of the systems to be developed, and on the design process itself, according to Hubka & Eder. It is also explained that the aim of design science is to produce suitable information for designers. The development of design science has two alternative paths, as presented by Hubka & Eder (1988, 1996):

- "*Design science can develop by the conventional empirical way of observing, describing, abstracting, generalising, formulating guidelines, modelling, refining.*"
- "*Design science can develop by postulating a set of hypotheses, formulating a theory, modelling, refining and only subsequently testing.*"

Other kinds of definitions about design science also exist. Olkkonen (1994) explains that design science can be applied to research topics in which complete positivism is impossible because of limited possibilities for observing.

There are two means for improving design practice, according to Blessing & Chakrabarti (2009). They define that design research integrates the development of understanding and the development of support in design, as described in Figure 2.1. These two development tasks that make designing more effective and efficient and further on enable more successful products are, according to Blessing and Chakrabarti:

- "*Designing can be improved by formulation and validation of models and theories about design with all its perspectives (people, product, knowledge/methods/tools, organisation, micro-economy and macro-economy).*"
- "*Designing can be improved by development and validation of support founded on these models and theories.*"

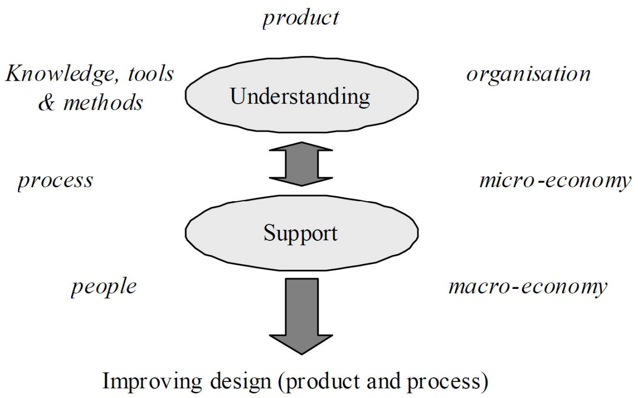


Figure 2.1. *Development of understanding and support and taking surrounding perspectives into consideration are key issues in improving design, according to Blessing & Chakrabarti (2009).*

How does design science relate to **other science views**? Figure 2.2 by Olkkonen (1994) presents a generic impression about different science views, highlighting **natural sciences** and **human sciences**. Several other definitions are presented when discussing research approaches. Leedy & Ormrod (2005) discuss the idea that positivist approaches are more common in **quantitative research** in which relationships among measured variables are studied. Niiniluoto (1997) explains that positivism aims to describe regularities related to observable events. Q**ualitative research** is often referred to as an interpretative, constructivist or post-positivist approach in which more a holistic view of the research process is allowed, according to Leedy & Ormrod (2005). Niiniluoto (1997) considers interpretative approaches as hermeneutics.

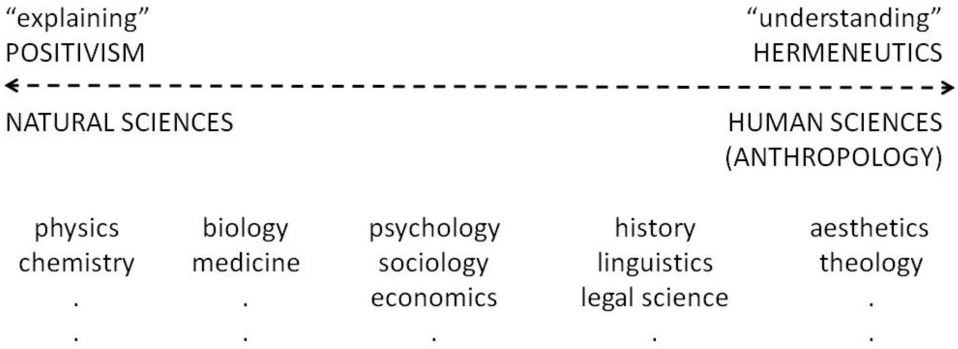


Figure 2.2. *Methodological continuum of real science views according to Olkkonen (1994).*

Although the study by Olkkonen is from an industrial economics perspective, it can also be recognised that design science is not considered as a major scientific whole in general. The positioning of design science on the line presented in Figure 2.2 could be somewhere in the middle because it cannot be considered as either purely positivism or hermeneutics.

Categorisation into descriptive and normative research has also been discussed (Kasanen et al. 1993, Olkkonen 1994). Descriptive research is also referred to as describing and explaining, according to Olkkonen (in his study he also refers to an encyclopaedia in Finnish (Iso Tietosanakirja, osa 13. 1937, Otava). Leedy & Ormrod (2005) explain that **descriptive research** examines a situation "as it is". This means that changing or modifying the studied situation and defining the cause-and-effect relationships is not done. Leedy & Ormrod present, for example, observation studies, correlational research and survey research for this category. Thus these kinds of research types are understood mostly as quantitative research and are not discussed in greater detail in this thesis. **Normative research** sets generic guidelines and appreciative or commanding special rules (Olkkonen 1994). Based on this definition, the aim of this research can be considered more as a normative research than descriptive research. Olkkonen also explains that normative research is considered often in human sciences.

There are several research designs that are suitable for qualitative research in general, such as case study, ethnography, phenomenological study, grounded theory study and content analysis. Leedy & Ormrod (2005) explain that the purpose of **case study** is to focus on one or a few situations or persons in depth. They discuss the idea that **ethnography** is suitable for the studying of the culture of a group. **Phenomenological studies** are aimed at understanding a particular phenomenon and experiences from the viewpoint of the participant, according to Leedy & Ormrod. **Grounded theory study** aims to derive a theory from field-based collected data, whereas **content analysis** is directed at the identification of patterns, themes or biases based on the examination of a particular body of material, according to Leedy & Ormrod (2005).

Blessing & Chakrabarti (2009) have observed that there are challenges in defining the contents, the research approach and the community of research in engineering design. Cantamessa (2001), according to Blessing & Chakrabarti (2009), analysed the reasons for the lack of established research methods in engineering design. He found that the main reasons are:

- the relative youth of the discipline
- different backgrounds of researchers
- no such academic discipline exists from which the design discipline could have been defined
- complexity of designing

Blessing & Chakrabarti (2009) summarised that there are three main issues in design research:

- "*the lack of overview of existing research*"
- "*the lack of use of results in practice*"
- "*the lack of scientific rigour*"

Recognised problems, especially the lack of scientific rigour and precision, resulted in the defining of **Design Research Methodology (DRM),** according to Blessing & Chakrabarti (2009). DRM includes four stages, as shown in Figure 2.3. The first step, Research Clarification (RC), includes literature analysis and results in goals for the research. The purpose of the second step, Descriptive Study I (DS I), is to obtain a better understanding of the research area. The third step, Prescriptive Study (PS), concentrates on supporting the research goal by, for example, tools or methods. The fourth step, Descriptive Study II (DS II), focuses on evaluation. (Blessing & Chakrabarti 2009)

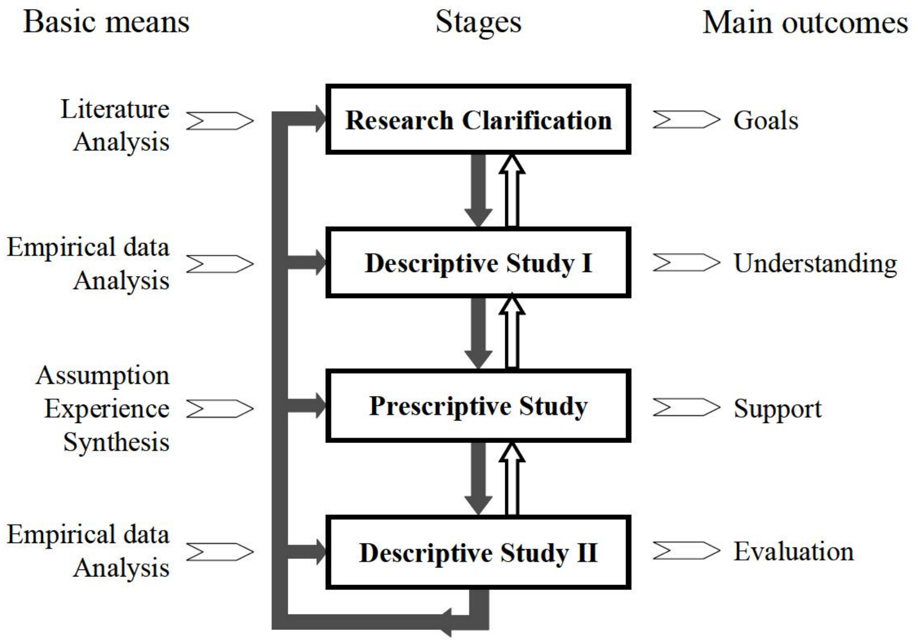


Figure 2.3. *Design Research Methodology framework (Blessing & Chakrabarti 2009)*

DRM framework is selected for this dissertation. The following sections 2.2.1 – 2.2.4 present the main content of each step on a generic level. DRM is justified for this research compared to other research methods in qualitative research because it supports the research context by presenting context-relevant supporting tools, checklists and examples of how the method can be applied in engineering design.

2.2.1 Research Clarification

Research Clarification includes defining the aim, focus or the scope of the research project. The aim is to find evidence, or at least indications, that support presented presumptions in order to create a realistic objective for the research. The literature review supports this step. The aim is to seek out factors from the existing literature that affect clarity of the task and also the success of the result, as well as links that connect these two issues. These factors are used for forming **a description of the current situation** and also a **description of the desired situation,** in order to present all assumptions explicitly. DRM also highlights defining of the criteria that can be used as a measure for evaluating the research result, such as design support. The authors of DRM explain that when these measures are defined, the time frame of the research project should be considered. This is because proof of some measures might take too long a time. (Blessing & Chakrabarti 2009)

DRM suggests different tools for this step, such as the initial **reference model** and initial **impact model**. Blessing & Chakrabarti explain that these kinds of models facilitate describing the situation in design and that these models can be used for benchmarking of the intended improvements. Models consist of elements known as influence factors. These factors can be defined based on literature finding, presumption, experience, research objectives, focus, research questions or hypotheses, according to Blessing & Chakrabarti (2009).

Blessing & Chakrabarti (2009) also discuss research plans. They define that the plan should include research focus and goals, research problems and main research questions and hypotheses, relevant areas to be consulted (explored), approach (type of research including main stages and methods), expected (area of) contribution and deliverables and time schedule.

2.2.2 Descriptive Study I

Descriptive Study I focuses on literature review. The aim of this step is to find more influencing factors in order to describe the current situation in more detail. Authors of DRM state that a description of the current state needs to be detailed enough in order to define factors that would improve the clarifying of the task. Blessing & Chakrabarti (2009) explain that this step can also include an analysis of the empirical data, such as interviews of designers, if enough evidence is not found from the literature. They argue that analysing of empirical data might reveal typical properties of the insufficient clarifying of the task. Blessing & Chakrabarti conclude that insufficient defining of the research problem might cause unnecessary modification to be needed in the later steps.

2.2.3 Prescriptive Study

Prescriptive Study also considers the literature review because direct findings from the literature can also be used for improving designing. Because of improved understanding regarding the current state, a description of the desired situation is made. This description describes the vision by considering how one or more factors of the current state lead to a realisation of the desired state. In this step, design work that aims to improve the research problem is done, as Blessing & Chakrabarti also explain. Prescriptive Study requires an understanding of the different influence factors that have relations with each other and a description of the desired state. (Blessing & Chakrabarti 2009)

2.2.4 Descriptive Study II

Descriptive Study II focuses on evaluating the developed concept. In this step, the impact of the design support is discussed and the ability of the design support to realise the desired state is analysed. Blessing & Chakrabarti (2009) explain that this step typically includes empirical study with the help of a case for gaining an understanding of the actual use of the design support. This way the applicability of the support can be analysed. DRM defines that usefulness of the design support is based on the success criteria that need to be defined until the design support is realised.

2.3. Scientific novelty and contribution

Scientific novelty and contribution of this thesis is as follows:

- Reviewing of the existing design methods of modular product families.
- Suggesting key design information elements that facilitate the designing of modular product families (answer to RQ1).
- Suggesting a design method that considers the above-mentioned key design information elements in the rationalisation of an existing product assortment towards a modular product family (answer to RQ2).
- Comparing of the suggested novel method to existing methods in the designing of modular product families and also to other views in engineering design.

Based on RQ1, this thesis presents the key design information elements that facilitate the designing of modular product families. Suggested elements are partitioning logic, set of modules, interfaces, architecture and configuration knowledge.

- **Partitioning logic** defines viewpoints that affect product structuring decisions from a business and customer perspective.
- **A set of modules** includes building blocks of product variants of a product family.
- **Interfaces** (standardised) enable efficient defining of product variants in the order/sales-delivery process.
- **Architecture** describes how modules and their interfaces are related to each other. Architecture also considers layout issues such as space reservations.
- **Configuration knowledge** describes relations between product family elements and customer needs that cause the need for variety. Configuration knowledge can also present compatibilities of product elements or customer needs.

The literature review reveals that these elements are considered important in this research field of product development, but that design processes that aim at considering all of these elements are missing. Thus the answer to RQ2 suggests a design method known as the Brownfield Process (BfP). This is the major contribution of this thesis. This method includes ten steps:

- **Step 1: Target setting based on business environment**
- **Step 2: Generic element model of the Module System**
- **Step 3: Architecture: generic elements and interfaces**
- **Step 4: Target setting based on customer environment**
- **Step 5: Preliminary product family description**
- **Step 6: Configuration knowledge: generic elements and customer needs**
- **Step 7: Modular architecture: modules and interfaces**
- **Step 8: Configuration knowledge: module variants and customer needs**
- **Step 9: Product family documentation**
- **Step 10: Business impact analysis**

In the ten steps of the method, the previously mentioned five key elements (partitioning logic, set of modules, interfaces, architecture and configuration knowledge) are considered. The method is presented in Chapter 4 in detail.

2.4 Outline of the dissertation

This thesis includes seven main chapters. Chapter 1 includes introduction of the thesis. Chapter 2 explains what this research is all about, including a discussion of research objective, research questions and research method. Chapter 3 is the largest chapter in the thesis, and includes a literature review focusing mainly on the product development aspects. Chapter 4 presents design support for this thesis. In this case, the design support is a design method for the designing of modular product families. This support is the main contribution of the thesis. Chapter 5 explains how the design support is used in an industrial case. Thus this chapter validates the design support. Chapter 6 considers conclusions and the value of the proposed design support. Contributions and answers to research questions are summarised in this chapter. Chapter 7 includes discussion with suggestions about the need for future research. Chapter 8 presents a final summary of the thesis.

From a DRM perspective, RC is done mainly in Chapters 1, 2 and 3, DS I in Chapter 3, PS in Chapter 4 and DS II in Chapters 5, 6 and 7.

3 LITERATURE REVIEW

This chapter includes a literature review of the thesis. The main focus is on products and product structuring. The role of products as artificial and non-natural objects is first examined. This provides a fundamental foundation for this thesis. Then a review of production paradigms from a product perspective is discussed. An understanding of dominant paradigms is significant because they provide model solutions and present different beliefs. The third section considers the role and properties of a product from a competitiveness viewpoint. These aspects are important in order to guarantee that products are successful not only from a customer viewpoint but also from a company and business viewpoint. After that, in the fourth section, a collection of knowledge regarding design context known as Design Science is presented. This is an often- presented area in the research field of engineering design because it includes a wide perspective on designing and thus it is also discussed in this thesis. The fifth section explains how products can be defined from different perspectives and what kind of product structuring techniques exists in general. This section considers the main topics of this thesis such as modularisation, product platforms and product families, topics which are presented as high-level model solutions for the research problem. Different product development processes and industrial viewpoints are also discussed in this chapter. The purpose of studying these topics is to gain an understanding of the contents of typical engineering design processes and to understand what kind of product design is emphasised in an industrial environment in general. The final section of this chapter presents existing design methods related mainly to modularisation, product platform and product family development. The aim of studying these topics is to facilitate suggesting of a contribution that could aid in answering the research questions presented in the previous chapter.

3.1 Artificial objects and designing

Simon (1996) discusses artificial objects and phenomena as an opposite to natural objects and phenomena. Simon defines four main differences between artificial and natural:

- People have made artificial objects, not nature
- Artificial objects can imitate natural things, but they are not natural
- Artificial objects can be described according to their functions, goals and adaptability
- Artificial objects are usually described using imperatives and are descriptive when they are being developed

Simon (1996) also explains that an artefact can be understood as an interface between the internal and external environment. He defines the internal environment as including the core of the artefact and its structure and function, whereas external environment means the environment in which the product is used. Goals are pursued by adapting the internal environment to the external environment, driven by the business goals and capabilities of company. This is a significant challenge to designers. (Simon 1996)

According to Simon (1996) a theory of design includes principles for deciding priority and sequence in the design process as well as a consideration of the essential shape of the design. He continues that the aim of the design process is often to find a satisfactory design rather than an optimum design. Simon also underlines the fact that the sequence of a design process and the division of labour can affect both the nature of the final design and the efficiency of the design work. (Simon 1996)

To conclude, it was discussed by Simon that there exist artificial objects such as man-made products and natural objects. By using this kind of high-level classification, it can be encapsulated that this thesis focuses on the former. Simon also highlighted the basics of design processes. These are important fundamental aspects because the research objective of this thesis also considers design processes.

3.2 Product view in production paradigms

In this chapter, the backgrounds of the topic of the thesis are studied from a paradigm perspective. Evolution of a production environment is commonly explained using paradigms. The aim is to understand and describe briefly the "big picture" path that has led to core topics of this thesis. First the definition of paradigm is discussed and then multiple production paradigms are presented and the nature of product in each paradigm is discussed.

3.2.1 Definition of paradigm

Thomas S. Kuhn has been considered to be one of the most significant persons in the field of the philosophy of science. He was originally a physicist but eventually ended up studying the history of science. When Kuhn was working with social scientists he noticed that, compared to natural scientists, social scientists have more disagreements about the nature of legitimate scientific problems and methods. In researching the source of difference to the above-mentioned issue he began to use the term "paradigm", leading to the discovering of the role of paradigms in scientific research. Kuhn defines the word paradigm as follows: "*Paradigms are universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners*". (Kuhn 1996)

Kuhn explains that paradigm suggests which experiments are worth performing and which are not (latter e.g. too complex or not focusing on the main objective). It is explained that paradigm facilitates ending the interschool debate and constant iteration of fundamentals and unites the group of researchers to study the selected phenomena in greater detail. When working in a specific paradigm, fact collection and theory articulation are highly focused activities and the effectiveness of the development of science increases, according to Kuhn. Thus paradigm-based research can also be referred to as highly directed research. In the pre-paradigm period, when there are multiple competing schools, evidence of progress is hard to find except for the progress inside certain schools as defined by Kuhn.

There also exist other publications in which paradigms have been discussed. Blessing & Chakrabarti (2009) discuss the idea that each discipline has its underlying paradigms. They also explain that it is important to be aware of existing paradigms because they might constrain and set requirements on designing, and also suggest potential approaches and methods to apply.

Kuhn defines transformation from one paradigm to another as scientific revolution (progress) and a usual development pattern in mature science. The process from one paradigm to another includes producing a synthesis able to attract most of the next generation's practitioners and the gradual disappearance of the older schools, mainly because most of their members transfer to the new paradigm and abandon the practice of the science the old paradigm defines. The success of a paradigm depends on the ability of the paradigm to solve problems that the group of practitioners has recognized as critical. Success is not necessarily to solve the problem completely but the success can be simply a promise of success in selected and still incomplete examples. (Kuhn 1996)

Kuhn introduced three focus classes for factual scientific investigation which aren't usually distinct in paradigm-based research, according to him. A first class of facts is particularly revealing of the **nature of things in a certain paradigm**. Paradigm enables the research of these facts in more detail and in a larger variety of problems. A second class of factual determinations includes **facts which can be compared directly with predictions from the paradigm theory**. A third class defines **fact-gathering activities** of normal science (the basic assumption in normal science is, according to Kuhn, that the scientific community knows what the world is like). These activities consist of empirical work to define the paradigm theory, to resolve ambiguities and to permit the solution of problems. (Kuhn 1996)

Paradigms in the scientific environment have been discussed in this section. These definitions can also be expanded to human and goal-oriented activities. Thus in the next section impressions regarding production paradigms are studied.

3.2.2 Overview on production paradigms

There are different views on what kind of paradigms have existed, exist and will exist based on different backgrounds of authors. Victor & Boynton (1998) recognized five paradigms, each describing a different kind of work. The recognized paradigms are craft, mass production, process enhancement, mass customization and co-configuration. The wholeness of paradigms can be understood as a learning system, according to Victor & Boynton. They argue that each paradigm has its own typical properties (especially markets) and it is not possible to operate in the latest paradigm without experiencing the previous paradigms. Transformation is needed in order to move from the previous working paradigm to the next. For example, modularisation is an enabler of transformation in moving from process enhancement work into mass customization work. This has been illustrated in Figure 3.1 and discussed more in the following paragraphs. (Victor & Boynton 1998)

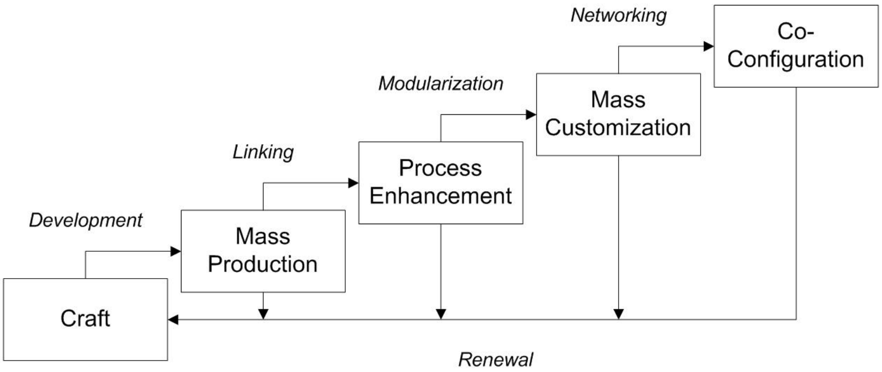


Figure 3.1. *The transformation path from craft to co-configuration. Renewal of work is possible from any paradigm. (Victor & Boynton 1998).*

Victor & Boynton (1998) have summarised craft, mass production, process enhancement and mass customisation paradigms from a knowledge point of view (see Figure 3.2). They highlight the important role of the development of knowledge and discuss the correct path that is needed in order to apply a certain kind of work.

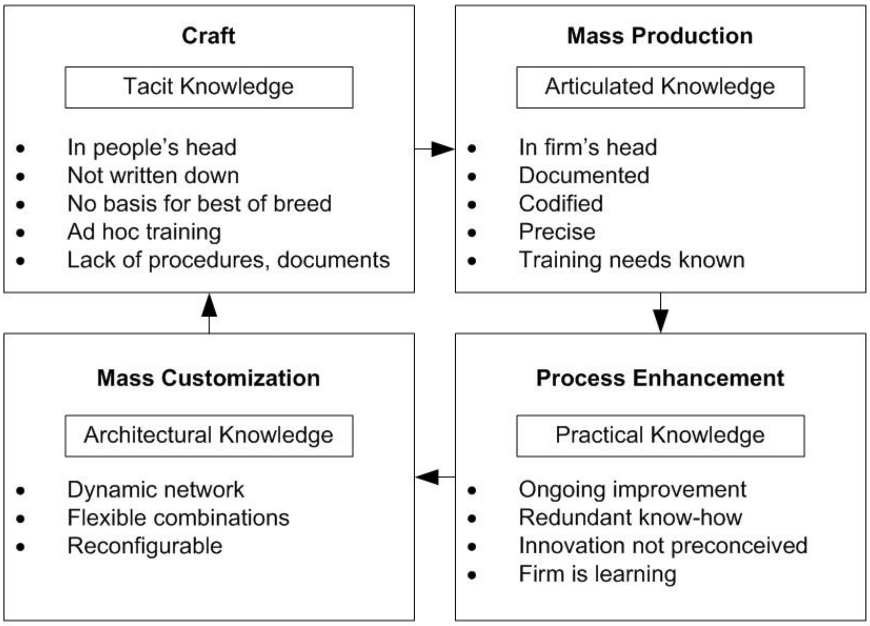


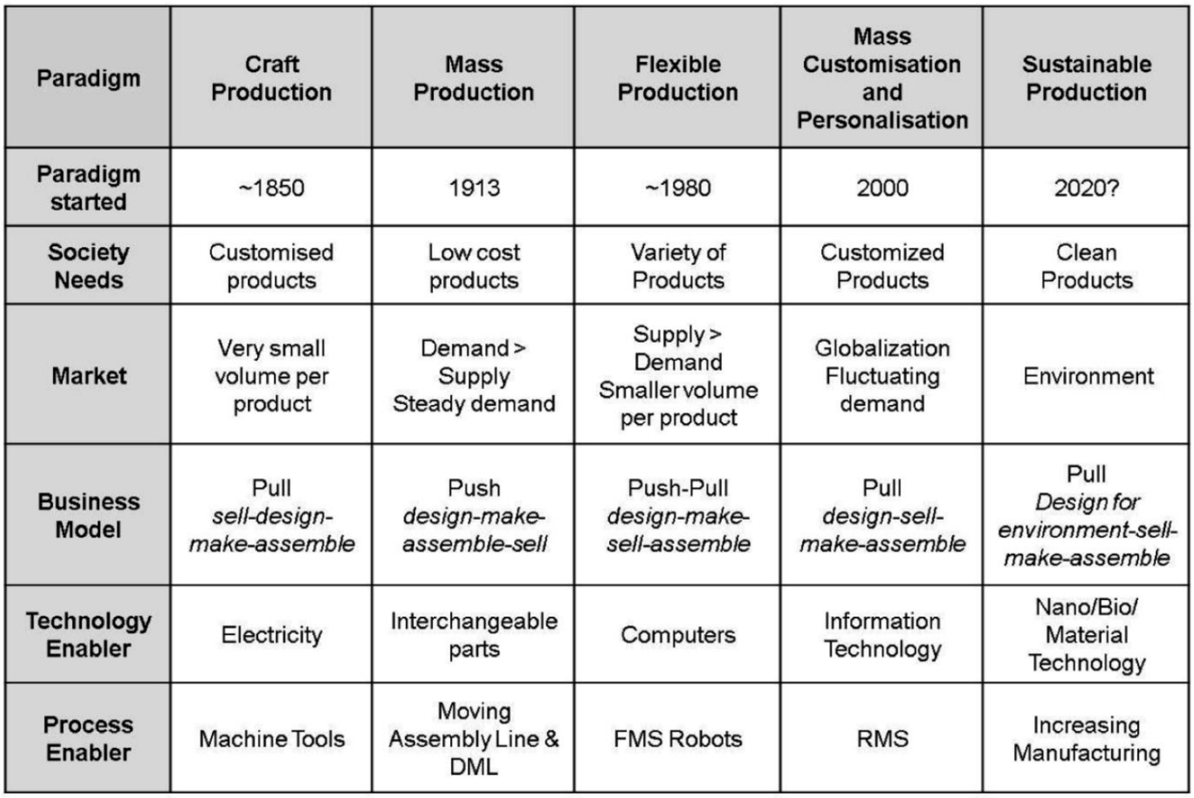
Figure 3.2. *Victor & Boynton (1998) illustrate transformation of work strictly linked with evolution of knowledge starting from tacit knowledge in craft work. In the figure the link from mass customization to craft means renewal of work.*

Victor & Boynton (1998) highlight that it's not common to achieve a certain paradigm without learning from earlier paradigms; however, exceptions do also exist. These companies have market positions which allow for inefficiency and bad performance. It is critical to identify the market type aimed for by analysing demand alternation and the need for variations and globalism. Not every company needs precision products made using mass customisation, according to Victor & Boynton.

There are also other descriptions of how the type of work has evolved during the time. Jovane et al. (2003) present viewpoints highlighting production and automation points of view. They define that the role of the manufacturing industry has a significant role in regard to wealth, creation of jobs and quality of life. Manufacturing is covering the human industry value chain, from human needs to industry response, using products, services and processes of the company. As Kuhn (1996) described, the paradigm changes as scientific revolutions occur, while Jovane et al. define that drivers to these revolutions (or in other words: demand) come from social, technological, economic and ecological environments. They introduce the idea that flexible manufacturing systems have been major enablers for mass customisation. Hence flexible production falls between the work paradigms of mass production and mass customisation in their description. Jovane et al. also define that sustainable production might be the next paradigm beyond mass customisation. This has been presented in Table 3.1. (Jovane et al. 2003)

Table 3.1 includes definitions of key drivers and enablers of each paradigm. Of this presentation, it can be seen that society's needs describe the nature of the product in each paradigm. Jovane et al. suggest that customised products are related to craft production and mass customisation and personalisation. The driver of mass production is low cost of products. Flexible automation is considered as an enabler of variety of different products. Jovane et al. predict that emphasising the environmental friendliness of products is very important in the future.

Table 3.1. *An alternative viewpoint on production paradigms that suggests that flexible automation has lead to mass customization and which further on might lead to sustainable production. (DML = Dedicated Machining Line, FMS = Flexible Manufacturing Systems, RMS = Reconfigurable Manufacturing Systems) (Jovane et al. 2003)*



Paradigm	**Craft Production**	**Mass Production**	**Flexible Production**	**Mass Customisation and Personalisation**	**Sustainable Production**
Paradigm started	~1850	1913	~1980	2000	2020?
Society Needs	Customised products	Low cost products	Variety of Products	Customized Products	Clean Products
Market	Very small volume per product	Demand > Supply Steady demand	Supply > Demand Smaller volume per product	Globalization Fluctuating demand	Environment
Business Model	Pull *sell-design-make-assemble*	Push *design-make-assemble-sell*	Push-Pull *design-make-sell-assemble*	Pull *design-sell-make-assemble*	Pull *Design for environment-sell-make-assemble*
Technology Enabler	Electricity	Interchangeable parts	Computers	Information Technology	Nano/Bio/ Material Technology
Process Enabler	Machine Tools	Moving Assembly Line & DML	FMS Robots	RMS	Increasing Manufacturing

Juuti & Lehtonen (2006) have described relations between mass products, mass customised products, partly configurable products and unique products if economies of scale and the fit to customer needs are observed. This is presented in Figure 3.3. Based on the paradigms discussed by Victor & Boynton (1998) and Jovane et al. (2003), it can obviously be stated that mass products represent mass production paradigm, mass customized products represent mass customization paradigm and unique products represent craft production paradigm. But what about partly configurable products? Juuti & Lehtonen suggest that, based on empirical findings from the shipbuilding industry, partly configurable products are located almost at the same position as the unique products, since they meet the customer requirements almost as well. If economies of scale are studied, partly configurable products are not as good as mass products or (fully) configurable products because there are unique elements in the partly configurable product structure. Nevertheless, partly configurable products are considered better than unique products from economies of scale viewpoint as represented in Figure 3.3 Partly configurable products are discussed in more detail in Chapter 3.5.8.

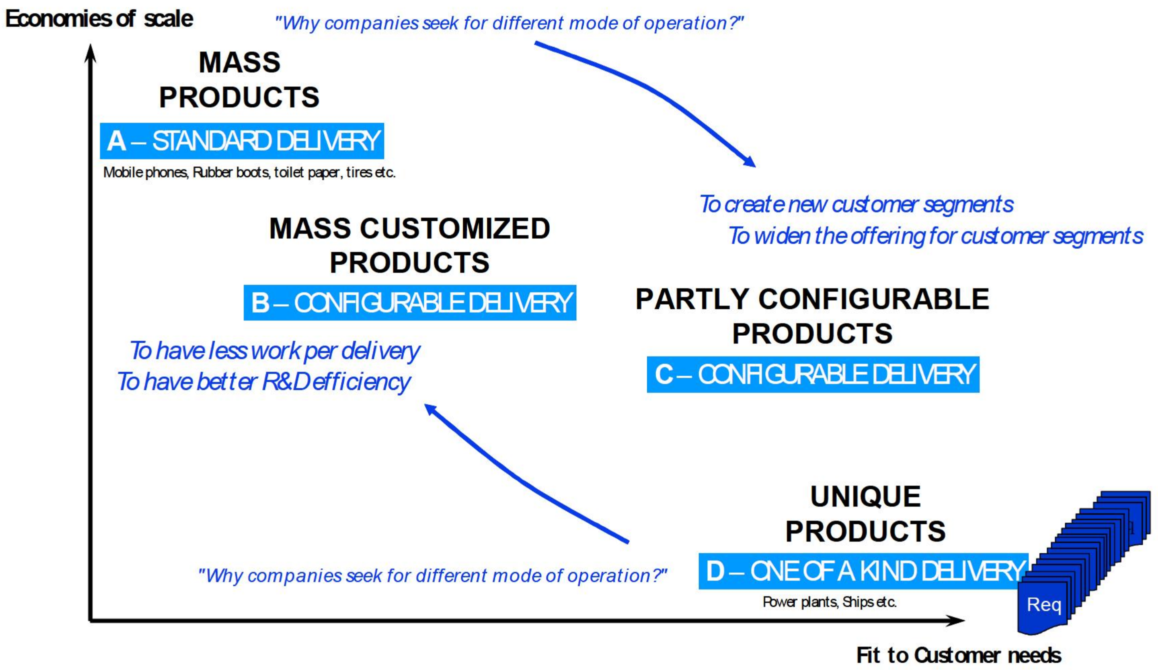


Figure 3.3. *Partly configurable products are a relevant product type besides mass products, unique products and mass customised (fully configurable) products, according to Juuti & Lehtonen (2006).*

There is also research in which other separate production-related paradigms have been discussed. One example is the study by Umeda et al. (2000) in which a paradigm after mass production, known as Post Mass Production Paradigm, is discussed. Chapters 3.2.3 – 3.2.11 present the basics of the paradigms, mainly focusing on the recognised paradigms by Victor & Boynton (1998) and Jovane et al. (2003). The emphasis is to study what the ideology is in each paradigm and how the product is seen in each paradigm.

3.2.3 Craft

According to Jovane et al. (2003), craft work means producing exactly the product that the customer wants, usually one at a time. Hubka & Eder (1988) have defined that these kinds of one-off products can cause widely differing degrees of complexity for work, especially for product development because the product must be successful. The strength of craft is nevertheless said to be in inventing new things, according to Victor & Boynton (1998). Thus craft can also be defined as engineered-to-order (ETO) kind of work. In craft work, the personal know-how (implicit knowledge) is applied to create value. It is explained that craft is typical for small groups in which the way things can possibly be done is located in one’s head and is not documented anywhere. This means that personal experience has a high role in craft work. Craft work is also the most customer-oriented and flexible way to fulfil the demand or the requirements in niche areas where investments in mass production are not reasonable. The cost of craft solution is typically high. There are also other challenges in craft. If people with the implicit knowledge of the work change companies, the knowledge disappears with them. Quality varies in craft because the people who perform the product instance may be different. The third issue concerns the management of the work. Management is difficult if a clearly described understanding of the work is missing. Craft work disappears when one of the best ways to do the work is found by way of learning and the work is described in more detail. This description of work creates articulated knowledge. (Victor & Boynton 1998; Jovane et al. 2003)

3.2.4 Mass production

Craft is not the best way to do work if the market becomes more and more interested in the result of the work and the demand increases. In mass production, products are identical and standardised and they are made in high quantities, according to Pine (1993) and Jovane et al. (2003). An enabler of mass production is to transfer the accumulated or articulated knowledge of the craft workers, which is documented and collected by management, to create a step-by-step production process. The achieving of more efficient production than in craft is possible by selecting best processes and developing repeatable tasks, hierarchical control systems, standard routines, automation and training people. Requirements of workers are reduced in mass production work compared to craft work. This results in more stable quality. Mass production is suitable for achieving value through predictable, standard, no-surprise and low-price commodities. Thus mass products can be defined as having a made-to-stock (MTS) kind of order-delivery process. Many companies stay in the mass production paradigm as long as markets have demand for their products. The downside in mass production is high investment cost. There has to be enough demand for enabling economies of scale. The role of managers is central in mass production. Managers have to choose correct indicators for control so that operating goes as planned. Mass production systems have also been said to have low flexibility. Making of changes to the mass production system is said to be hard if the system is highly integral and includes many relations between its elements. Thus the introduction of product variety (product variety is discussed in more detail in Chapter 3.5.4) is costly. (Pine 1993; Victor & Boynton 1998; Jovane et al. 2003)

3.2.5 Process enhancement

Victor & Boynton (1998) explain that as in the transformation from craft to mass production, the impulse from mass production to process enhancement is a managerial issue. They argue that it is possible that customers learn to ask for higher quality when they understand the important properties of the deliverables. This results in the introduction of quality systems and the enhancement of processes. Learning from mass production, when performing the same work time after time, produces practical knowledge. This is a key enabler in process enhancement work. Process enhancement links the working and thinking aspects of improvement of production. The capability to improve the process improves the quality of a deliverable (a product). This is a main goal in process enhancement. One condition for improvement is said to be that the goal and the current state should be explicit; there should be a vision of the goal state and a documentation of the current state for motivational purposes. Learning occurs by modification of activities, technologies and inputs of production processes. By continuously modifying the existing elements, an understanding of how changes effect value creation improves. In practice, the workers are equipped with tools and techniques (e.g. suggestion systems, process improvement tools) that aid them in applying their practical knowledge for improving tasks and processes. (Victor & Boynton 1998)

3.2.6 Flexible production

Duguay et al. (1997) explain that flexibility is the capacity to deploy or redeploy production resources efficiently as required by changes in the environment. They add that flexibility facilitates managing of variability. There can be different sources for variability, such as demand variability that requires product flexibility according to Duguay et al. They also explain that variability, causing the need for flexibility, can be a result of seasonal material availability, uncontrollable lead times from suppliers or breakdown. Jovane et al. (2003) explain that flexible production was the answer to a request for more diversified products compared to mass products. Flexible production includes elements from mass production. Jovane et al. state that lot sizes were reduced in flexible production because new products were introduced more often to the market than earlier. Components of products are manufactured using mass production principles but they are assembled when the customer has chosen some options. Flexible production work type fulfils the made-to-order (MTO) kind of order-delivery process type, but if all the parts are in stock when the order arrives, the process is known as assembled-to-order (ATO). Duguay et al. link quality improvement activities and better customer responsiveness with flexible production compared to mass production. (Duguay et al. 1997; Jovane et al. 2003)

3.2.7 Mass customisation

Victor & Boynton (1998) and Jovane et al. (2003) have stated that at some point, existing products with better quality are not enough to satisfy customers. Quickly changing customer requirements and a variety of needs cause the need for product variety. New products lead to the introduction of new processes. In process enhancement work, workers get used to continuous changes, also resulting in the improvement of design skills for changes. This deep understanding of interactions and interdependencies is known as architectural knowledge, according to Victor & Boynton. Architectural knowledge includes an understanding of the structures of work processes, their interconnections and the possibilities for reconfiguring them to new combinations or sequences. Thus architectural knowledge enables systematic adaptation of processes for producing products that the customer wants. This type of work is called mass customisation. The basic principles of mass customisation work underline the following activities:

- standardising systems,
- offering high-quality services for different needs,
- listening to market,
- understanding and sharing knowledge about customer context,
- re-use of information and knowledge regarding internal processes and external needs and
- reconfiguration of people, information, products, services and processes when needed to meet ongoing individualised demand. (Victor & Boynton 1998)

The main objective in mass customisation is to organise resources and capabilities without creating extra expenses to meet a changing and unpredictable demand, according to Victor & Boynton. One example for adaptable production systems can be found in the dissertation by Järvenpää (2012). Pine (1993) states that the goal of mass customisation is to develop, produce, market and deliver affordable goods with enough variety and customisation so that nearly everyone finds what they want. Victor & Boynton (1998) sum up three steps that are important in transformation work, known as modularisation, which goes from process enhancement to mass customisation:

1. Identifying modules and making them accessible
2. Building a network of modules
3. Developing a configurator

Victor & Boynton explain that resources and capabilities need to be independent and modular units in order to reconfigure them efficiently and flexibly. Architectural knowledge is needed for breaking down these resources into reconfigurable product or service system elements. It is explained that independent units or modules can be humans, software objects, factories, participants in the supply chain, separate organizations or other resources. Modularisation (as mentioned also in Figure 3.1) in this "high level" paradigm context means the establishment of a network of dynamic units, according to Victor & Boynton. Modularisation connects each module in a network. This network makes it possible to use (or not to use) each module according to the needs of each customer, as stated by Victor & Boynton. Each module fulfils a different customer need. Modularisation is discussed in more detail in a product context later on in this thesis (Chapter 3.5.6) but these previously discussed explanations have strong similarities to product modularisation. It is explained that new individualised products or services are created when modules are combined, ordered or configured (product configuration is discussed in Chapter 3.5.7). Bringing individual modules together can be based on physical or informational aspects, according to Victor & Boynton. In a product development context, product modules are linked using interfaces (see Chapter 3.5.6 of modularisation). In reconfiguring the whole production system, the interfaces between independent resource units also have an important role, as Victor & Boynton state. Otherwise the adaptation process might not be efficient when market needs change. Configurators are presented for controlling the dynamic network. These can be either humans (managers) or computer driven information systems. As Victor & Boynton explain, configurators require an understanding of every possible component regarding its manufacturing requirements and its relationships with other possible components of the product. At this point it is important to notice that Victor & Boynton discuss here production system configurators and not sales configurators, as are often discussed in a product development context. This kind of order delivery process can also be referred to as a configured-to-order (CTO) process type. At a high level, the main idea of the configurator is nonetheless the same. Sales configurators are discussed in Chapter 3.5.7. Configurators embody the details of these relationships, so that they can recognise which modules can and cannot be used in reconfiguration. (Victor & Boynton 1998)

Based on the publications by Pine (1993), Victor & Boynton (1998) and Jovane et al. (2003) it can be summarised that mass customization is driven by globalisation and it is a good type of work when market requirements change quickly and customers are looking after quality with their own requirements without extra costs in product, services, delivery modes, logistics, methods of installation or information surrounding the core product. Modularisation of products is seen as a potential solution for this kind of environment.

3.2.8 Co-configuration

Co-configuring is an activity where an integrated system is built and upheld for sensing, responding and adapting to the individual need of the customer, according to Victor & Boynton (1998). Victor & Boynton state that configuration knowledge emerges when mass customization work is done. This kind of knowledge includes systematic understanding of the dynamics between product, customer and company and enables co-configuration. The products that are made by co-configuration are intelligent and adapt continuously to the changing demand of the customer without the involvement of customer or company. It is explained that the network between customer, product and company is important in achieving co-configuration. This creates one challenge. Some of the customers want privacy and might not be ready for this openness, which co-configuration needs, according to Victor & Boynton. Co-configuration includes other difficulties as well. Companies might not have the needed organizational, technological and knowledge capabilities. Victor & Boynton explain that one example product of co-configuration is a hearing device which adapts to the environment effectively. Although there might be customer application areas in which the co-configuration could be enabled well, production of these kinds of products might be too expensive to carry out in relation to the value they create, according to Victor & Boynton. If the enterprise seeks co-configuration, the path from mass customization to co-configuration is to organize an organic and expanding system, integrate the intelligence of the product into product development teams and commit to the relationship between customer, product and company (Victor & Boynton 1998).

3.2.9 Post Mass Production Paradigm

Umeda et al. (2000) discuss post mass production paradigm (PMPP), and highlight reducing the production and consumption volumes of products to an adequate and manageable number, considering natural and social constraints. It is suggested that maintenance, remanufacturing of products, reuse of components and recycling should be encouraged. Instead of selling only products, the sale of services that the products perform is also recommended. Selling of services can include focusing on upgrading, maintenance, operational support and collection of abandoned products. This kind of paradigm demands consideration of the whole product life cycle in the designing process, instead of just designing a product considering its main requirements, according to Umeda et al (2000).

3.2.10 Sustainable Production

Jovane et al. (2003) explain that society has come to a place where it emphasises environmentally friendly products more and more. This has put pressure on politicians and legislation to redevelop environmental laws, which in turn also causes change to products. There have been observations made about an emerging paradigm of sustainable production, but the direction of development is still hard to predict. (Jovane et al. 2003)

3.2.11 Renewal of work

According to Victor & Boynton (1998), the limits of capabilities are reached at some point. In this situation, the company is no longer able to respond to market demand. Markets are visible, but the capabilities for offering deliverables to this market are no longer available. In this case, Victor & Boynton suggest a renewal of capabilities. As presented in Figure 3.1, renewal can be the next type of transformation after mass production, process enhancement, mass customisation or co-configuration (or some other paradigm) if market needs can no longer be met with precise sufficiency. Renewal leads back to the beginning of the cycle - to craft work. Thus capability failure is the driver back to craft work to create new opportunities and changes to the production process, according to Victor & Boynton. For example, mass customisation capabilities once developed disappear over the years if nothing is developed in the company but market needs keep advancing. Victor & Boynton present three steps to renewal transformation. First, the capability failure must be allocated to some customer need. Second, learning must be prioritised. It needs to be analysed at the time the renewal is made and from the place where the major competitive advantage is achieved. The third step is to relate the existing capabilities to new learned things. New capabilities have to boost existing capabilities. Additions, changes and improvements are often suggested in renewal work. It is important to understand the relationships of changes to reference models. (Victor & Boynton 1998)

3.2.12 Conclusions of paradigms

This chapter discussed how the production environment has evolved from craft to newer paradigms. As it can be seen from the discussed paradigms, there is not just one view or opinion on how the production environment has developed and what the paradigms of the future could be. Craft, mass production and mass customisation are typically discussed in references about paradigms, but there are also differences between references. For example, Pine (1993) discusses the shift from mass production to mass customization. Victor & Boynton (1998) present the idea that process enhancement occurs between mass production and mass customisation. Jovane et al (2003) state that flexible automation has enabled progress from mass production to mass customisation. Umeda et al. (2000) discuss the idea that the Post Mass Production Paradigm should be considered as the paradigm after mass production. The type of work or paradigm that comes after mass customisation also has polarised opinions. Victor & Boynton (1998) discuss co-configuration and Jovane et al. (2003) have presented sustainable production as a follow-up paradigm to mass customisation. Probably the strongest reason for differing opinions among the authors regarding how things have gone, and how they might look in the future, comes from the backgrounds of authors. The paradigms discussed by authors represent the world views of their networks.

This chapter gave an introduction to what these studied paradigms mean from a product perspective. Table 3.2 includes a summary of how different production paradigms consider types or properties of products.

Table 3.2. *Summary of product view in production paradigms.*

Paradigm	Product viewpoint	Supporting references
Craft	Unique products	Victor & Boynton (1998); Jovane et al. (2003)
Mass production	Identical / standardised products	Pine (1993); Jovane et al. (2003)
Process enhancement	Standardised products with increased quality	Victor & Boynton (1998)
Flexible production	Variety of products	Jovane et al. (2003)
Mass customisation	Modular and configurable products	Pine (1993); Victor & Boynton (1998)
Co-configuring	Adapting products	Victor & Boynton (1988)
Post Mass Production Paradigm	Re-manufacturable products with re-usable and recyclable components	Umeda et al (2000)
Sustainable production	Environmentally conscious products	Jovane et al. (2003)

Table 3.2 underlines the fact that each paradigm has a different focus in relation to products. Why is this an important issue in the thesis? The research objective relates to the rationalising of an existing product assortment towards a product family. Thus it is important to understand the possible design paths of products and the elements they include for the drafting of design support to facilitate the research problem. Consideration of paradigms helps with understanding the big picture regarding environments in which different product types are strong and against which requirements or premises the product decisions have been possibly made.

3.3 Product competitiveness and competitive company

In the previous section, different production paradigms and types of products that are pursued in each paradigm were discussed. That section revealed things that describe the environment in which these different product types bring benefits. There is also another kind of research in which important characteristics of the products are discussed. The aim of this section is to consider what kinds of issues are related to product competitiveness and a competitive company on a generic level.

Fujimoto (2007) discusses different types of product elements, explaining that standardisation is one important aspect in competence capability building. Standardisation has been discussed later on in this thesis in more detail (Chapter 3.5.5). Fujimoto defines that capability building is linked to every phase of product life, including research and development (R&D). Fujimoto's background is in the Japanese car industry. He explains that in Japan there is a special style of manufacturing philosophy known as *monozukuri*. Fujimoto discusses his thoughts on capability within this context. The scheme of things in this manufacturing style is to focus on the duplication of design data to a material that eventually forms a final product to be used, according to Fujimoto. Fujimoto defines organisational capability as a continuous exchange of design information between product development, company and market. Thus, according to Fujimoto, a competitive product considers both market and company perspectives. He also explains that product competitiveness in the market considers the four aspects of:

- product,
- price,
- promotion and
- place.

This categorisation follows the often-presented 4P view on marketing that is discussed e.g. by Kotler & Keller (2006, p. 19). 4P was originally presented by McCarthy in the book *Basic Marketing: A Managerial Approach*. There has been discussion about the choice of words in 4P, as for instance in Lauterborn (1990), where he states that 4P focuses too much on the producer's viewpoints and therefore customer viewpoints (4C) should be highlighted instead of the four P's:

- Customer needs: do not focus on the product because you cannot sell whatever you can make.
- Cost to satisfy those needs: do not focus on the price but understand the cost for the customer.
- Communication: do not focus on the promotion because it is more important to create a dialogue.
- Convenience to buy the product: do not focus on the place but understand how the market prefers to buy in different segments. (Lauterborn 1990)

Fujimoto (2007) introduces also the idea that a company's view on product competitiveness should consider quality, cost, delivery and flexibility (QCD&F).

Quality can be categorised in regards to the quality of designing and manufacturing that goes into a product. Fujimoto (2007) explains that the quality of designing considers performance and a level of functionality as shown in design documents and drawings. Manufacturing quality again discusses efficiency of manufacturing processes in creating products that fulfil design specifications. Product quality focuses on several issues such as functionality, durability, dimensional accuracy, performance, appearance, value of status, safety and reliability. (Fujimoto 2007)
Cost objectives should be formulated based on the market, and after that the objectives should be defined in relation to functions of the company in such a way that satisfactory

margins with competitive prices are enabled (Fujimoto 2007). Fujimoto explains that improvement of productivity is the best way to reduce unit costs.

Delivery time is critical because the passing of a long period of time between buying and receiving times for the product decreases the impression of quality and low price according to Fujimoto (2007). By using principles discussed by Lauterborn (1990), long lead time can create additional costs for the customer. When developing new products, development times are important. In MTO order-delivery type (MTO was also discussed in Chapter 3.2.6), development lead time is meaningless to the customer, because in this type of production only production lead time (including delivery) should exist (Fujimoto 2007). In MTS, the customer buys the product from, for instance, a warehouse or a shop and there is neither development nor production lead time (Fujimoto 2007). Another example in which different production types have been discussed is presented by Vanhatalo et al. (2010). In that paper, characteristics of these different production types such as ETO (ETO was also discussed in Chapter 3.2.3), MTS (MTS was discussed also in Chapter 3.2.4), MTO, CTO (CTO was also discussed in Chapter 3.2.7) and assembled-to-order (ATO) were analysed, particularly from a lead time perspective.

Flexibility is needed because of alternating demand; customer’s expectations have spread out widely, as discussed already in the chapter on mass customisation. Flexibility is related to quality, cost and delivery, according to Fujimoto (2007). He states that, for example, cost flexibility can be achieved by sharing components between different product models and by adapting the production process to this. The challenge lies in providing high flexibility combined with high productivity (Fujimoto 2007).

Lau Antonio et al. (2007) discuss the idea that the traditional view of competitive capabilities, including low price, product quality, delivery, flexibility and customer service, argues that companies have to make trade-offs across these competitive capabilities. Lau Antonio et al. also highlight that if all competitive capabilities cannot be developed simultaneously, improving one capability may cause another to degrade.

Fujimoto (2007) categorises competitiveness as surface and deep competitiveness. In surface competitiveness, competition occurs in issues that are visible to the customer such as price, performance, reliability, usability, serviceability and style. Price competition is the most common mean in aiming for surface competitiveness. Fujimoto notes that one can always lower the prices, but this is not a sustainable strategy in long term. He continues discussing the idea that deep competitiveness is not as visible to customers as surface competitiveness. Improving of deep competitiveness requires improving organisational capabilities, which can be very challenging (improving of basic systems), as stated by Fujimoto. He highlights that productivity and production quality are important indicators in the analysis of deep competitiveness and organisational capability. Routine manufacturing and improvement capability are mentioned to be the fundamental areas in organisational capabilities. These two areas form long term capability; capability-building capability from the manufacturing point of view (Fujimoto 2007). Fujimoto (2007) summarises that companies need to develop capabilities which strengthen their product offerings and overall competitiveness to keep customers satisfied in alternating markets. Thus statements by Fujimoto (2007) are different compared to issues presented by, for instance, Perera et al. (1999) regarding the role of labour in an environment with standardisation. Fujimoto (2007) underlines the importance of long-term capabilities more, which is justified, especially from a sustainability point of view. Modularisation is recognised by Fujimoto (2007) as a critical aspect in designing products and in the building of competence capabilities. Lau Antonio et al. (2007) also highlight that modularisation has an impact on competitive capabilities. The objective of this thesis relates to modularisation approaches. Thus modularisation that is enabled by standardisation is discussed in the later sections in greater detail but until then other aspects are studied in order to gain a comprehensive view of designing.

3.4 Design Science

In the context of product development and design, there are publications in which design and the resulting products have been studied and described extensively from several viewpoints. In the research context, two often discussed studies, *Theory of Technical Systems* and *Design Science*, have been published by Hubka & Eder (1988; 1996).

Hubka & Eder (1996) define Design Science as follows: "*The term Design Science is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for designing*". They continue that the goal of Design Science is to improve the situation in design and to eliminate existing problems via practice science and education. Hubka & Eder (1996) explain that Design Science has two main elements: the technical system and the process of designing. The technical system includes Theory of Technical Systems and design object knowledge. The process of designing includes Theory of Design Processes and design process knowledge. These categories are illustrated in Figure 3.4. (Hubka & Eder 1996)

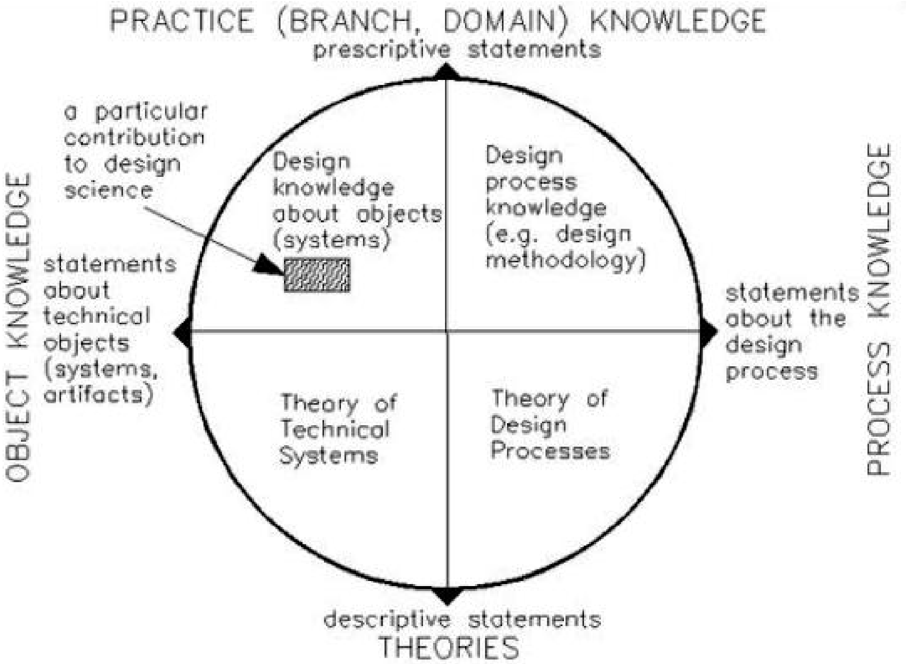


Figure 3.4. *Contents of Design Science. (Hubka & Eder 1996)*

Figure 3.4 describes the main content of Design Science and the area inside the circle consists of theories and knowledge. The Theory of Technical Systems and the Theory of Design Processes include descriptive statements. Design object knowledge and design process knowledge include prescriptive statements. These four categories of Design Science are discussed in the following sub-sections in more detail.

3.4.1 Theory of Technical Systems

Hubka & Eder (1996) explains that the Theory of Technical Systems (TTS) focuses on describing, explaining, establishing and substantiation of technical systems. Hubka & Eder (1988) define all technical means (especially products) as being systems with certain attributes. The aim of this kind of treatment is to enable the developing of working methods for engineers that are independent of product, and to facilitate the learning and teaching of designing technical systems beyond the case specific. (Hubka & Eder 1988; Hubka & Eder 1996)

The main elements and influences of the TTS are presented in a transformation system in Figure 3.5. The need for transformation emerges when requirements (basically human needs) for certain issues are not met. The subject of transformation is called an operand. The operand can be biological (human), energy, information or material and it has an initial state (Od1) and final output state (Od2). Transformation is needed in order to change the state of operand. Transformation is understood as a process in the Hubka & Eder model. The transformation process includes operations and working steps, whose purpose it is to transform the state of the operand to a desired state by:

- changing internal properties (changing the structure of operand),
- changing external properties (e.g. shape, form),
- changing location (spatial) and/or
- taking time into consideration (e.g. storage) (Hubka & Eder 1988; Hubka & Eder 1996).

Hubka & Eder (1988) continue that operations or working steps in the transformation process are generally divided into the areas of preparation, execution and finishing. Thus the operand also has intermediate states between Od1 and Od2. Working steps and the technology needed in achieving transformation have to be judged case specifically, depending on given requirements, available operators and available technical knowledge. (Hubka & Eder 1988)

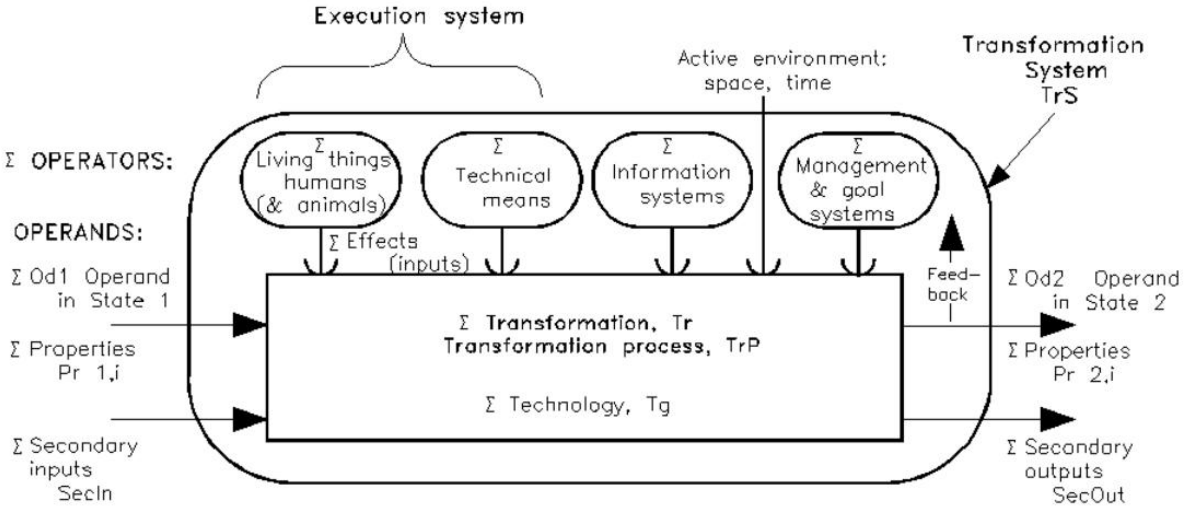


Figure 3.5. *The Transformation System. (Hubka & Eder 1996)*

In the transformation system other elements, operators, are also needed besides the operand and the transformation process in order for transformation to be able to occur. These are the human system (living things, humans & animals in Figure 3.5), the technical system (technical means in Figure 3.5), the information system, the management & goal system and the active environment. The human system and the technical system are key elements of the execution system to drive the transformation process. (Hubka & Eder 1988; Hubka & Eder 1996)

The human system includes living things, especially humans, but also includes animals, and even bacteria can be considered in this system if necessary. According to Hubka & Eder (1988), humans as operators are those who directly effect on the operand of specific transformation. Because the main focus of operators in TTS is on technical systems it is explained lastly and in greater detail. The information system is used for storage and as a source of necessary information needed in transformation. The management & goal system drives the transformation process indirectly. It sets the goals and monitors the progress of transformation. The active environment as operator includes effects on transformation from the surroundings. The active environment consists of those Earth-bound systems that have an effect on the transformation process. These can be the geosphere, the biosphere, the atmosphere, the technosphere and the part of the solar system that creates climate. (Hubka & Eder 1988)

The technical system as operator consists of artificial technical systems that effect on the operand of specific transformation bringing desired effects. All technical products are considered as technical systems. Technical systems use natural effects (e.g. lever effects, gravitation, electro-magnetic force) to fulfil their purpose. Technical systems can be modelled using design or requirements specifications, black box, function structure, organ structure (organ realises the function and it is made of components) or component structure. (Hubka & Eder 1988)

In addition to modelling, there are also several other ways to classify technical systems. Hubka & Eder (1988) explain that the goal of the classification is to help e.g. in the analysing, characterising, understanding, comparing and ordering of technical systems. Some of the classifications describe the internal characteristics of a technical system. Of the classification list of technical systems, classifications related directly to product life cycle phases such as designing, production and manufacturing and use can be recognised. An interpretation of these classifications of technical systems by the author of this thesis is given below. As can be seen from these classifications, the technical system takes all of these issues under consideration, although some of the topics may not be considered consciously when designs decisions are made.

Classification based on the internal characteristics of technical systems:

- degree of complexity
- degree of standardisation
- degree of novelty
- degree of abstraction
- quality

Classification related directly to a specific life cycle phase: designing

- difficulty of designing

Classification related directly to a specific life cycle phase: production / manufacturing

- production location
- manufacturing similarity
- type of production

Classification related directly to a specific life cycle phase: use

- type of operand
- application in the technical process (transformation)
- function (effect)
- action principles

Hubka & Eder (1988) state that: "*Every technical system, and each element and relationship at or within the boundary of a technical system, has certain properties that belong to the system and define it*". They have categorised properties of technical systems into external and internal properties. External properties relate the technical system to its environment. Internal properties include properties and relationships of the elements of the system. Internal properties can be divided further into design properties, which are the last means of a designer for achieving all other properties. This collection of properties, according to Hubka & Eder, is presented in Figure 3.6.

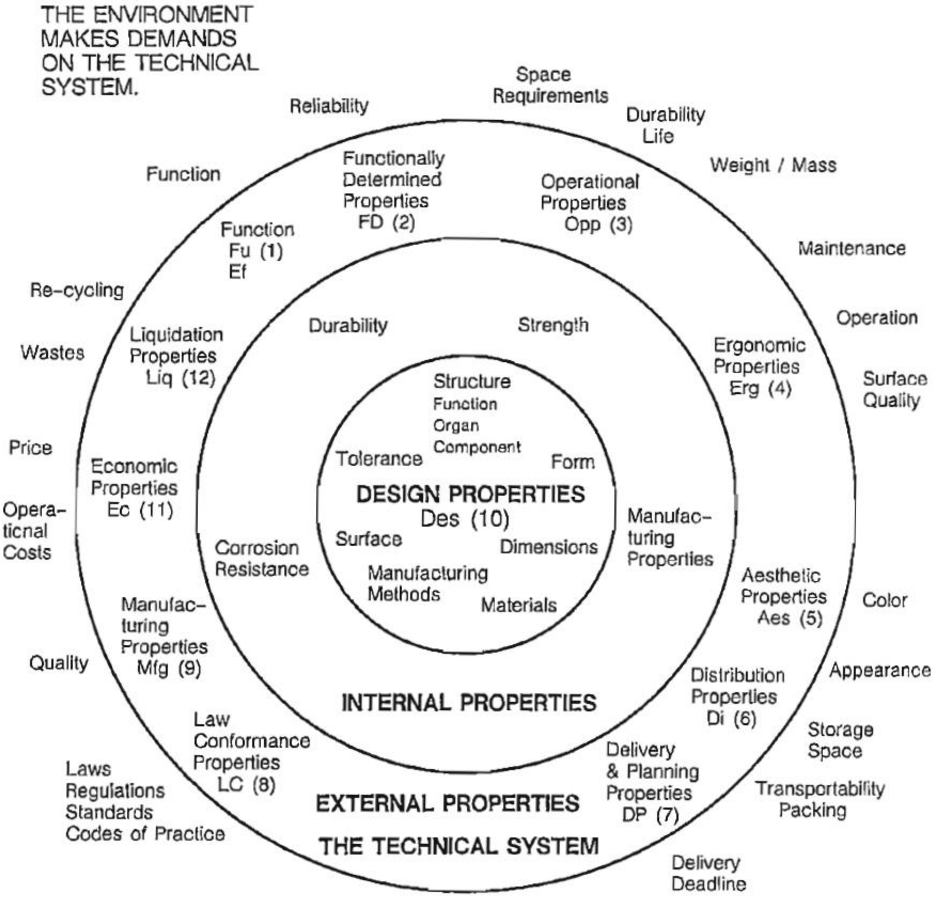


Figure 3.6. *A technical system consists of design, internal and external properties, of which the design properties are the most critical because they have direct influence on the other properties. (Hubka & Eder 1988)*

Hubka & Eder (1988) define that there are six different ways to choose or clarify properties for a technical system.

1. Measuring of the properties: This is a possible way of defining properties of the technical system when it is realised and properties are quantifiable.

2. Estimating of the properties: When properties cannot be measured, one option is to estimate them.
3. Modelling of the properties by experiments: This could be considered when the technical system can be modelled or simulated.
4. Calculating or reading of the properties: This could be applied when graphs or diagrams of the properties are available.
5. Defining of the properties by comparison: This is possible if a reference sample exists.
6. Determining optimal values for the properties: This is possible when knowledge of relationships between the properties exists.

The chosen properties are different in each maturity stage of the technical system. Thus the value of the system depends on the maturity stage the technical system is in, but the total value of the system is mostly created in the development phase, according to Hubka & Eder. For instance, an abstract concept or concrete product have different properties that describe it. Hubka & Eder define that the main phases of the life cycle of a technical system includes origination, distribution, operation and liquidation. (Hubka & Eder 1988)

The operand in state 2 is achieved when a transformation process is gone through, as explained in Figure 3.5. In this situation it is important to compare the outcome to the goals that were set in the beginning and to use this result as a feedback for the operators. It is also worthwhile to notice that secondary inputs (e.g. energy, materials) and outputs (e.g. waste materials) are related to the transformation system as shown in Figure 3.5. (Hubka & Eder 1988; Hubka & Eder 1996)

Although the TTS focuses mainly on technical systems, Hubka & Eder (1988) remind that those should not be thought of in isolation. The whole transformation system should be considered in development cases. (Hubka & Eder 1988)

3.4.2 Theory of Design Processes

According to Hubka & Eder (1996), the Theory of Design Processes (TDesP) considers design as a comprehensive unit in which each scientific knowledge unit should be organised into an entire knowledge system where different units and their relationships are visible. Hubka & Eder (1996) the define task and purpose of design and the design process as follows:

"*Designing is transforming the given problem statement into a full description of a technical system. The content of the design process includes thinking out (conceptualizing) and describing structures of technical system.*"

This above definition represents a situation where designing succeeds. Hubka & Eder (1998) comment that the result of designing can also be imperfect. They have also presented other interesting points about design processes. It is explained that the importance of the design process is not broadly understood. The aim of the design process is to aid in the development of a technical system with optimal quality as quickly and cheaply as possible while taking organisational limitations into account. It is also pointed out that the design process should be transparent.

Hubka & Eder state that design processes can be described from several points of views. The results of process, duration and characteristic classes are mentioned. They also explain that characteristic classes can be used in the evaluation and classification of design processes. Three options for characteristic classes are listed by Hubka & Eder (1996):

1. Degree of originality of the operand (the system to be designed)
2. Degree of complexity of the operand (the system to be designed)
3. The state of embodiment of individual operators

Thus the first class considers whether the product development is new product development, or not. The second class considers how complex the result is. According to definitions of complexity by Hubka & Eder, this relates to the size of the system. The third class relates more to existing possibilities.

As described in TTS in the previous sub-section, transformation is a process where the state of the operand is changed in relation to a dedicated goal using operators. Different development processes (transformation technologies) are categorised typically as 1) traditional, 2) methodical or 3) mixed in TDesP, according to Hubka & Eder (1996). Traditional development processes are based on trial and error and intuition. Decisions are made based on instincts. This kind of development process is not teachable, clear or open/transparent, whereas methodical development processes are transparent and repeatable. One aim of Design Science is to produce these kinds of “technologies” within the design context defined by Hubka & Eder (1996). Thus from these three options, designing based on methods also needs to be examined in more detail in this thesis. In mixed development processes, some development steps are based on intuition and some on method. (Hubka & Eder 1996)

But what properties besides transparency and repeatability do these methods include? Hubka & Eder (1996) express that method guides the process according to plan in an appropriate way and limits the use of means that are available. They also define that in a design context design method is a system of methodological rules and instructions. It is also explained that method has a prescriptive nature. Hubka & Eder continue explaining that the classification of methods can be done based on the nature of guidance. Thus, method can be:

1. a strictly algorithmic or strictly regulated procedure,
2. heuristic instruction (relatively flexible procedure) or
3. relatively fuzzy instruction without clear references (a quite free procedure where only main principles work as guidance). (Hubka & Eder 1996)

Although this section is mainly about TDesP, other interesting definitions of method also exist and these are discussed here briefly. One of them is presented by Newell (1983). Newell defines method using four statements:

1. a specific way to proceed (includes steps)
2. a rational way to proceed (following the steps increases chances for solving the problem)
3. involves generic subgoals and subplans (method does not state exactly how those are realised)
4. existence is observable (it can be observed whether the method is used or not)

Hubka & Eder (1996) explain that the existence of method (see also Newell’s fourth statement above about methods) makes it possible to draw up a plan of action that creates rules for behaviour in a certain design activity in a certain concrete case. They add that a method can create a starting point for a series of action plans which change according to different task descriptions (for instance, different branches or types of design activity). When an individual is performing a design task in his/her own way, Hubka & Eder (1996) refer to it as procedural manner or designer's mode of action. Method can be used in defining this mode of action. In this definition the factors that effect on the operating of the designer (for example, knowledge and capabilities) must be taken into account.

Hubka & Eder (1996) describe every design process as being able to be structured using a general procedural model (explained in Figure 3.7) into more detailed partial processes, design operations and steps. Method guides every element of process towards a more defined goal.

Another classification of methods in TDesP is made according to their properties, which characterize the method either as a tool or information. In this theory, a checklist for determining the properties of method as a tool is presented. This checklist highlights, for example, the idea that the **background of the method** should be explained. The **source of the method** should consider e.g. origination, area of knowledge, discipline and domain issues. Generic information about the method should also be provided. This kind of information should include **purpose of the method**, **design activity areas where the method is applicable**, **breadth of application**, **usability in different fields**, **branches or domains** according to Hubka & Eder 1996). When determining the properties of method, requirement related to its use should also be known. It is explained that **condition requirements, resources, types of operators and time demands for using the method** should be considered. Hubka & Eder (1996) also discuss issues related to the functioning of the method. They explain that **working or behaviour, phenomena and mechanism of the method** should be explained.

Hubka & Eder (1996) also presented points concerning a method as information. In this case they highlight that a method's effects should be verifiable. They also suggest that correctness and completeness of contents are important aspects in defining methods but that these suggestions are nondescript alone. In ensuring that the method is correct, the goals set for it should be kept in mind. Completeness of the method considers the fact that all aspects needed in realisation are considered in method description.

According to Hubka & Eder (1996), the general design process model (as presented in Figure 3.7) serves as a preliminary model in the creation of more concrete procedural plans (plans of action), which are necessary in specific cases that designers meet. Hubka & Eder (1996) explain that methodical knowledge that would guide the designer to develop the desired solution with a higher probability is not available in all cases.

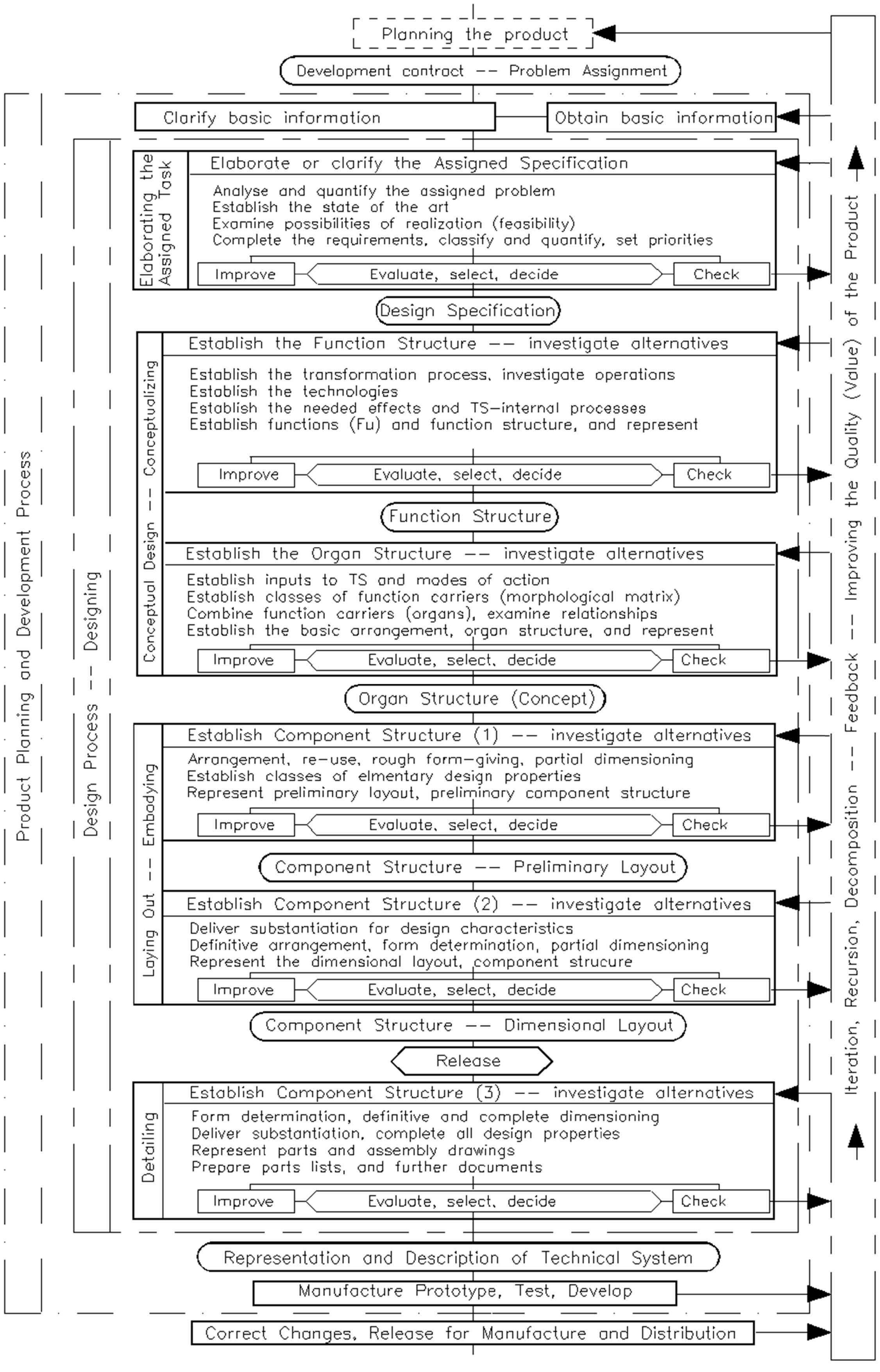
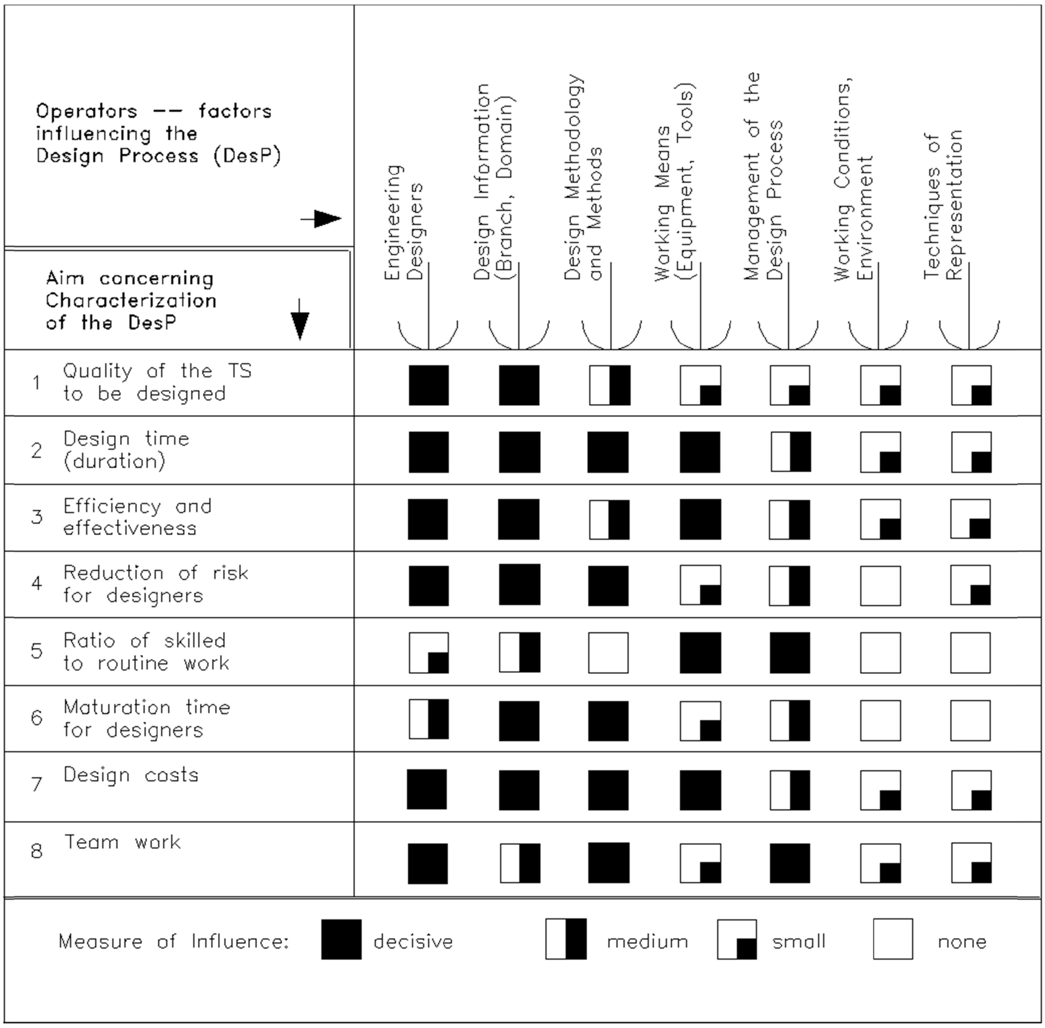


Figure 3.7. *General design process, according to Hubka & Eder, focuses on clarifying the assigned task and establishing the function, organ and component structures through the main phases of conceptualising, laying out/embodying and detailing (*1996*).*

Effectiveness of method and design process is also discussed in TDesP. Recognition and standardisation of psychological, technical and organizational elements and their relationships to each other facilitate progression of the method being used, according to Hubka & Eder (1996). It is also explained that effectiveness can be evaluated based on the time span (length of the path) between establishing a design property and determining its real value from the realised properties (e.g. in the use phase of technical system). Evaluation can be done based on either measuring based on facts or reliable predictive methods (Hubka & Eder 1996). One approach in analysing the difference between design properties and realised properties has been presented by Weber & Deubel (2003) in the theory of Property Driven Development (PDD).

As discussed in TTS, there are different operators involved in the transformation or design process. Figure 3.8 summarises the effect of operators on the different aims of the design process.



Operators -- factors influencing the Design Process (DesP) → / Aim concerning Characterization of the DesP ↓	Engineering Designers	Design Information (Branch, Domain)	Design Methodology and Methods	Working Means (Equipment, Tools)	Management of the Design Process	Working Conditions, Environment	Techniques of Representation
1 Quality of the TS to be designed	■	■	◨	◲	◲	◲	◲
2 Design time (duration)	■	■	■	■	◨	◲	◲
3 Efficiency and effectiveness	■	■	◨	■	◨	◲	◲
4 Reduction of risk for designers	■	■	■	◲	◨	□	◲
5 Ratio of skilled to routine work	◲	◨	□	■	■	□	□
6 Maturation time for designers	◨	■	■	◲	◨	□	□
7 Design costs	■	■	■	■	◨	◲	◲
8 Team work	■	◨	■	◲	■	◲	◲

Measure of Influence: ■ decisive ◨ medium ◲ small □ none

Figure 3.8. *Factors influencing the Design Process. (Hubka & Eder 1996)*

The designer is a major force in designing, as can be seen from Figure 3.8. For designers it is important to know the type of knowledge they need and where to find this knowledge (Hubka & Eder 1996). Also, estimating the quality of the knowledge and organising the knowledge are important issues in designing (Hubka & Eder 1996). These are discussed in the following subsections 3.4.3 and 3.4.4.

3.4.3 Design object knowledge

The word ‘knowledge’ has already been mentioned several times in this thesis. Hubka & Eder (1996) explain that in Design Science knowledge consists of design object and design process knowledge. Hubka & Eder (1996) also use the terms ‘**branch knowledge**’ and ‘**domain knowledge**’ as synonyms for **design object knowledge**. The history of design object knowledge is related to work paradigms (discussed in Chapter 2) and to personal experiences (of craft work) that were not stored in any artificial systems. Hubka & Eder (1996) present the idea that engineering science in the 1920’s began to change this situation when engineering science became the most important source of design knowledge. It is also explained that natural science is still important because all the needed knowledge cannot be derived from or was not available in engineering science. (Hubka & Eder 1996)

According to Hubka & Eder (1996), design object knowledge or branch knowledge elements have to adapt in regard to design objective, different situations in designing and the type of the operand (the technical system to be developed). Thus, branch knowledge includes knowledge of nature, effects, modes of action and structuring of a specific technical system. In Design Science, it is explained that different knowledge is needed in different steps of the design process. This means that **branch knowledge should be primarily categorised based on the design activity type**. Categorisation based on the type of design activity is suggested to be done in more detail, based on the design operations (e.g. establishing of function structure, technologies to be used, re-use point of views, form giving etc.) and basic operations (defining of the problem, searching solutions, evaluating/deciding, communicating about solution, preparing of information, verifying, representing/documenting).

Other options for categorising branch knowledge are also presented in Design Science besides categorising, based on the type of design activity. If branch knowledge is independent of the steps of the design process, the operand of the transformation system can be used in categorisation of knowledge. Categorising based on the type of the operand takes, for instance, the type of industry and the level of originality and complexity and life cycle phases into account. (Hubka & Eder 1996)

The literature is not a sufficient source of branch knowledge because there is a lot of experience in every branch that is not documented anywhere, or else the knowledge includes business secrets. In spite of this recognised problem, several possible sources for finding branch knowledge are mentioned in Design Science (Hubka & Eder 1996):

- catalogues about design situations
- design for x (DFX) approaches
- design rules
- experiments / results of measuring
- heuristics
- presentations
- requirement lists
- solution catalogues
- standards

The main goal of branch knowledge is to give direct answers to designer questions according to statements presented in Design Science. Thus, availability and the form of knowledge are explained as being critical because the knowledge has to be able to be used effectively in the design process. Hubka & Eder (1996) also underline the importance of using pictures, diagrams and equations instead of using only text because the learning and applying of knowledge is more efficient in this way. Hubka & Eder (1996) present, for example, tables where the relations (direct or indirect relation) among external and internal properties are shown. These kinds of presentations of knowledge can help in choosing properties for the operand (Hubka & Eder 1996). One example of knowledge presentation based on properties is presented by Vanhatalo & al. (2010). In that matrix-based approach, the relations of the product concept's properties were made explicit by answering the following question: what is the behaviour like when two properties meet? In this approach, the business environment was also described using properties and their property groups were analysed in relation to properties of product concept.

3.4.4 Design process knowledge

Design process knowledge includes knowledge of transformation. This knowledge is challenging to represent because the quantity of different situations is very high (Hubka & Eder 1996). Hubka & Eder (1996) discuss the fact that design process knowledge considers several areas:

- available and suitable methods for specific problems,
- relations inside design process,
- progression and actions in certain design tasks,
- content and location of branch knowledge needed in certain design situations,
- management and organisation of designing,
- development of a technical system's evaluation and
- development of designer's work.

Hubka & Eder explain that this area of Design Science should consider **available and suitable methods for a specific problem**. This would require a "method library" with definitions of their preferred use cases. Hubka & Eder also discuss the idea that design process knowledge considers **relations inside design process**. As discussed by Newell (1983), a typical method includes steps. Based on this statement, one could draw the conclusion that these relations inside a design process would describe how different steps are linked with each other. **Progression and actions in a certain design task** support method thinking. Design process should facilitate designing in a case context in which the process is intended. **Content and location of branch knowledge needed in certain design situations** is necessary in order to facilitate concrete designing. **Management and organisation of designing** relates to division of labour in designing and to managing and organising of certain design tasks. **Development of a technical system's evaluation** considers how evaluation could be done better. **Development of designer's work** should also be considered in design process knowledge. This knowledge relates to the suggesting of improvements in the work of designers, according to Hubka & Eder.

Design Science discusses the designing of new technical systems (Figure 3.9) or the redesigning of existing technical systems (Figure 3.10) in liaison with design process knowledge. It is written that several design cases are based on the changing, adjusting, varying or adapting of existing solution against updated objectives. Hubka & Eder (1996) define that in these kinds of situations a roughly linear procedure with concurrent (or simultaneous) engineering (CE/SE) is possible in establishing needed information for later phases of the life cycle (e.g. manufacturing). CE/SE is discussed further in the thesis under the title of Integrated Product Development (IPD)) in Chapter 3.6.3 (IPD is based on the book by Andreasen & Hein (2000)).

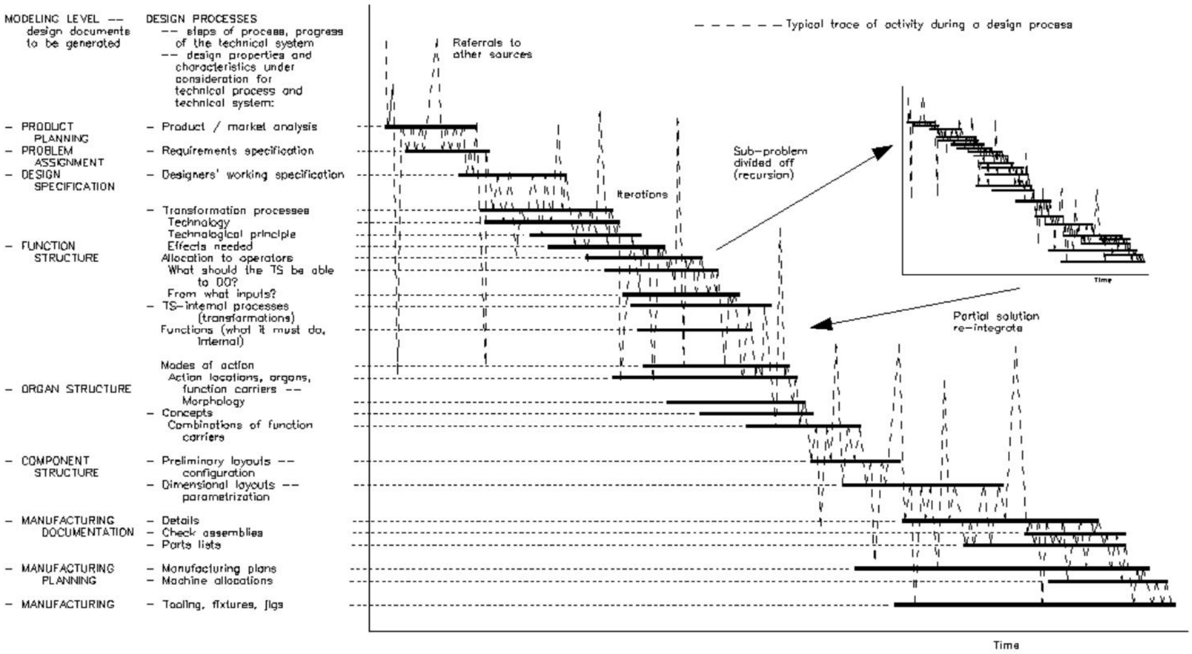


Figure 3.9. Designing of a new technical system proceeds in a linear fashion according to Hubka & Eder (1996).

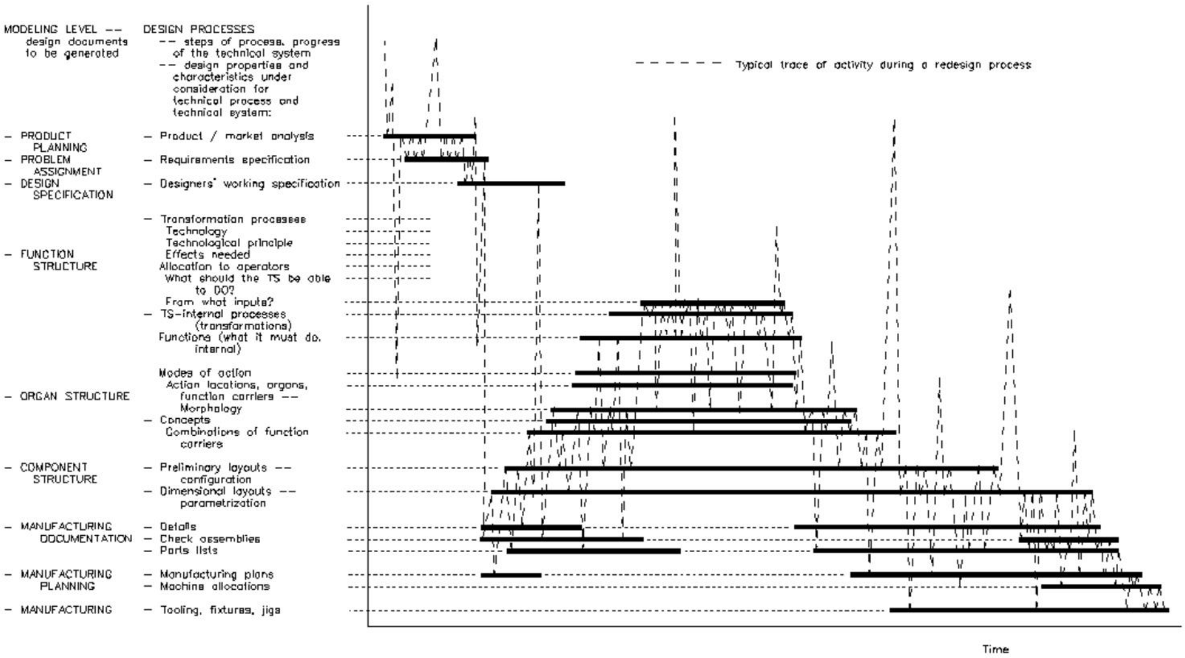


Figure 3.10. Re-designing of an existing technical system has a different focus than in the designing of a new technical system. Knowledge of existing solutions and how those have been produced is available in a re-design task. This knowledge is used in the re-designing of structures. (Hubka & Eder 1996)

Hubka & Eder (1996) summarise that design process knowledge can be found in catalogues, including processes, process steps, rules, applicable conditions and criteria, models of processes and methods and tables to, for instance, present relations and combinations.

3.4.5 Conclusions of Design Science

Design Science by Hubka & Eder (1996) can be considered as one of the foundation blocks in this thesis and in engineering design in general. It adds more insights to the **artificial objects** presented by Simon (1996) by addressing the nature of **technical systems** and **design objects**. Hubka & Eder (1996) have classified technical systems and design objects rather extensively in their book. But what is the benefit of these kinds of classifications? In the book, it is explained that classifying of objects helps in analysis and comparison of things and thus facilitates understanding of certain topics. Design Science considers also **design processes**, and classification examples are also given for this topic. For instance, a checklist for the determination of properties of the method and tool can be useful when defining a method. One of the most important viewpoints from a design process perspective is the remark that design processes start from an empty table and design process that has to use existing designs is different. When re-designing existing designs, available knowledge of the solutions can be used and the order of design activities is typically different, according to definitions by Hubka & Eder.

3.5 Product structuring

This section focuses on different product structuring tactics and approaches. Andreasen et al. (1996) explain that every product has a structure. Product structure describes how a product is built up (the way in which its elements are related) and determines the behaviour of a product, according to Andreasen et al. They also explain that a product has more than one structure, meaning that a product can be described from several viewpoints. Andreasen et al. discuss that the need for different structures emerges from the business itself and its life phases. For example, manufacturing and sales benefit from different views: manufacturing needs highly detailed information about properties of a product, whereas sales can typically operate with simpler descriptions. It is also mentioned that drivers from life phases to structuring of a product are overlapping and designers need to alternate between various viewpoints. Andreasen et al. also mention that determination of a product’s elements and its structuring is referred to as “synthesis” and the result of designing can be understood as a system. Thus these definitions have similarities with definitions by Hubka & Eder (1996). Figure 3.11 includes a classification of views in product structuring according to Andreasen et al. (1996). This classification includes:

- **a domain or genetic view**: domains explained in the Domain Theory (see Chapter 3.5.1) offer a possible sequence for synthesis (iteration is often needed in practice)
- **a functional view**: overlapping tasks and disciplines of the product cause a need to alternate between different viewpoints in design work
- **a product life view**: product life phases cause requirements in designing
- **a product assortment view**: variants and the familiarity (later in this thesis the word ‘commonality’ is used) of products need to be taken into account in product structuring if a market needs variance

Thus it can be understood that there is no one way to model a product. The chosen theory basis behind modelling affects the results. The previously mentioned authors have also noticed that assisting approaches in description of a product structure might have seemed useless when the structure was first developed. But if that developed structure has potentially re-usable elements (solutions, knowledge), then these supports will have proven to be highly beneficial, according to Andreasen et al. (1996).

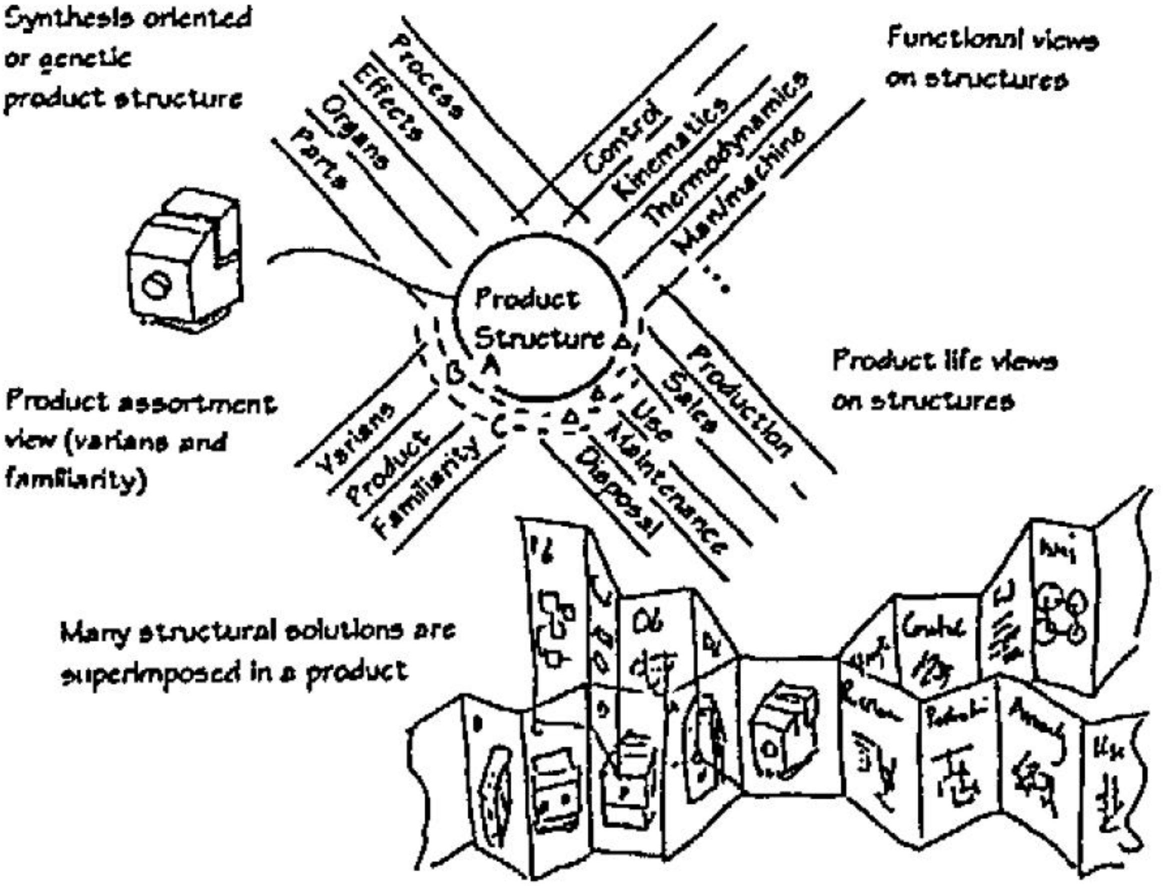


Figure 3.11. *A total view of the structuring of a product includes domain, functional, life and product assortment views. These different views can overlap each other. (Andreasen et al. 1996)*

The above classification in Figure 3.11, and the issues discussed regarding different views, leads us further into a discussion of relevant topics for this thesis. The Domain Theory explains the nature of process (activity), organ and part domains. This is discussed in Chapter 3.5.1. Andreasen et al. (1996) explain that a product's life affects the structuring of a product. Issues related to product life are studied further in Chapter 3.5.2. Juuti et al. (2007) and Lehtonen (2007) have discussed a framework known as Company Strategic Landscape (CSL) that represents important issues, including life phases when the structure of a product is developed. CSL is discussed in Chapter 3.5.3. The product assortment view has an important role in this thesis because the research problem relates to the rationalising of an existing product assortment. This view includes definitions, models and theories related to product variety and commonality (Chapter 3.5.4), standardisation (Chapter 3.5.5), modularisation (Chapter 3.5.6), product platforms and product families (Chapter 3.3.7) and configuration (Chapter 3.5.8). Conclusions regarding product structuring are made in Chapter 3.5.9.

3.5.1 The Domain Theory

In TTS and TDesP it was discussed that a technical system (a product) can be modelled from a function, organ and component point of view. Danish professor M.M. Andreasen developed these ideas further, presenting the Domain Theory in his dissertation "Syntesemetoder på systemgrundlag – bidrag til en konstruktionsteori" in 1980 (in English: "Methods for Synthesis Based on a Systems Approach – Contribution to an Engineering Design Theory").

Later on, several publications related to this theory were also presented in English and updates to the theory have been presented as well.

Andreasen (2011) defines that Domain Theory explains the structuring of the synthesis, and consists of three viewpoints regarding a product: activity (process), organ and part domains, as presented in Figure 3.12. Originally the theory included also a function domain (Andreasen et al. 1996), but later on it was removed from the theory based on the following reasons defined by Andreasen (2011):

- *"Each domain shall contain a synthesis dimension in relation to the design task. Hubka's transformation model tells us that both transformation process, in my terminology activity, and the technical system shall be synthesised. The technical system needs two understandings or synthesis operations: how it functions, i.e. organ domain, and how it is built up, i.e. parts domain."*

- *"In each domain we can reason backwards from wanted behaviour to structure as shown in Gero's model (Figure 3.13 in this thesis). In the activity domain we reason based upon operands: material, energy, information and biological objects. In the organ domain we reason from functions (effects), and in the part domain we reason from the part's tasks."*

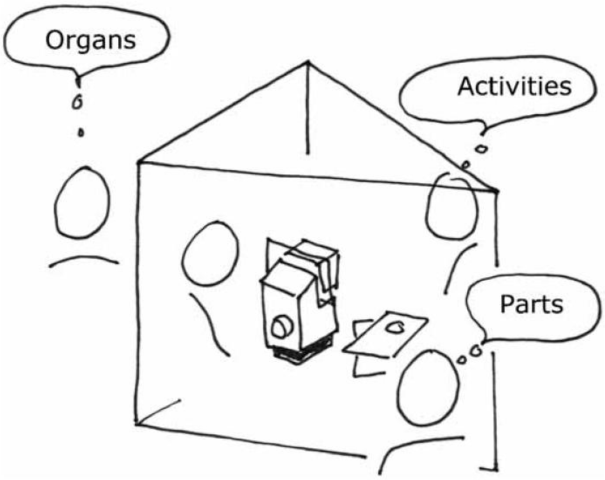


Figure 3.12. *Domain Theory includes three domains: activity, organ and part domains. (Andreasen 2011)*

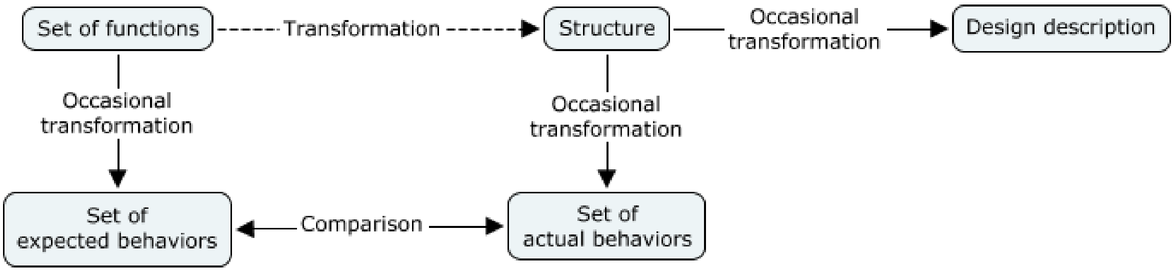


Figure 3.13. *Function-Behaviour-Structure design model adapted from Gero (1990). The principles of this model can also be identified in the CPM/PDD theory of Professor Weber (Weber & Deubel 2003).*

Activity domain (originally process domain) concentrates on the transformation of material, energy and information of the product, leading to a description of a process structure, according to Andreasen et al. (1996). From Hubka's transformation system point of view, technical activity can be single or a sequence of transformations in which the product is used (as operator) or is transferred (as operand) (Andreasen 2011). The total product life activity (including all the different steps, such as manufacturing and assembly, for instance) can be expanded from the technical activity, according to Andreasen (2011). Thus the activity domain explains the product's purpose and the satisfaction of human needs with the product (Andreasen & McAloone 2008).

Organ domain explains the functionalities and the (behavioural) properties of the product resulting in organ structure (Andreasen & McAloone 2008; Andreasen 2011). Jensen (1999), according to Andreasen (2011), has defined that organs are made up of active or activated form elements, which are important features of parts in part structure. It is also said that an understanding of organ structures includes understanding state transitions and reactions of active or activated form elements, and this relation pattern is a major point in developing a solution. Andreasen (2011) summarises that an organ is a functional element of the product that has the ability to make changes, and organs are made up of material areas (parts) and their connections. This kind of designing is illustrated in Figure 3.14.

Part domain includes a view of parts and their assembly relations regarding a product (Andreasen et al. 1996; Andreasen 2011). Materials, forms, dimensions, tolerances and surface quality of parts (in Hubka's model these can be understood as design properties, see Figure 3.6) and the inter-relations of parts can be seen from part structure; thus part structure enables organ structure (Andreasen et al. 1996).

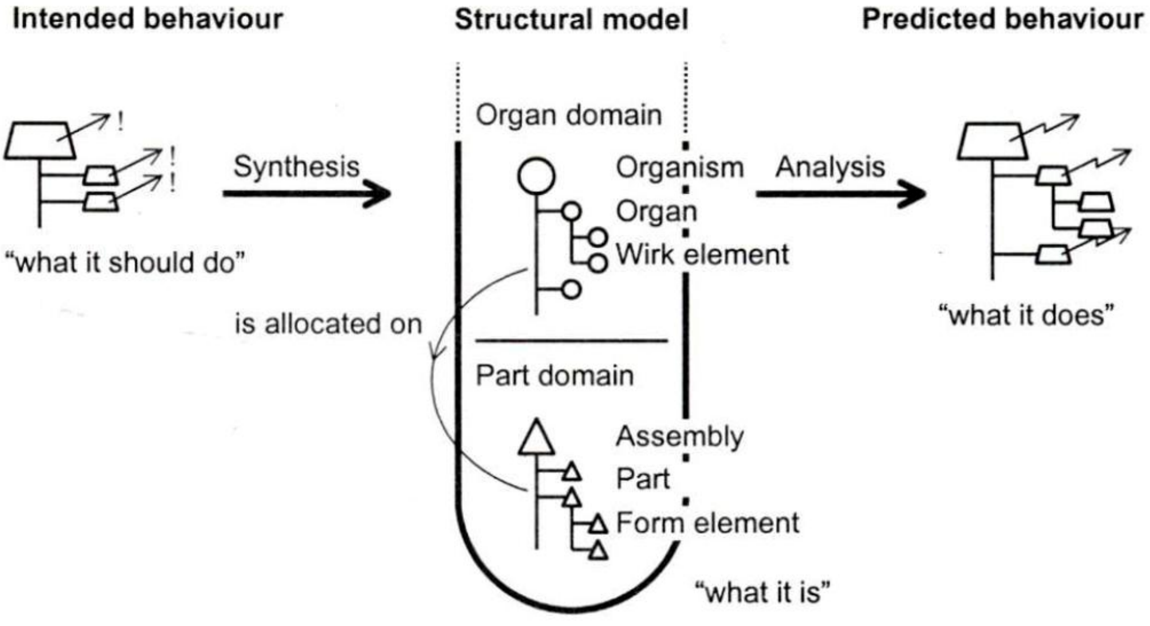


Figure 3.14. *Domain Theory highlights the idea that designing is founded on reasoning of active or activated form elements ("Wirk elements") and their realisation in part domain, according to Andreasen & McAloone (2008), in a figure originally by Jensen (1999). Activity domain is not shown in this figure.*

Andreasen (2011) summarises that designing is the reasoning of organs and organ structures (how a technical system should function) before or parallel to a defining of part structure (how a technical system should be built up). As was discussed in the research clarification, the support of this thesis should help in the rationalising of an existing product variety; thus the design situation is re-designing. Referring to differences in design situations of new design (Figure 3.9) and redesign (Figure 3.10), it is important to understand how existing parts or organ structures can be used in re-designing. The design support should consider these issues.

3.5.2 Product life

As Hubka & Eder (1996) explained, DFX approaches are one way to find branch knowledge and to consider a specific life cycle phase in more detail in designing. The aim in DFX approaches is to consider designing from a chosen 'X' viewpoint. 'X' can be almost any point of view as long as it is critical in the design situation. Manufacturing, assembly and other life phases are these kinds of typical viewpoints and are often discussed in literature examples. Hubka & Eder (1996) list property, life cycle, function, usage, manufacturing, distribution, delivery, human, operation, appearance, regulations and economics points of view. Thus their example list also includes other aspects besides life cycle phases. Research done by Olesen (1992) relates to this DFX thinking. Olesen has recognised general measurable quantities that can be found in development projects. He has named these measures as universal virtues:

- cost
- throughput time
- quality
- efficiency
- flexibility
- risk
- environment

Olesen (1992) notes that these virtues have to be broken down into operational quantities and prioritised differently based on the situation at hand. He states that typically the focus is on some particular measure but that even in these cases the other virtues are not completely neglected. Concentrating on all measures is typically not possible because of a limited amount of resources and the complexity of designing. Lau Antonio et al. (2007) also stated that designing often involves trade-offs, as discussed in Chapter 3.3.

Olesen (1992) argues that it is possible to describe relationships between inter-functional parameter relationships and their controllable effects. He explains that in order to achieve positive effects in some areas where the benefits are seen as an important objective, the realisation of those benefits is not possible until a product with updated parameters is exploited in this area. Olesen (1992) continues by stating that the choosing of parameters is reasonable when understanding that the effects and relationships of parameters to other areas also exist. Here the concept of disposition is used. The model of disposition is presented in Figure 3.15. According to Olesen (1992) *"disposition is a part of a decision taken within one functional area which affects the type, content, efficiency or progress of activities within other functional areas"*.

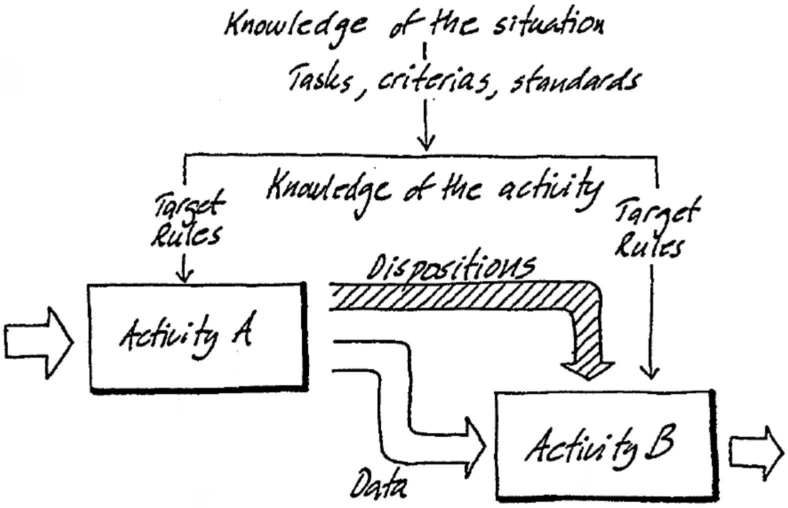


Figure 3.15. *A generic model of dispositions according to Olesen (1992). Olesen explains that there are always dispositions when decisions are made.*

In Figure 3.15, two activities, activities A and B, are presented. Based on the analysis of the situation, different rules for each activity are given. These rules can consider tasks, criteria or standards, which should be taken into account in activities. If activity A affects Activity B, decisions made in activity A cause two kinds of flows for activity B: data and dispositions. Data helps to describe the task of activity B. Dispositions describes the conditions of how decisions made in Activity A affect Activity B. (Olesen 1992)

The life cycle of a product has to be considered in the situation where the product has possible influences on all the systems and phases that it goes through (Olesen 1992). Figure 3.16 illustrates how a decision of development effects on the total sum of the Universal Virtues. Every system has its own resulting quantity in relation to the seven virtues. The estimated result is evaluated during the product development process and the actual result can be obtained when the product is ready to be produced, according to Olesen (1992).

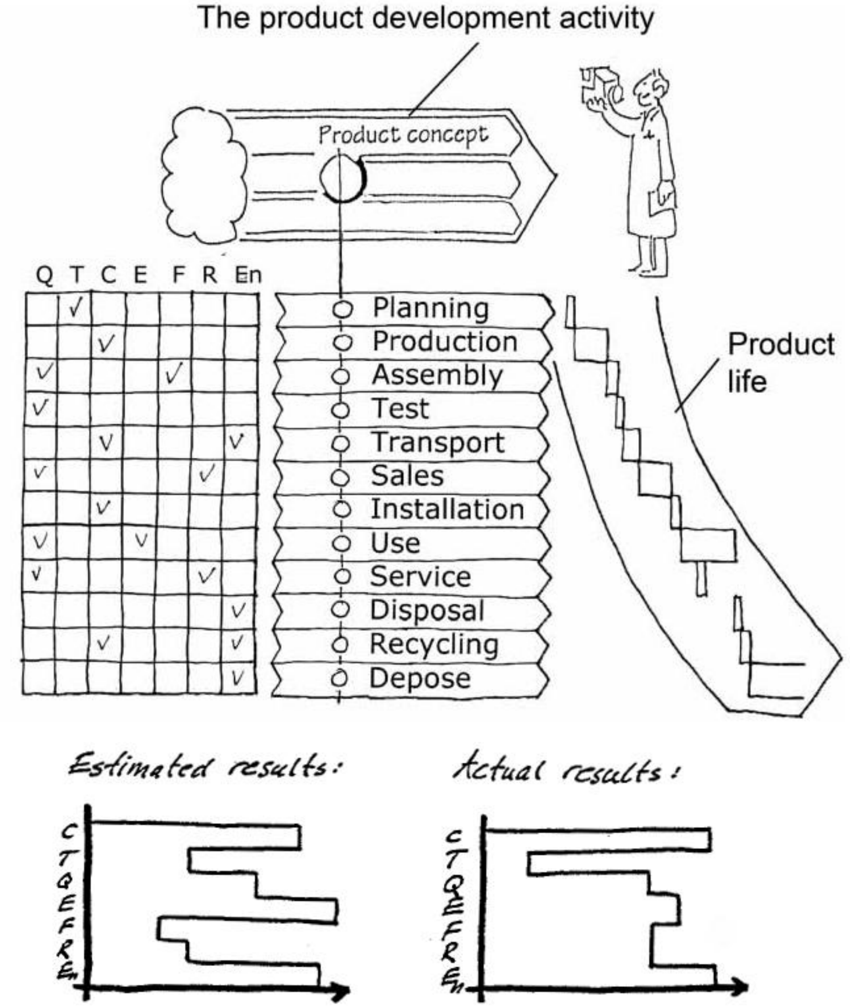


Figure 3.16. *An example of a score model of all systems, which dispositions effect on a product development activity. Figure combined using original figures from Olesen (1992) and Andreasen (2011).*

Olesen (1992) summarises that estimating the results in relation to the Universal Virtues at an early stage can be done by clarifying dispositions. He continues by explaining that estimation and control of dispositions calls for knowledge regarding the relationships between different parameters which characterise the systems.

3.5.3 Company Strategic Landscape

Juuti et al. (2007) and Lehtonen (2007) have presented a framework for defining elements of business-oriented product development. They discuss how business-oriented product development emphasises the goal of designing, in which the product should fit the order-delivery processes of the company and fulfil the needs of the customer or market. It is said that this is possible only if an overall view that includes the design intent (interactions of elements to be designed with other important elements in business environment) of the development situation can be described. Juuti et al. (2007) and Lehtonen (2007) explain that in the forming of this overall view the outlining of a map of a company’s product strategy can be helpful. They call this map/framework for business-oriented product development Company Strategic Landscape (CSL) and argue that every company has their own map. On a general level, the CSL is seen as in Figure 3.17.

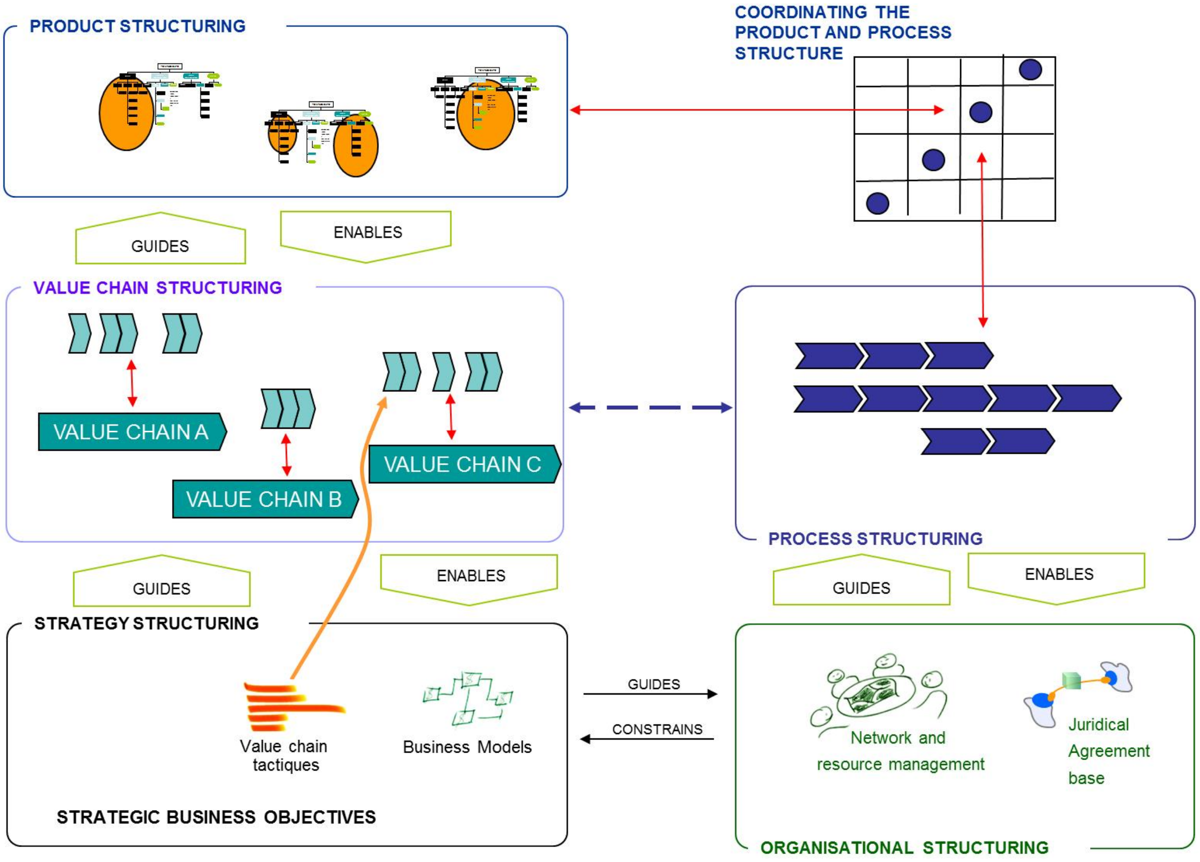


Figure 3.17. *Company Strategic Landscape (CSL) framework. (Lehtonen 2007)*

In the forming of an overall view, the elements and their relationships in a business environment need to be analysed, according to Juuti et al. (2007) and Lehtonen (2007). In earlier chapters of this thesis (the chapter on mass customisation), modularisation aspects were discussed briefly as an effective means for the adaptation of products to the alternating demands of customers and markets. In pursuance of the CSL's definition, it is explained that modularity is not purely related to products but rather to business objectives and thus to processes, value chains and environment of the business of the company, according to Juuti et al. (2007) and Lehtonen (2007). Five elements have been presented in the CSL:

- product structuring,
- value chain structuring,
- strategy structuring,
- process structuring and
- organisational structuring.

Relationships among these elements are either guiding or enabling, as shown in Figure 3.17. In research that aims to develop operations, the focus should be on the management of guiding relations because these actually have an effect on operations. The objective of the CSL is to describe the important areas and their relations, especially from a product-structuring point of view.

Product structuring in this framework does not mean bare composition hierarchy and bill-of-materials/list of parts because a product made from the same parts can be partitioned differently from the viewpoint of product structuring management. The value chain (structuring) in which the product has to operate guides product structuring. On the other hand, characteristics of product structure enable and limit the number of possible value chains.

Juuti et al. (2007) and Lehtonen (2007) do not explain exactly how value chains should be analysed in detail and what they really consist of, but Oja (2008) has discussed this topic further. According to Oja, in a design context value represents how well the needs of someone are fulfilled. Oja explains that product value and value chains are not very typical approaches in defining requirements for the product. He describes how in a business environment each company has regulations, rules, strategic selections or tacit preferences guiding values and their importance and the product should offer more value and benefit to the customer than the amount of the needed investment.

Connecting value and cost is typically sought in value analysis. Oja states that this kind of approach can be suitable within the realm of configurable products, in which the customer can select which properties he/she wants. In the context in which the customer purchases a complete product, and not just separate properties, linking product properties or functions with price can be more challenging, or even pointless, according to Oja. There are also other possibilities besides just linking cost with value. Oja explains that the seven universal virtues presented by Olesen (1992) could be one approach in analysing value, but many of those virtues are hard to measure. Value analysis bases itself on the best knowledge at that particular analysis moment, according to Oja.

Value chains describe and define the actions which create and accumulate the product or process value, according to Oja (2008). He continues by stating that this is typically considered as including only direct manufacturing and production actions; however, during the product design, conceptual solutions and decisions should also be considered as value chain. Value chain ends when all product responsibilities and services have been closed. Oja adds that the value content of the product is different for the producer and user of the product because they have different viewpoints regarding the product; thus, there are at least two different value chains. This means that product development includes the managing of trade-offs if common aspects are lacking. Oja defined these two value chains in the following way:

- *“The value chain of the producer includes the engineering process from product idea or opportunity identification to the end of product support. There can be several value chains if product responsibilities are directed to the separate units or companies.”*
- *“The value chain of the user includes stages from handing over the product for operation to disposal.”*

It is said that the overlapping of value chains is typical because, for instance, producer of the product might offer services that continues even longer than the value chain of the user. Each provider has its own value profile and some of the elements are neutral, elements which just have to exist at acceptable level and some of the elements are more critical in purchasing and decision making for the customer. Oja concludes that value assessment may provide better understanding to develop products in which value profiles match between producer and user.

As discussed in Figure 3.17, value chains are determined with the help of strategy structuring. Processes of sales, designing and producing etc. are in the middle on the right hand side in Figure 3.17. Structures of a company’s resources and network (organisational structuring) and chosen modes of operation (operative interfaces), can be seen in the background of process structuring. Organisational structuring and strategic business objectives have a guiding and constraining relationship between them. (Juuti et al. 2007; Lehtonen 2007)

The upper right corner of the CSL reflects the central idea of the framework: the relation between the internal structure of the product and the delivery process. In principle, the product structure and its delivery process can be chosen separately. Often either product structure or process structure is discussed at the same time while simultaneously accepting the other as standardised background material. When operations are required to be more optimal, then the product structure and process structure cannot be managed as unconnected areas anymore and they need to be aligned to each other. Thus the upper right corner of the CSL exemplifies the pairs of product structures and process structures in which the operations are rational and fulfil the chosen objectives. (Juuti et al. 2007; Lehtonen 2007)

Figure 3.18 presents the connection of product and process structures in relation to evolution of paradigms (mentioned paradigms are according to Victor & Boynton (1998)). This figure does not show the correct pairs in detail but it suggests how it could be possible to advance from unique products to partly configurable products (explained in Chapter 3.5.7.) by also acknowledging process view.

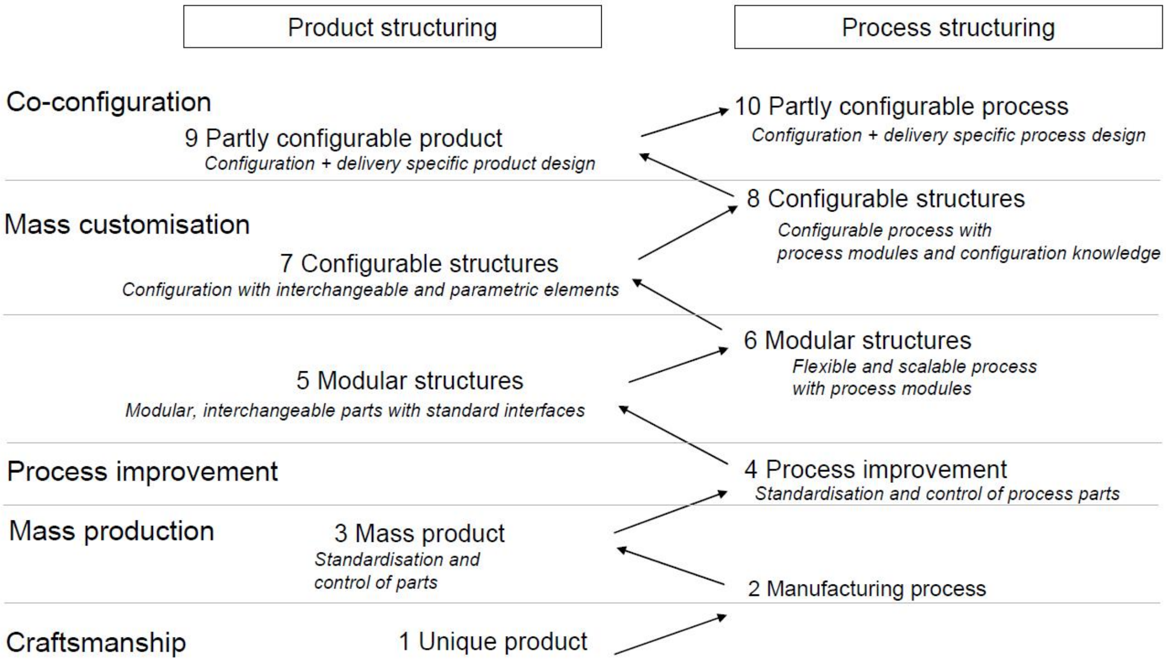


Figure 3.18. *Paradigms in relation to product and process structuring. (Juuti et al. 2007)*

In some cases, the situation can appear such that good pairs of product and process structures cannot be found at all. Different types of delivery processes have different abilities to support the objectives. To summarise, a certain process determines the product structure that supports the process in the best way. Defined product structure enables only certain value chains, which respond only to certain business objectives. (Juuti et al. 2007; Lehtonen 2007)

3.5.4 Product variety, commonality and design reuse

According to Ulrich & Eppinger (2008) the term ‘product variety’ explains the range of products the company can offer within a particular period of time in response to market demand. Victor & Boynton (1998) discuss how product variety has increased in several, but not in every, industry, eventually causing a need for a means of mass customisation to enable effectiveness of operations. Lengths of product life cycles have decreased and markets have learnt to expect customised products that can be adapted to different market segments, users and use cases, according to Andreasen et al. (1996) and Victor & Boynton (1998). Also globalisation is mentioned a causing the need for several product attributes in order to enable the fulfilment of demands in different cultural and regional areas (Victor & Boynton 1998). If the best option of the company from a competitiveness standpoint is to operate in a paradigm in which markets ask for personalised products, the need for product variety exists. Andreasen et al. (1996) have discussed the nature of variety. In that presentation, variety is understood as a cost factor and an eraser of the benefits of producing mass products. Variety can create additional costs to several phases of product life unless commonality of the products is not considered. Kristjansson (2005) has recognised that costs related to variety can originate, for instance, because of complexity, risks of design faults, slower learning curve, greater scrap rates in manufacturing, higher logistic costs and higher purchasing costs. Thus the challenge to companies is to design products that consider the need for variety (external requirements emerging from the market), as well as the benefits of commonality (internal requirements of the company) (Juuti 2008).

Pulkkinen (2007) discusses how the means for increasing production productivity have been developed over time and how many of these means are based on economies of scale in mass production. He continues by stating that in projecting companies the whole engineering function can become a bottleneck, bringing overload to the delivery projects. Pulkkinen has recognised three common options to solve the effects of overload, but he emphasises that none of these is a sustainable solution and does not solve the cause of overload:

1. doing overtime work,
2. hiring more personnel or
3. negotiating longer delivery times.

Consequently Pulkkinen (2007) suggests that systematic design re-use is a better solution for improving productivity. Duffy et al. (1995) have presented a framework for design re-use as shown in Figure 3.19. Duffy & Ferns (1999) explain that there are six knowledge resources in this framework:

1. domain knowledge: sources of knowledge concerning past designs or artefacts
2. domain model: a designers conceptualisation of a design domain applicable to the current design task
3. re-use library: an organised storage for storing reusable knowledge
4. design requirements: a statement of a design need
5. evolved design model: a description of an incomplete, proposed or final design, at any level of abstraction
6. completed design model: the complete definition of a new design

Duffy et al. (1995) and Duffy & Ferns (1999) continue by discussing how there are three design re-use processes:

- domain exploration: the analysis of a design domain from which reusable fragments of knowledge can be identified, rationalised, extracted, stored and later used to develop new designs

- design for re-use: the identification and extraction of possible reusable knowledge fragments and the enhancement of their knowledge content
- design by re-use: the re-use of existing concepts in new design situations

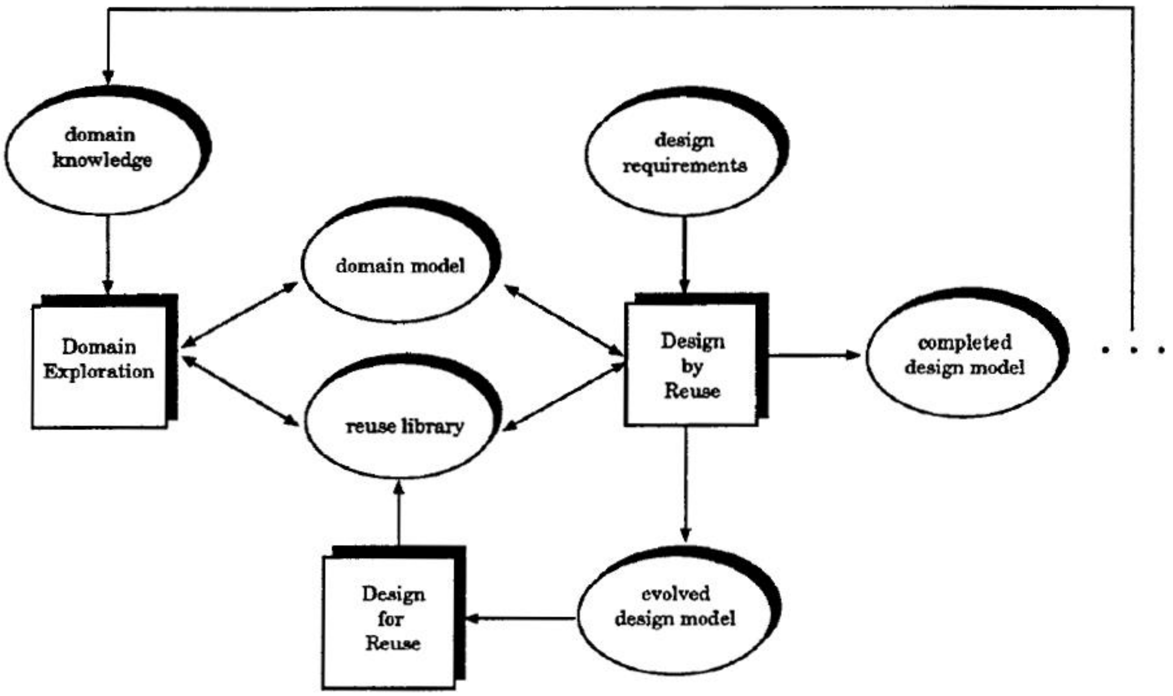


Figure 3.19. *Design for Reuse and Design by Reuse. (Duffy et al. 1995)*

Figure 3.20 presents the cause-effect chain regarding to why to design variety with commonality to technical systems, as developed by Juuti (2008). Standardisation and modularisation have been presented as enablers of commonality and thus the re-use of existing elements. Modularisation facilitates the adapting of a product to market needs, as also discussed by Andreasen et al. (1996) and Victor & Boynton (1998), for example. The possibility of reusing existing elements and the possibility of adapting the product to specific needs may create multiple benefits. Reusable existing elements (categorisation of product element types is discussed in Chapter 3.5.5: Standardisation and 3.5.7: Configuration) are beneficial to production systems, but flexible production systems are another way to make the production of variants easier, according to Andreasen et al. (1996). A discussion of flexible production systems in more detail is outlined outside the scope of this thesis. Re-use enables repetition in a delivery chain and allows for the removal or reduction of certain efforts needed, based on the issues presented in Figure 3.20. From an R&D standpoint, re-use reduces the needed design effort which effects on R&D efficiency, freeing more capacity for developing new variants. In this way a company has the possibility of increasing market share, sales and profit from an R&D point of view. Cost reductions are confirmed in, for example, the study by Ettlie & Kubarek (2008), in which they explained about how in 23 manufacturing company cases, 74% of the companies reported cost reductions and a faster time to market, as benefits of re-use. In addition, focused innovation, shortened testing and quality improvements were reported by Ettlie & Kubarek. Victor & Boynton (1998) explain how some companies are in a situation in which they seek out fragmented market segments with product variety that no longer fulfils economies of scale. In this kind of situation, inventory creates a major disturbance in production. Thus production steps is the other path in which major cost saving can be achieved with commonality that enables repetition, as also portrayed in Figure 3.20.

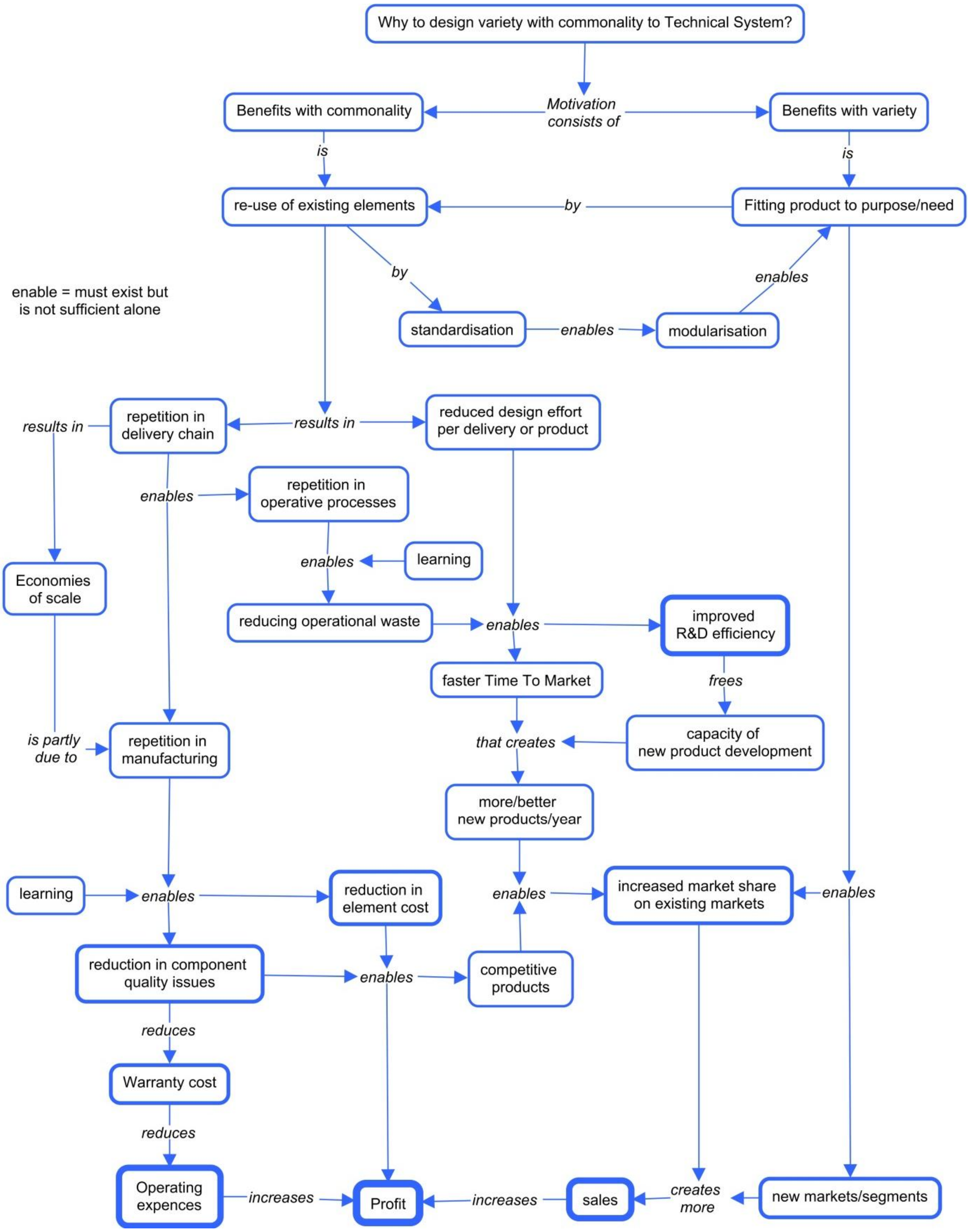


Figure 3.20. *Designing of variety with commonality in regard to Technical System. (Juuti 2008)*

Andreasen et al. (1996) state that a major challenge for designing is to fulfil the customer needs with as low a quantity of different variants as possible. In that paper, the reduction of variety was categorised using levels of the Domain Theory (the effect/function domain, which was later removed, is discussed here also). The process units should be able to be combined by developing and utilising defined interfaces. At an effect level, added functionalities should be added as “building blocks,” with interfaces enabling independent and flexible assembly. Organs should also have defined interfaces so that different configurations can be created without modification and thus without extra production costs. Variety could be reduced in the part level by modularisation, parametrisation or through use of group technology principles. (Andreasen et al. 1996). In the group technology concept, the similarity of parts is analysed based on the commonality of the manufacturing machines assigned to them (Kusiak 1987; Kamel et al. 1994; Dasari & Moon 1997). Part families are defined by the same kinds of parts and each family is manufactured in a specific manufacturing cell (Kusiak 1987).

In the development of variety, one has to consider which structures of the product it actually falls upon. In the CSL, it was recommended that the structures of value chains and processes should be analysed in order to find the factors and relations that must be taken into consideration in the development of product structure. This chapter focused on the role of commonality and variability in product development. Products with commonality can be used in the achieving of economies of scale. Thus commonality is closely related to the re-use of existing elements. Variability focuses on fulfilling customer or market needs. Several approaches, such as standardisation and modularisation, are presented as an aid for developing products with variability based on commonality, and thus in the next sub-sections these topics are discussed.

3.5.5 Standardisation

Pahl & Beitz (1996) explain that designers should always try to use components that do not need to be specially manufactured but rather are readily available as standard, repeat or bought-out parts. They add that easily available bought-out parts are usually cheaper than parts that are made in-house.

Several definitions of standardisation exist. Ulrich & Eppinger (2008) defines component standardisation as *the use of the same component or chunk in many products*. *A chunk can be standardised if it consists of only one or a few functional elements that are widely used in several different products.* Perera et al. (1999) define standardisation of components in the following way: "*Standardisation refers to a situation in which several components are replaced by one component that can do the functions of all of them*". Perera et al. (1999) continue by explaining that there are three possible situations in standardising components:

1. Component standardisation within a product: Several unique components are replaced with a common component in a product. By doing this, one expectation is to reduce development complexity of the product (Wacker & Treleven 1986).
2. Component standardisation among/between products: Several unique components are replaced with a common component in different products
3. Component standardisation among product generations: Common components are used in different products or in upgraded products across the time frame.

As discussed in TTS, the degree of standardisation is one way to categorise technical systems. Hubka & Eder (1998) divide machine groups, sub-assemblies and parts into two main categories, forming eight totally different types of elements as shown in Figure 3.21.

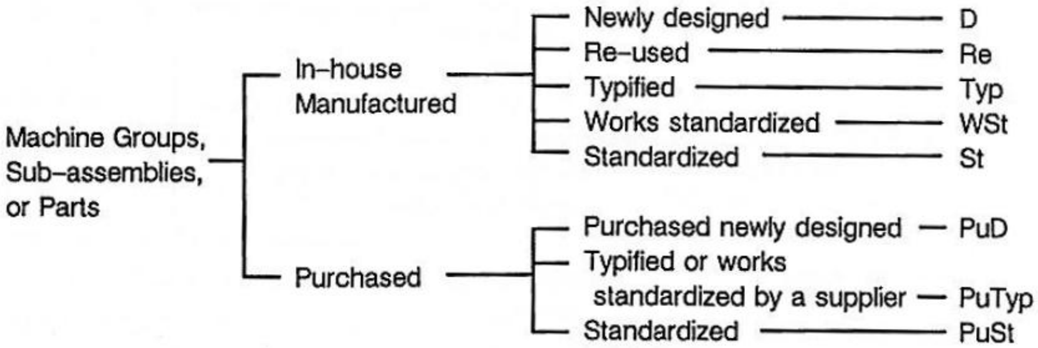


Figure 3.21. *Hubka & Eder (1988) state that the degree of standardisation depends on the number of different types of machine groups, sub-assemblies or parts. They also discuss the idea that standardisation can be used in managing the quality and interchangeability of technical systems or sub-groups.*

It is explained that standardisation can follow from international, national, industrial or company-in-house agreements or from market trends. Hubka & Eder (1998) separate standard parts from standardized parts. They explain that standard parts are usually results of international and national agreements, whereas standardised parts are the results of other procedures. The word “standard” thus covers both situations in this thesis. Rationalisation of the same kinds of systems or families into a smaller number which allows greater manufacturing quantities for each has been recognised as an important trend by Hubka & Eder (1998). The goal is said to be that of eliminating the need for newly designed in-house and purchased elements in this trend, and it is suggested that the number of different kinds of elements in new designs should be monitored.

Fujimoto (2007) discusses the measuring level of integrity or modularity in product architecture. Fujimoto defines product architecture as a description of how parts are put together (more discussion on architectures is seen in Chapter 3.5.6: Modularisation). The assumption in this suggestion by Fujimoto is that products are made of basic systems and sub-systems and numbers of parts. The goal is to analyse each functional part and categorise it based on the following categories:

- model specific: designed for and used only in a single-model family
- company specific: designed for and used in multiple models produced by the same company
- industry standard: used in multiple models produced by different companies

According to Fujimoto, this categorisation is made separately for functional components and peripheral interface components. The latter consists of components that are used in linking functions in the overall product architecture. Fujimoto gives an example from the passenger car industry, which is represented in Figure 3.22. The categorisation of parts can be used, for example, in calculating the share of industry-standard parts used in the product.

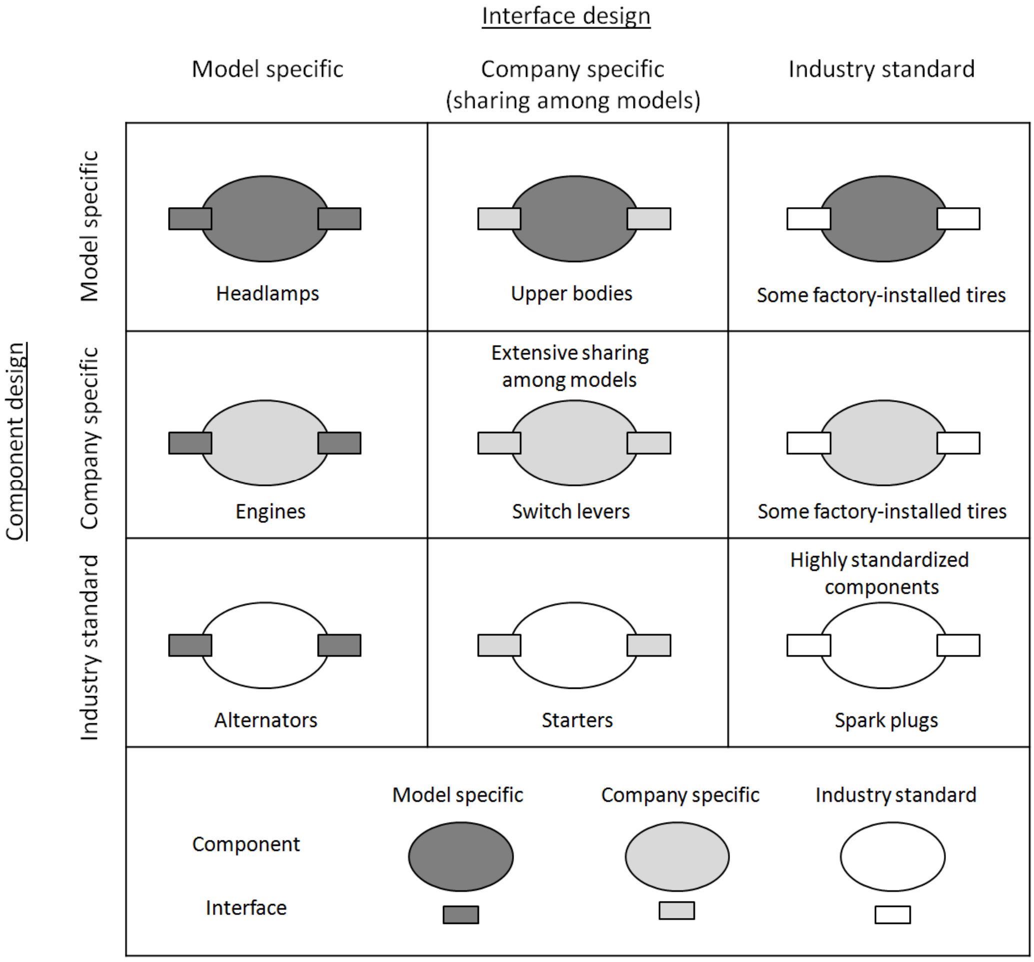


Figure 3.22. *Examples of industry-standard, company-specific standards and model-specific standard components and interfaces in the car industry. (Fujimoto 2007)*

Hubka & Eder (1998) and Fujimoto (2007) explain how machine groups, sub-assemblies, components and parts can be categorised based on the degree of standardisation. Wacker & Treleven (1986) state that measures indicating the degree of standardisation are needed if a higher degree of standardisation is desired. But why should one carry out this kind of analysis? This kind of information could motivate the company to seek more commonality in their products in order to enable greater profitability, as presented, for example, in Figure 3.20. Standardisation enables benefits of commonality, such as cost and resource savings and other benefits, as already explained by Juuti (2008). Perera et al. (1999) discuss how component standardisation effects on different phases of the product life cycle (the phases the product goes through). They explain that the whole life cycle should be analysed from an advantage/disadvantage cost perspective before standardisation decisions are made. Figure 3.23 presents the effects of standardisation collected mainly from research done by Perera et al. (1999), and also from Wacker & Treleven (1986).

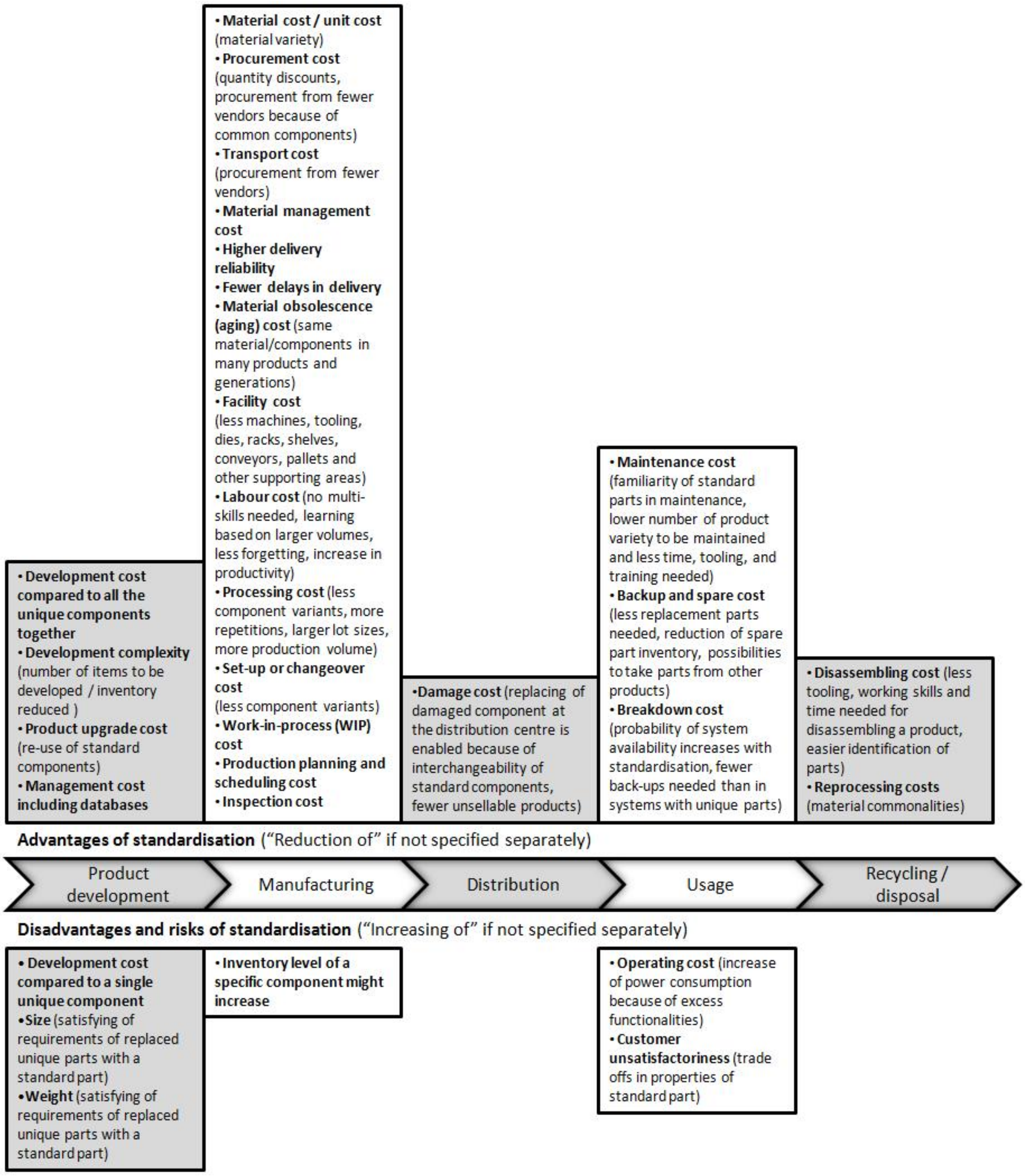


Figure 3.23. *Possible effects and possibilities of component standardisation on the product life cycle. The figure is composed from articles by Perera et al. (1999) and Wacker & Treleven (1986).*

Both pros and cons can be found when it comes to the standardisation of parts, as can be seen from Figure 3.23. Several effects can exist, especially in regard to product development and manufacturing phases. The statements summarised in Figure 3.23 also include prejudices. Size, weight or power consumption might not increase in all cases because of standardisation. For example, in respect to these issues, one should treat this summary cautiously. If comparing statements made, for example, by Perera et al. (1999) and Fujimoto (2007), one can say that there are fundamental differences on where to focus in the developing of business operations. From the issues presented in Figure 3.23, one could say that the level of labour skills needed in "optimal" situations would be low, whereas Fujimoto highlighted more about long time capability building related to personnel.

3.5.6 Modularisation

As stated earlier, standardisation enables modularisation. There are several definitions regarding modularisation and what elements are related to this context. Andreasen (2011) defines the terms module, modularisation and modularity in the following way, also reflecting these concepts within the Domain Theory:

"*A **module** is a product entity, which from a function or organ point of view has distinct function and requested properties, but at the same time such interfaces and interactions with other entities that you can see it as a building block in the parts structure*."

*"**Modularisation** aims for creating variety from the customer's viewpoint, whilst at the same time showing commonality between module variants, and such structural properties, that it reduces the complexity in the company's operations. Modularisation includes designing of modules, modular architecture and harvesting of benefits in areas where the effects can be seen by creating optimal conditions for these areas."*

*"**Modularity** is a relational property; it has no meaning to analyse and describe a product's seemingly modular structure unless its fit to a certain company area is known: how benefits of modularisation are created."*

Lehtonen (2007) discusses how at least two categories can be identified in modularity: M-modularity (the letter 'M' refers to the Finnish word for configuration, muuntelu) and life cycle modularity. He discusses M-modularity, influenced by the approaches and ideas presented by Karl-Heinz Borowski in his book "Das Baukastensystem in der Technik" (Borowski 1961).

*"**M-modularity** aims at configuration and enables product variation."*

"In M-modularity, *a **module** is a block (any assembly of the product or part of the system) that has an assigned interface and it is a part of a modular system. The existence of **interfaces** enables the independence and interchangeability of the modules in the same place, the use of one module in several product variations, or using a bus-type structure or a structure with a free layout."*

*"In M-modularity, a **modular system** is a system consisting of blocks which involves the interchangeability of the blocks."*

Later on in this chapter, we discuss modular systems in more detail. Configuration is discussed in more detail in the next Chapter 3.5.7. The other class of modularity Lehtonen talks about is related to the life cycle of the product. Examples of life cycle modularity are given in Figure 3.24.

*"**Life cycle modularity** considers of modularity based on reasons of manufacturing, maintenance or logistics. Variation is not considered in life cycle modularity. In this type of modularity, division to modules can be made based on the reasons for instance in manufacturing, assembly, logistics and service but alternative modules are not needed. A modular system is thus not needed, and in most cases it does not even exist and neither does*

product family containing variation. The definition and managing of the interfaces is sufficient.”

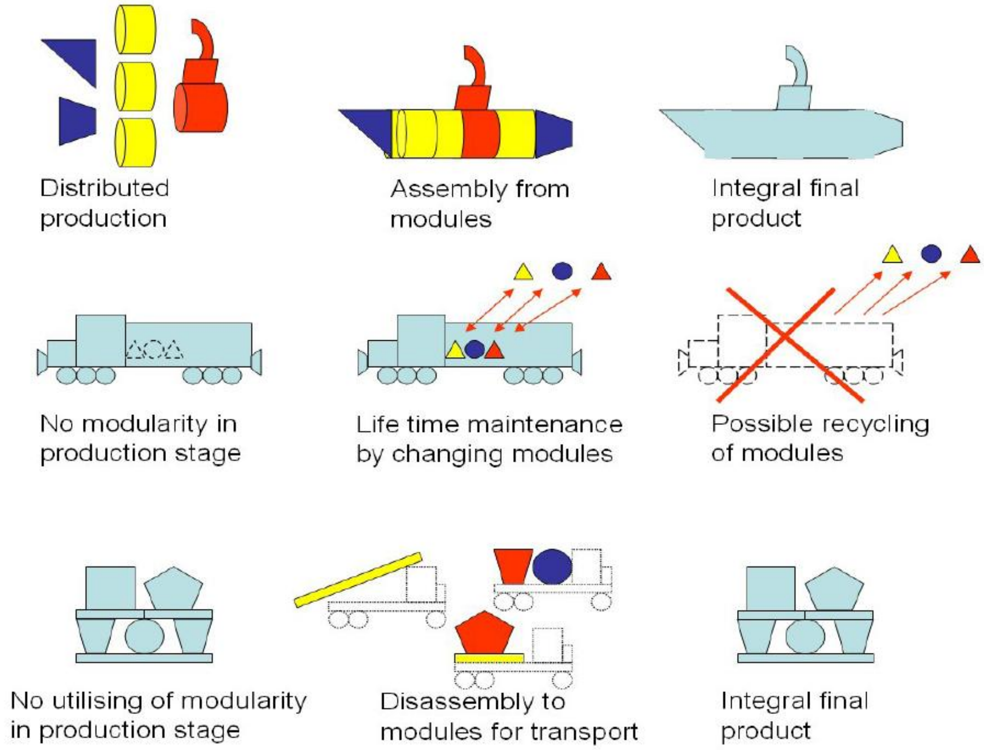


Figure 3.24. *In life-cycle modularity, module divisions are made based on possible positive effects which could be enabled by modularisation in certain phases of the product life cycle. The modules are presented with bright colours in this figure. (Lehtonen 2007)*

As Lehtonen (2007) explained, the interchangeability of modules is important in modularity aiming at configuration. Pine (1993) states that at least six types of interchangeability can be recognised. Some of these types are discussed also by Ulrich & Eppinger (2008). Figure 3.25 illustrates these types of interchangeability and modularity and in the following these types are briefly explained:

- **Component-sharing modularity** uses the same component in multiple products.
- **Component-swapping modularity** complements component-sharing modularity. Components are paired with the same basic product and as many products as there are components to be swapped can be created.
- **Cut-to-fit modularity** considers one or more components which are continually variable within pre-set or practical limits.
- **Mix modularity** considers mixing components together in a way that something different is created.
- **Bus modularity** uses standard structure in which a number of different components can be attached.
- **Sectional modularity** allows the configuration of types of components which have standard interfaces in arbitrary ways. This type of interchangeability allows the greatest degree of variety and customisation and also enables re-configurability, but it is the most difficult to achieve.

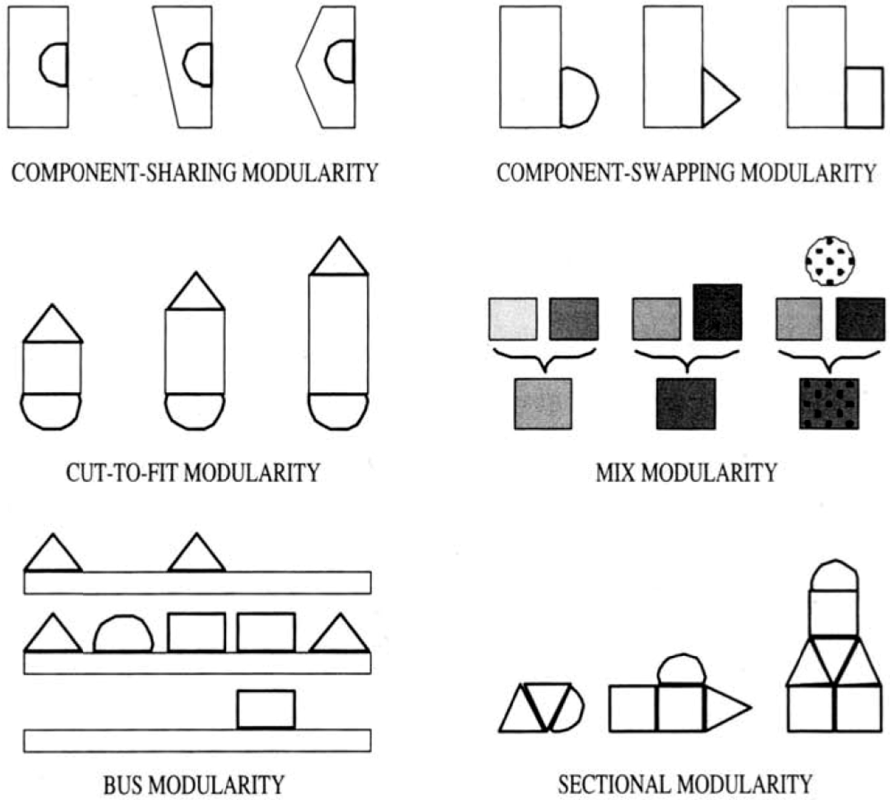


Figure 3.25. *Types of modularity according to Pine (1993). Originally these types were presented by Ulrich & Tung (1991) without mix modularity. Fixson (2006) discusses how these alternatives describe different types of interfaces.*

When discussing modularisation, the word architecture is also often introduced. Fujimoto (2007) defines product architecture in the following way:

*"**Product architecture** is an aspect of design concept comprising of components. Product architecture is a description of how to put parts together."*

Fujimoto (2007) has discussed the fact that there are different kinds of architectures and how combinations of these exist. He categorises architectures in two ways:

- integral or modular architectures
- open or closed architectures

Integral architecture brings together parts that interact in complex and overlapping ways with each other, according to Fujimoto (2007). He also explains that the functionality and performance of a product with integral architecture depends on the capabilities of designing and manufacturing to make parts work and interact with each other. Fujimoto also discusses open and closed architectures. Integral architecture is explained as closed architecture in all situations. Fujimoto argues that this is because it is a complex system and interchangeability of parts is often impossible without modifications due to the fact that each part has several functions to fulfil. Thus, when speaking about modularisation, the main objective is not to design integral architecture for products.

Modular architectures are the opposite of integral architectures. There are several definitions regarding modular architectures. Here the definitions of Andreasen and Fujimoto are presented. Andreasen (2011) defines modular architecture in the following way:

*“**Modular architecture*** respects *the desired variety, creates commonality for efficient use of resources, and reduces effects of complexity in all actual operations. Modular architecture enables configuration of modular products. Modules, interactions and interfaces needs to be defined in modular architecture.”*

Fujimoto (2007) also discusses modular architecture. Fujimoto’s definition includes the same elements as presented by Andreasen (2011):

“*In* **modular architecture***, interactions between elements occur through clearly defined interfaces. Modular architecture enables using of off-the-shelf and commodity parts only if part interface-physical connections adhere closely to industrial standards.*”

Fujimoto (2007) continues by explaining that the idea in modular architecture is that only a minimal exchange of energy, information etc. is necessary for the modules to work properly. Fujimoto states that modular architecture makes the designer’s task easier. Designers do not need in-depth knowledge for designing a module, and working principles for other modules are not necessarily needed to be known as long as interfaces between modules are known (Fujimoto 2007). The latter statement opposes statements presented by Fujimoto about capability-building capability being the most important factor of long-term competence capability (not only from a manufacturing point of view) if this capability building should also improve skills of designers towards a more holistic understanding of the products to be designed. If all design tasks are independent and only interfaces are given to the designers who don’t understand the overall architecture or platform, the risks of developing in a closed “silo” emerge. This could result in unnecessary variety. Fujimoto (2007) explains that integral architecture is always closed architecture but that modular architecture can be open or closed. Examples of integral/modular and open/closed architectures are given in Figure 3.26.

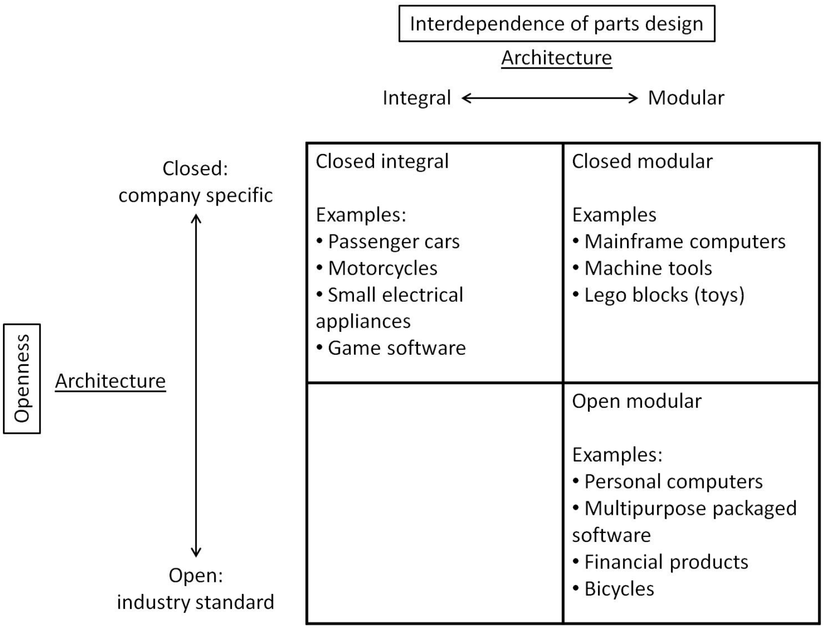


Figure 3.26. *Architectures can be integral/modular and open /closed. (Fujimoto 2007)*

Lehtonen (2007) presents the idea that desks made by Mauser-Werke are a good example of a closed and modular architecture. In this type of architecture, all the possible elements and combinations are defined. Architecture description, including a layout of every desk variant, is presented in Figure 3.27.

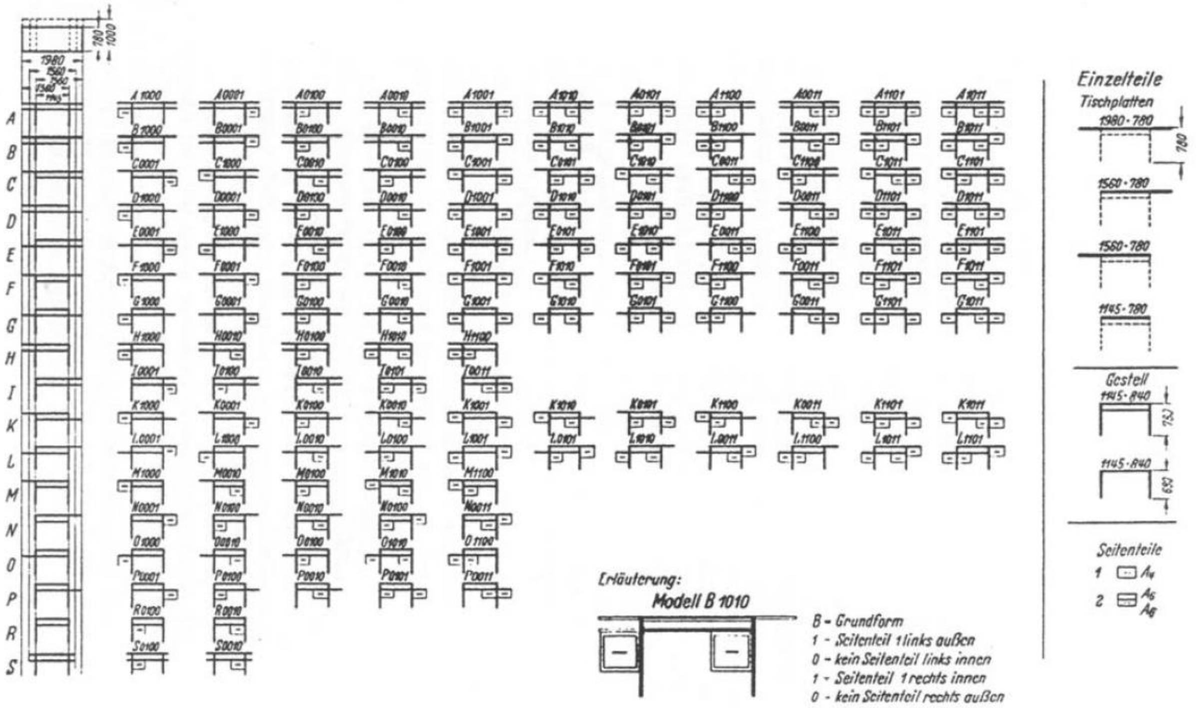


***Figure 3.27.** Desks made by Mauser-Werke give an illustrative example of closed and modular architecture in which all elements and combinations are defined. This figure includes also configuration rules of the variants. Figure is attached from Lehtonen (2007) and originally presented by Borowski (1961).*

As explained in Figure 3.26, for example, bicycles are products which have an open and modular architecture, according to Fujimoto (2007). In the frame of a bicycle, interfaces with other necessary components are typically standardised. Nowadays there are several alternative standards for each interface in the bicycle industry. From a modularity perspective, one could ask, however, whether the bicycle is modular or founded only on standardisation. As presented earlier, interfaces are related both to standardisation and modularisation. Lehtonen (2007) explained that in modularity aimed at configuration (type of modularity which requires product variants), only a module that belongs to a modular system can be considered as a true module based on the principles and definitions of Baukastensystem (system of constructional elements according to Lehtonen) presented originally by Borowski (1961). Thus if the bicycle is considered modular according to previously mentioned definitions, a module system of bicycle could include also other modules besides just the ones that one specific company offers as presented in the desk example. Thus, defining whether the product is modular or not depends on how the modularity is defined.

There are different suggestions about how the architecture should be designed and managed in order to support modularity. Chapter 3.7 focuses on state-of-the-art method-like approaches in this field but some of the generic suggestion are also presented in this section. Holmqvist (2004) has discussed management of product variety by means of product architecture and interfaces. He gives an example in which a vehicle manufacturer has divided the chassis into four sections, as shown in Figure 3.28. Holmqvist explains that each of the sections should be able to handle the variety related to it without affecting the other sections.

In the description of this example from the industry, he emphasises that the sections should be as independent as possible. Holmqvist also explains how if a new section variant is required it can be added without changing the whole chassis. He suggests that areas in which two sections meet are called bases and these bases prevent the variety from spreading to other sections in the product. He discusses the idea that a base is not a single interface but a combination of interfaces between sections that are close to each other. Holmqvist also explains how a good place for a base is where a combination of interfaces, parts or fractions of the product can be kept constant and forms a base with determined variety. He states that the defining of these kinds of bases is challenging and that a great deal of product expertise is needed. A major design challenge is that the variety in each section can be created without affecting other sections, according to Holmqvist.

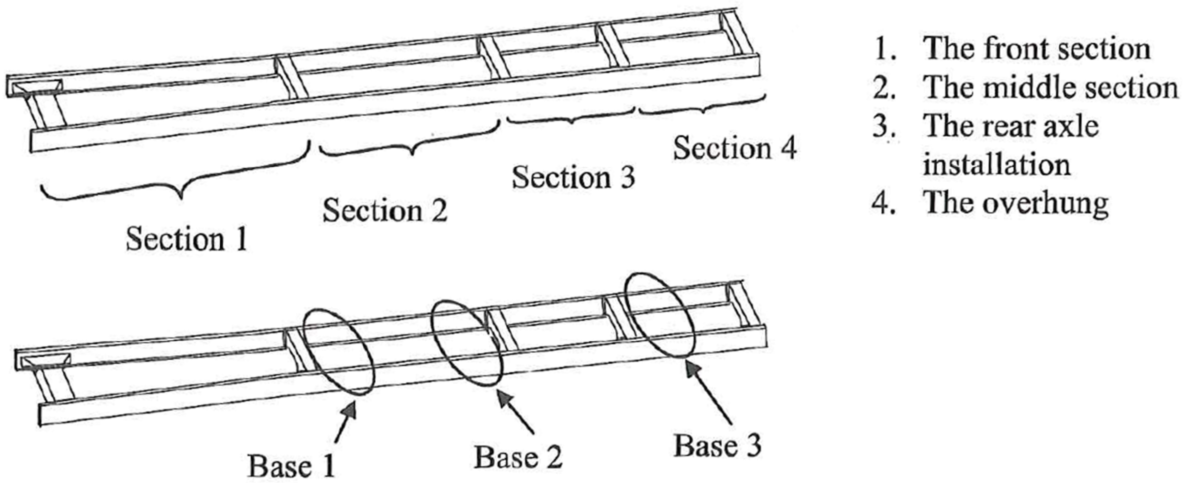


__Figure 3.28.__ Holmqvist presents the architecture/layout and the interface-oriented approach for managing the design of variety. The figure shows an example of a vehicle chassis in which variety is managed using defined sections and bases. Variants for each section cannot break the base areas. Figure combined from Holmqvist (2004).

Holmqvist (2004) argues that this kind of definition is justified in situations in which a large number of variants, large physical differences between the variants and several technologies and functions exist. He states that if interfaces are managed one by one between different chunk variants, each variant interface will be unique because there is no common product architecture (product family architecture). Holmqvist also notes that if the number of variants is large it is often impossible to define interfaces after defining the variants. Thus he discusses that the development of good interfaces starts with planning and managing the variety in each variant of each chunk. Holmqvist adds that not all of the interfaces can be considered as bases but that the bases will make the managing of other interfaces easier because there will be at least some areas that can be understood as unchangeable.

Other suggestions for interface management and documentation can be found in, for example, systems engineering. Systems engineering aims to define the requirements and the product to be built by providing a framework for different engineering disciplines (Stevens et al. 1998). Stevens et al. (1998) discuss that there are benefits in keeping components as independent as possible, but components must be able to interact with each other. They suggest that a separate interface control document (ICD) between any two components, agreed upon by both parties, should be formed. Stevens et al. suggest that this kind of ICD restricts how an interface is created and changed. Similar definitions can be found in, for example, the book by Ulrich & Eppinger (2008), wherein they also state that interfaces represent the contracts between chunks (modules) and can be represented using formal specification documents. Stevens et al. emphasise that the design (product architecture) should be modular in order to define interfaces independently from the components that use interfaces. They explain that this allows an interface to be reused in different contexts and to be decoupled from certain components. Stevens et al. mention that too many interfaces with an external system can make the product difficult to manage and thus they suggest that it might be beneficial to make several external systems to work to a single standardised interface if possible. Thus, the statements of Stevens et al. (1998) about the interfaces have similarities with statements made by Holmqvist (2004).

How are product variants for customers discussed in a modularisation context? Andreasen (2011) explains that the defining of modules, interactions and interfaces is facilitated by the defining of a market-oriented **product family**. Andreasen emphasises that modular architecture and product family should include only a minimum number of modules for creating the needed variety (obviously due to cost factors, as discussed earlier in the product variety and standardisation chapters). Andreasen stated in the earlier-mentioned definition of modularisation that modularisation should be focused only on the areas or life cycle phases where benefits of modularity are foreseen. This definition of modularity by Andreasen (2011) is parallel to the categorisation carried out by Lehtonen (2007). Both the M-modularity and life cycle modularity defined by Lehtonen (2007) aim at bringing modularity to where it is useful, depending on the business case. Here also the term **platform** is introduced by Andreasen (2011) for the describing of aligned structures. Andreasen has presented a framework around product architecture, which is shown in Figure 3.29. Product family and platform concepts are discussed more extensively in Chapter 3.5.7.

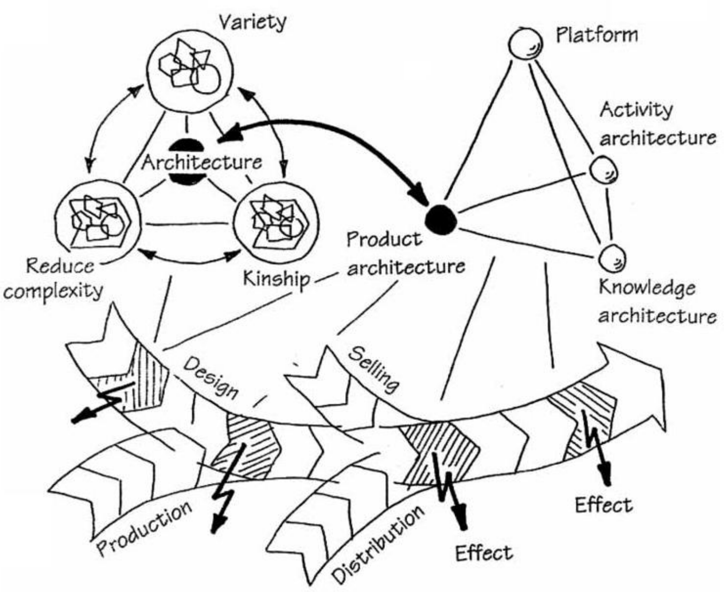


Figure 3.29. *According to Andreasen (2011), product architecture relates to consideration of variety, commonality and complexity. The figure also shows that a platform are related to product architecture. Andreasen emphasises that it is important to recognise the areas in the product life cycle in which modularity could bring benefits and, based on this, to design product architecture that could enable these benefits.*

Several approaches presented in the literature (Pahl & Beitz 1996; Fujimoto 2007; Ulrich & Eppinger 2008) explain that the defining of the functions of the product, including the splitting up of the overall function into sub-functions, is important point in modularisation. The viewpoint of Fujimoto (2007) regarding the relation of functional design and structural design is explained in Figure 3.30. In this definition, sub-functions of the required function affect the division of modules. Structural design in Figure 3.30 presents abstract modular architecture according to Fujimoto (2007).

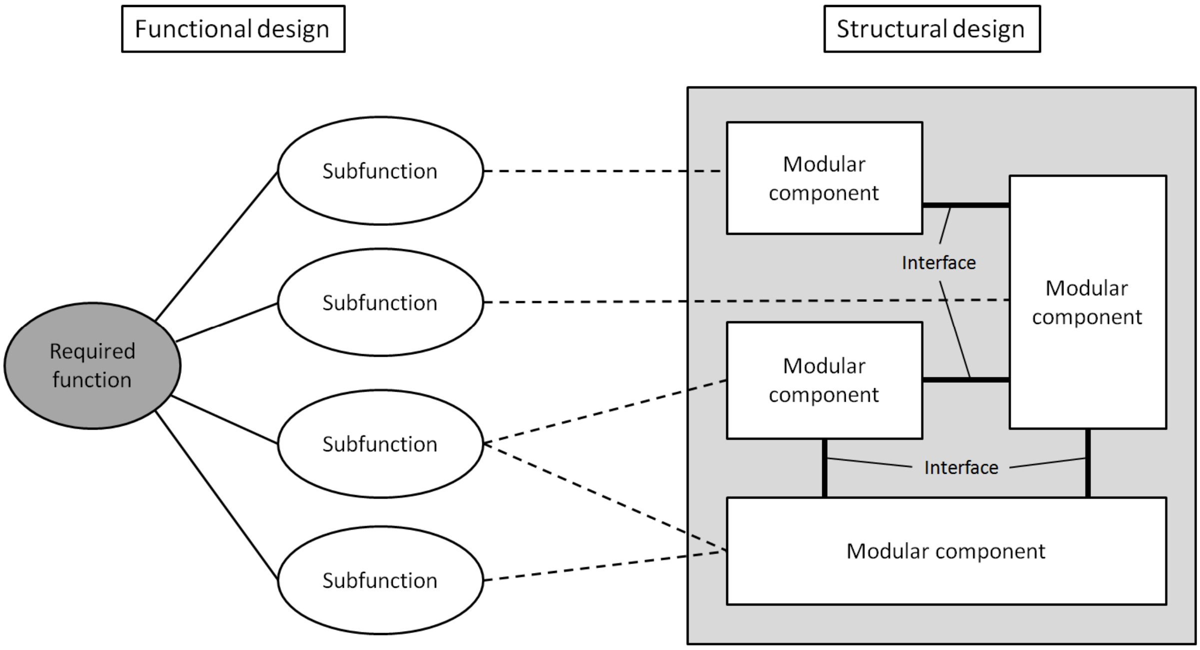


Figure 3.30. *Product architecture as functional design and structural design, according to Fujimoto (2007).*

Fujimoto's (2007) consideration about modular architecture includes the idea that each module corresponds to a specific function. The interesting point is to discuss a definition of a function more. Andreasen (1996) discusses how modularity can be used in the management of variety from a Domain Theory point of view. In the process/activity domain, process units should have interfaces which enable combining and reconfiguring. In the organ domain, the main functional units should be designed so that they have interfaces which enable the creation of functional configuration options without the need for design work. In the part domain, component modularity, parametric or group technology principles can be used in management of the variety (Andreasen 1996). Later on, Andreasen (2011) defined that *function is the ability of organ, organism or product to create an active effect*.

Andreasen (2011) has defined that a desired function relates to two different phenomena and thus function has two different meanings in our research context:

- A strict effect-oriented function concept in the product composition or configuration activity for reasoning interactions between organs. This function concept explains what the product can do, and the definition is found widely in German language literature. (Andreasen 2011)
- A more informal function concept couched in terms of the customer's daily language. This function concept explains what the customer can do with the product. Thus the definition is linked to the need, goal or use formulating activity. (Andreasen 2011)

Pahl & Beitz (1996) present this German language literature issue, as discussed by Andreasen (2011). Pahl & Beitz suggest that the consideration of functions and their relationships is one viewpoint in dividing the system.

Lehtonen (2007) has investigated the capabilities of a systematic design process to facilitate in the development of modular products. One typical presentation regarding the systematic design process is presented in Figure 3.31 by Hubka et al. (1988), upon which statements by Lehtonen are also reflected. Lehtonen has made the following statements about what issues the phases of the studied systematic design process consider (or not) in the development of a modular product:

1) Elaborate upon or clarify the assigned specification

Lehtonen (2007) states that the first phase of a systematic design process should consider the goals and definitions regarding why the product must be modular. Lehtonen discusses that reasons for modularisation are often not product-internal requirements but are instead related to the business and production processes, processes which are often not considered as part of product design.

2) Establish functional structure and
3) Establish concept

In the second and third phases of a systematic design process, the layout issues of the products should be discussed in order to enable the development of the modular structure, according to Lehtonen (2007). He states that in the systematic process, this cannot be done. These phases should include tasks related to the organisation of the part structure to be created later, according to Lehtonen (2007).

4) Establish a preliminary layout

Lehtonen explains that the fourth phase includes the most critical design decisions regarding the implementation of the module structure. The concepts developed in the previous phase either enable or exclude possible module structures, but the fourth phase is a crucial phase in the enabling of a certain module structure at the latest. (Lehtonen 2007)

5) Establish dimensional layout and
6) Detailing, elaboration

In the fifth and sixth phases of systematic design process, there are two options for considering the product structure, according to Lehtonen (2007). He explains that if the part structure enables modular structure, then it can be implemented on the detail level. The second option is to fix conceptually independent entities as integral elements, as defined by Lehtonen. Thus the result of this is integral architecture according to the definition by Fujimoto (2007). The fifth and sixth phases make it possible to create more preconditions for modularity, but usually it means the addition of elements and the division of individual parts into a number of parts, which does not yield as good a modular structure as the one created earlier in the conceptual design phase (Lehtonen 2007).

Lehtonen (2007) explains that the first phase (to elaborate or clarify the assigned specification) and the fourth phase (establish the preliminary layout) in systemic design process are the most important phases from a modularisation perspective. Analysing the driver of the modularisation and ensuring that the selected draft structure meets the requirements are both key issues. Lehtonen continues stating that the second phase (establish functional structure) and the third phase (establish concept) do not include critical design decisions considering module structure. Thus he argues that the systematic design process and especially the functional structure do not indicate one ideal division into modules in designing a new modular product.

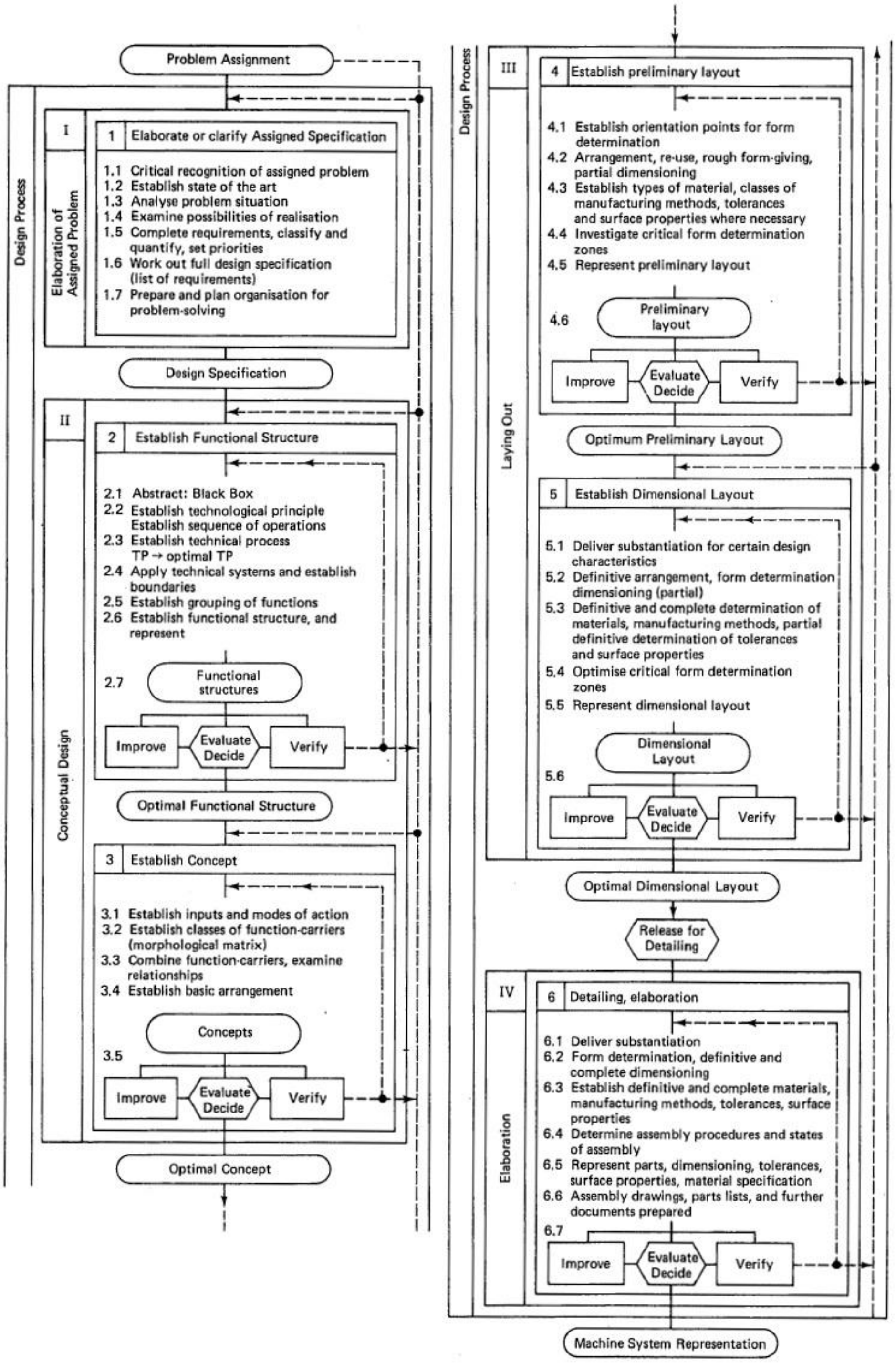
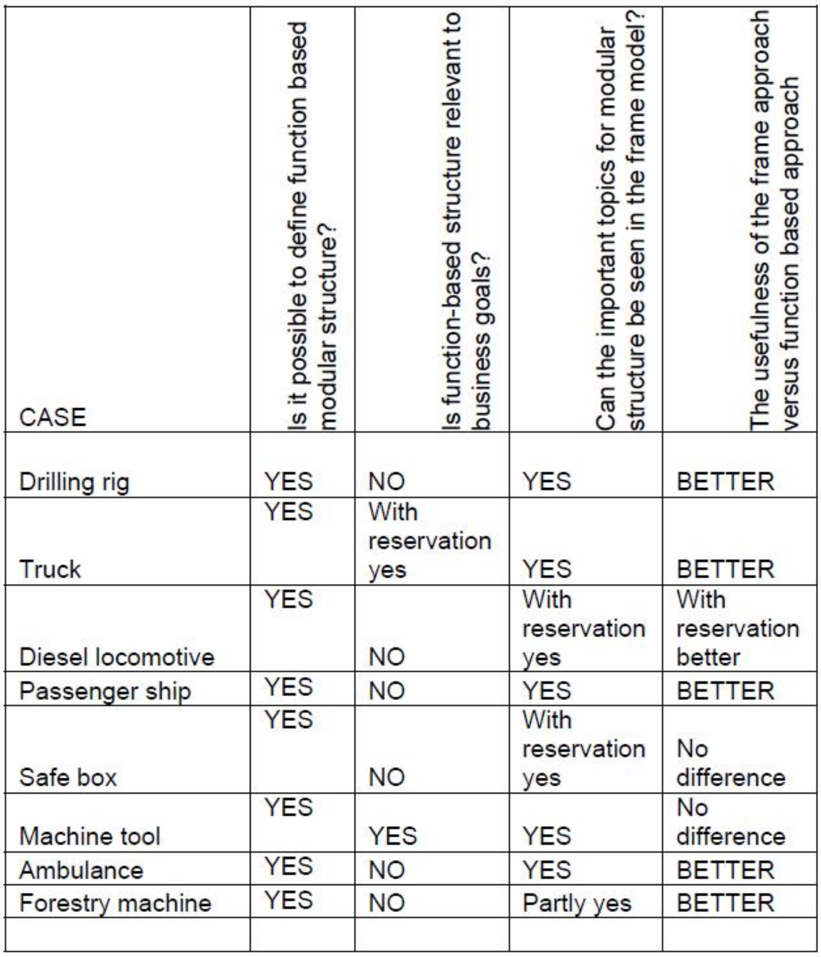


Figure 3.31. *Lehtonen (2007) states that the systematic design process (Hubka et al. 1988) is an important starting point in the designing of a technical system but that the process does not consider the most important issues in the development of new modular products.*

Lehtonen (2007) has also analysed possibilities for function-oriented modularisation in different industrial cases. He studied eight industrial cases in which he found out that in every case modularisation based on the functions would be possible, but if the module division were to be made by analysing business environment areas such as those presented in CSL, the module structure could be better in the most cases, from a business viewpoint. The results of his analysis are shown in Table 3.3.

Table 3.3. *Lehtonen (2007) analysed eight industrial cases considering modularisation. He found out that in all of the cases, module division based on the functions would be possible but that in most cases better results could be achieved by analysing the drivers for modularisation from the business environment of the case companies.*



CASE	Is it possible to define function based modular structure?	Is function-based structure relevant to business goals?	Can the important topics for modular structure be seen in the frame model?	The usefulness of the frame approach versus function based approach
Drilling rig	YES	NO	YES	BETTER
Truck	YES	With reservation yes	YES	BETTER
Diesel locomotive	YES	NO	With reservation yes	With reservation better
Passenger ship	YES	NO	YES	BETTER
Safe box	YES	NO	With reservation yes	No difference
Machine tool	YES	YES	YES	No difference
Ambulance	YES	NO	YES	BETTER
Forestry machine	YES	NO	Partly yes	BETTER

Lehtonen (2007) explains that functional structure is related to the transformation implemented by the technical solution, and therefore that is why it is the dominant element in the area of product structuring. He states also that if the product is modular for configuration purposes, the modularity of the product is not just related to the transformation implemented by the technical system (model of Hubka & Eder). Lehtonen explains that value chains, in which a technical system is included as a part, as well as production processes of the technical system, must all be considered in modularisation in order to achieve good solutions.

We have discussed that modularisation can be done for example based on the function structure or based on the results drawn from the analysis of the business environment. There are publications in which examples of driving forces behind modularisation have been presented. One of them is carried out by Erixon (1998), where he categorises 12 module drivers which relate to different phases of the product life cycle. These are discussed in Table 3.4. These drivers explain generic reasons, which can be valid in a specific modularisation case and might cause pressure for the modularisation of products.

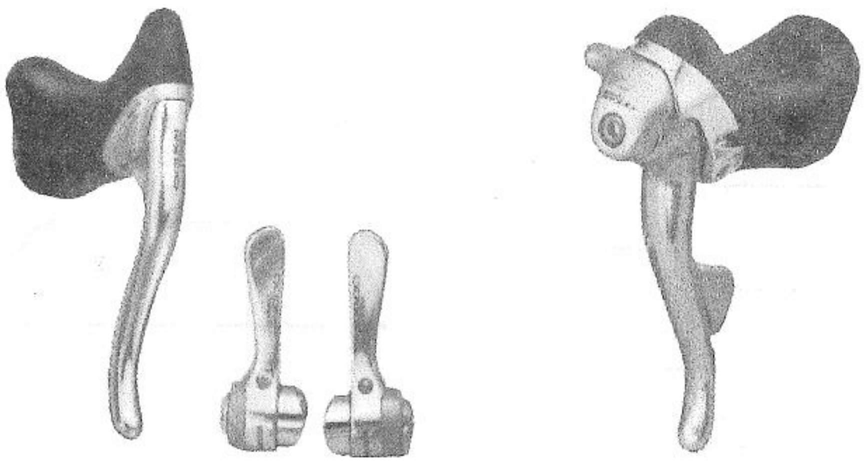
Table 3.4. *Summary of module drivers presented originally by Erixon (1998).*

LIFE CYCLE PHASE / FOCUS	**MODULE DRIVER**
Product development and design	**Carry-over:** Re-use of a part, a sub-system or a product in new product generations or in other product families.
	Technological evolution / technology push: Possibility of technology shift during the product life cycle in a product which changes rapidly.
	Planned design changes / product planning: Introducing consistent products.
Variance	**Technical specification**: Handling of product variation and customisation effectively by allocating variations to one or a few parts of the product. This facilitates possible inventory savings, customer service and overall costs by keeping the product generic as long as possible.
	Styling: Strong influence of trends and fashion justifies styling modules.
Production	**Common unit:** Using part or sub-functions in the entire assortment of products increasing volumes of certain parts at a particular point of time.
	Process and/or organisation re-use: Organisation of a shop floor work around a module. Facilitates increasing of automation, learning, re-using of process equipment and skills.
Quality	**Separate testing of functions:** Testing before the module is supplied to the main process enables the reducing of feedback times.
Purchasing	**Supplier offers black box:** Possibility to purchase complete standardised modules enables need for lower assortment and lowers the administration costs of logistics if deals can be made with fewer suppliers.
After Sales	**Service and Maintenance:** Replacing of damaged area of the product needs to be effective.
	Upgrading: Upgrading and life-cycle issues such as rebuilding of the product are highlighted.
	Recycling: Limiting number of materials in each module. For instance, materials that are hard to recycle can be implemented in one module if possible.

Although the module drivers presented by Erixon (1998) are generic, they don’t necessarily consider all the cases in modularisation. Thus the introduction of a generic approach such as CSL for recognising the module drivers from the business environment is justified. The list of Erixon gives good examples, however, of what kinds of reasons for module division can be recognised in different modularisation projects.

Based on the research done by Lehtonen (2007) regarding functional structures and modularisation, one could say, regarding the reasoning of module division in Figure 3.30 by Fujimoto (2007), that it is justified only if one or two sub-functions per module are the most important module drivers in the business environment of the company (presuming that the sub-functions in Fujimoto's figure are strict effect-oriented functions as defined by Andreasen (2011)). If functional thinking is not the most important module driver in the business environment, the possibility for developing more beneficial module structures and architectures could exist based on the arguments by Lehtonen (2007). Lehtonen (2007) argued that better results could be obtained overall by describing the overview of business as a starting point in modularisation in several cases.

Another good example of modular and integral architectures and function-oriented modularisation is given by Ulrich & Eppinger (2008). They discuss the fact that most modular architecture is that in which each functional element of the product is implemented by exactly one physical module and that there are few well-defined interactions between the modules. Ulrich & Eppinger discuss architectures using an example from bicycles, as presented in Figure 3.32. They explain that separate brake and shift levers are examples of products with modular architecture and that a product in which the brake and shift levers are integrated together has more integral architecture.



Courtesy of Shimano

Figure 3.32. *The left-hand side of the figure gives an example of module division that is based on the principle of 'one important function in each module'. This module division did not lead to ultimate success in the market, as can be seen by analysing the structure of brake and shift levers in modern road bicycles. One solution of current dominant design is presented on the right-hand side of the figure, in which braking and shifting are integrated into the same product. In this example, major module drivers, or in other words, logic for the partitioning of the product, including reasons for implementing modularity in a certain way, could have been recognised from the use phase of the product: safety and ergonomics create important requirements for the structuring of the product. Of course, the maturity of the technology available in each era, for example, has to be taken into consideration in these statements. Figure presented originally by Ulrich & Eppinger (2008).*

Referring to the earlier-discussed categorisation of functions by Andreasen (2011) and statements presented in the previous paragraph, one could still question the role of function's definition in analysing the quality of functional modularity. Even if the division of modules is carried out in a business-oriented way (not purely in a function-oriented way), the most important function can still be defined from every module. The previous statement is a self-evident fact if the definition of function is unrestricted, but the structuring of a business-oriented function without a guiding framework can be challenging.

There are several aspects related to modularisation. Juuti (2008) has summarised modularity and configurable products (these are discussed in greater detail in Chapter 3.5.8), highlighting the separation of the design process, the order-delivery process and management elements, based on the publications by Lehtonen (2007), Pulkkinen (2007) and Tiihonen et al. (1999). This summary is presented in Figure 3.33. The figure explains how customisation strategy considers customisation principles and policy meaning as far as who can customise in certain life phases and what kind of variability is enabled in a certain life phase. The main elements of a module system are architecture, modules and configuration knowledge, as shown in Figure 3.33. It is explained that technology enables modules, and these modules enable certain architecture. Juuti (2008) explains that configuration knowledge includes information about interchangeability rules and constraints. From the design process perspective, these three elements are important in the designing of a module system, but of these elements, other critical elements in the developing of a module system can be further derived. Juuti (2008) discusses both the idea that interfaces are explained in order to partly define modules and their interdependency, and how modules can be partitioned. Partitioning logic has been explained as affecting directly on the partitioning of the product elements and thus it has an effect on the product architecture and interfaces as summarised in the figure below. Partitioning logic is guided by customisation tactics, which consider how variability can be enabled by, for instance, using configurable or modular structures.

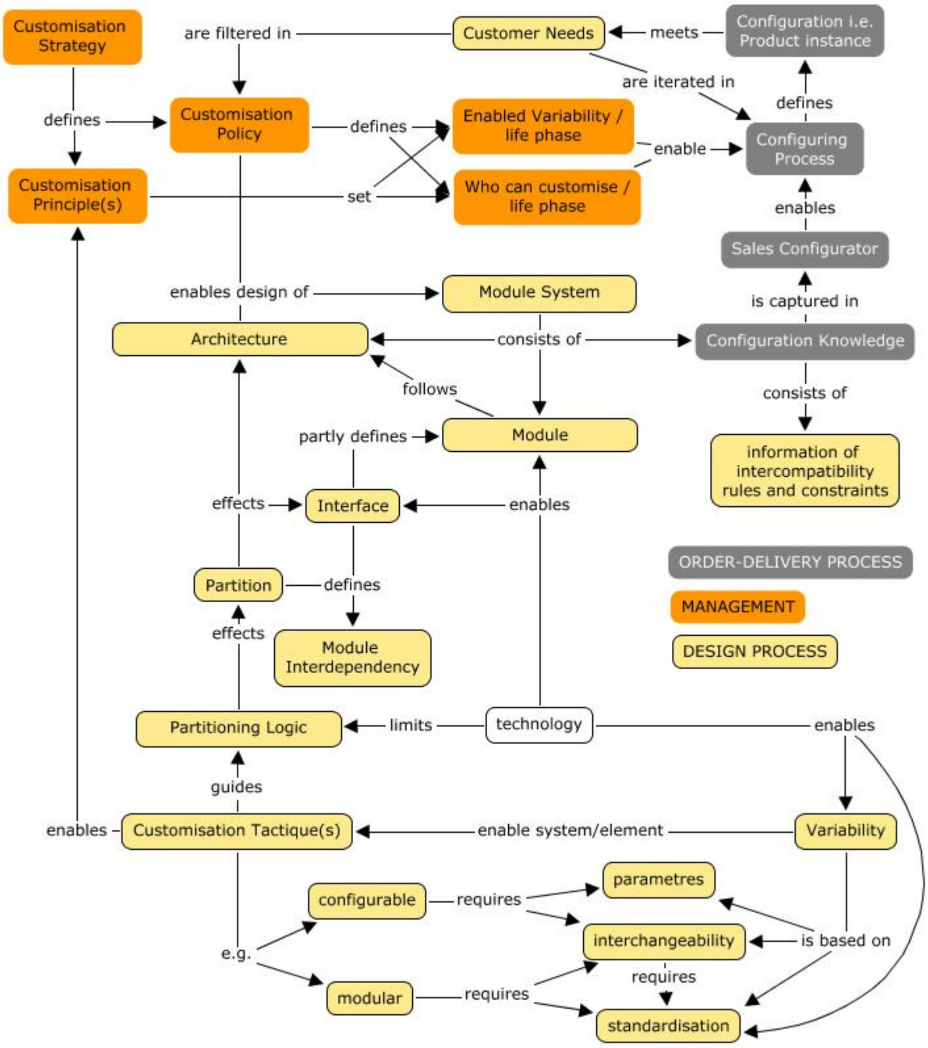


Figure 3.33. *Key elements in modularisation and configuring according to Juuti (2008).*

Based on the summary carried out by Juuti (2008), the structure of the module system has been discussed further in a paper by Pakkanen et al. (2013). In the designing of a module system, division of the necessary design information into partitioning logic, modules, interfaces, architecture and configuration knowledge may be beneficial. In that paper, the Module System elements are summarised in the following way:

- **Partitioning logic** describes reasoning leading to a certain module division.
- **Modules** are the building blocks of the Module System.
- **Interfaces** are the enablers of interdependency and interchangeability of the modules.
- **Architecture** describes the layout definition of the structure of a Module System and defines how modules and their interfaces are located within the product
- **Configuration knowledge** describes the compatibility and constraints of the modules and customer needs.

To summarise, **partitioning logic** considers reasoning regarding modular product structure, thus including statements regarding module division. As stated by Lehtonen (2007), it is beneficial if the development process of a modular product begins with setting the objectives from a business and customer context and ends with validation, in which it is ensured that the result of development fulfils the expectations and requirements. The objectives for the development of a modular product can, for instance, be instance linked to different steps of the product life cycle, as discussed earlier. Juuti (2008) explains that there can be standard, configurable (modular), partly configurable and unique elements in the product. These are discussed in more detail in the next chapter on configuration. Partitioning logic should reveal why elements of the product structure are of a certain type. In the case of modular products, partitioning logic should explain which elements or areas of the product have a need for variants and why. Lehtonen et al. (2011b) states that it is important to understand how the need for variety arises from the processes in which the customer uses the products.

As explained in Lehtonen (2007) and Lehtonen et al. (2011b), the designing of **modules** can proceed from the defining of preliminary or generic modules to the designing of definitive and detailed modules. This means that at first the modules can be understood as module candidates, and that later on in the development, when the need for variety is understood better, they should be designed with detail. Different module versions may also have to be considered because of possible technological evolution and other aspects. Product and feature roadmaps have been presented in regard to this issue (Lehtonen et al. 2003; Juuti 2008).

Interfaces concerning mechanical structures are typically discussed abstractly in the academic publications of modularisation. Typical interface discussions consider, for instance, electrical devices such as the example presented in the book by Ulrich & Eppinger (2008). There are a limited number of research disciplines in which more precise suggestions concerning the definition of interfaces can be found. Some of these are discussed later on in this thesis. As discussed earlier, Stevens et al. (1998) discuss the fact that in Systems Engineering an agreement concerning the interfaces between two or more modules should be made. They call this agreement an interface control drawing or interface control document, considering, for instance, requirements set by the environment around the modules (e.g. free space), accessibility (e.g. service), type and number of connectors, mechanical properties or parameters related to the energy. The approach of Holmqvist (2004), which was discussed earlier in this section, emphasised the defining of product into sections and bases for managing the spreading of variety in the product. According to the case discussed by him, this kind of definition relates also to the often discussed generic definitions of interfaces in the product architecture, as shown in, for example, Figure 3.30 by Fujimoto (2007).

Modules, interactions and interfaces are defined in modular **architecture** according to Andreasen (2011). Modular architecture can be divided into closed and open modular architectures, as Fujimoto (2007) suggested. Lehtonen (2007) discussed that in closed architecture all possible modules and combinations are defined. In open modular architecture the situation is the opposite: interfaces are defined but there is no definition of all the possible modules and their combinations. Examples of open architecture were given by, for instance, Fujimoto (2007). Product architecture considers the technical compatibility of the modules on a level which has also a role in the defining of the configuration knowledge.

Although the title of this chapter is modularisation, a short journey into the topic of configuration is taken here because it facilitates the use of modular structures in the order-delivery process, as presented by Juuti (2008). **Configuration knowledge** explains the possible combinations in relation to the modules and requirements, such as customer needs that cause the need for variety. There are approaches in which matrices are used for the defining of configuration knowledge (Bongulielmi 2003; Nummela 2006). There are also other techniques in which, for instance, Unified Modelling Language (UML) is used to describe the configuration knowledge (Felfernig et al. 2002). Haug et al. (2012) present the idea that the representation of configuration knowledge as a separate description has been found to be advantageous in several cases where a product configurator as IT support system is considered. Table 3.5 includes examples of what kind of information is related to each suggested element of the Module System.

Table 3.5. *The elements of Module System and suggestions for the information content.*

Module System elements	**Information content**
Partitioning logic	• objectives related to the life cycle phases of the product • reasoning for element types of the product (standard, fully configurable, partly configurable, unique) • reasoning for the need of variety (customer / market context) • estimated or realised business effects of the module system
Modules	• information about module candidates (this can include for example hierarchic lists and sketches made during the designing of the Module System) • information about definitive modules (detailed descriptions and drawings of the modules)
Interfaces	• definitions and/or agreements of interfaces between two or more modules
Architecture	• preliminary architecture/layout descriptions including modules and their interfaces • definitive architectures/layout descriptions with final modules and their interface descriptions
Configuration knowledge	• preliminary and definitive technical compatibilities of the modules • compatibilities of customer needs causing the need for variety • preliminary and definitive compatibilities of the customer needs and the modules

Thus the examples given in the above table suggest that not only the final information of designing is important but also that information concerning modularisation “work in progress” should be documented and stored because this kind of development information can be important in the future.

The list of five elements is not definite in a way such that the module system should always include all of these design information elements. If it is the case that variants are not needed and the type of modularity in question is life-cycle modularity, as defined by Lehtonen (2007), the need for configuration knowledge might not exist at all. For instance the submarine example in Figure 3.24 explained that life-cycle modularity can mean that the reason for module division can come from production. In this case, one module can only be in one place in the product. Thus there are no configuration possibilities or variants for the customer, but for instance the production has to have information related to the technical compatibilities of the modules. This is more like assembly information than the actual configuration knowledge often discussed with modular products with customer-oriented variants. For example, Lehtonen (2007) defined this as M-modularity, as discussed earlier in this section. The argument is that this kind of division of modularisation into five design information elements facilitates the structuring of information and tasks related to the development of modular products. In this section, configuration and configuration knowledge were discussed briefly; these issues are discussed later on in more detail. Until then an overview of product platforms and product families will be done.

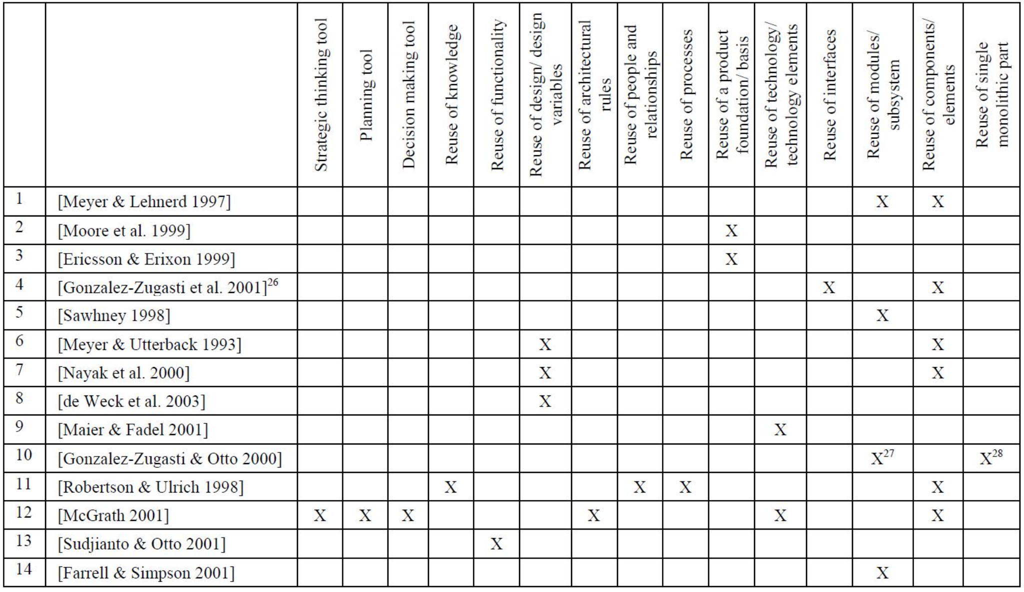
3.5.7 Product platforms and product families

This section focuses on definitions of the product platforms and product families. These terms have appeared in earlier sections of this thesis, but in this section more attention to the definitions are given.

Kristjansson (2005) explains that platforms have been introduced in order to lower internal cost by economies of scale and standardisation, and at the same time enable the creation of product variants and decrease the time to market. Ulrich & Eppinger (2008) describe how the planning of the product platform includes managing the trade-off between commonality and distinctiveness. The benefits of utilising a platform relate also to the benefits of re-using existing elements and offering variants to the market, as was already discussed in Figure 3.20 by Juuti (2008). Oja (2008) also explains that from a company point of view there are several benefits to using a basic product platform as a base for a product instead of providing full variability and configurability for the customer. Kristjansson (2005) discusses the fact that there are also risks with platforms. He expresses the point that one risk is that the products become too similar from customer point of view and there is also a risk that long term innovation might suffer if platforms are too dominant (presuming that the platform is static).

Different definitions related to platforms exist. Kristjansson et al. (2004) has studied how platform terms such as product platform, technology platform, brand platform, global platform, modular platform, process platform, customer platform, integral platform, scalable platform and high-tech platform are discussed in the engineering design context. He also notes that different definitions for the same type of platform exist. Kristjansson et al. has made a summary considering the definitions of product platform that is shown in Table 3.6.

Table 3.6. *A summary of product platform definitions done by Kristjansson et al. (2004) shows that different words and topics are used when defining product platforms. Superscripts in the table are explained in the original paper.*



		Strategic thinking tool	Planning tool	Decision making tool	Reuse of knowledge	Reuse of functionality	Reuse of design/ design variables	Reuse of architectural rules	Reuse of people and relationships	Reuse of processes	Reuse of a product foundation/ basis	Reuse of technology/ technology elements	Reuse of interfaces	Reuse of modules/ subsystem	Reuse of components/ elements	Reuse of single monolithic part
1	[Meyer & Lehnerd 1997]													X	X	
2	[Moore et al. 1999]										X					
3	[Ericsson & Erixon 1999]										X					
4	[Gonzalez-Zugasti et al. 2001][26]												X		X	
5	[Sawhney 1998]													X		
6	[Meyer & Utterback 1993]						X								X	
7	[Nayak et al. 2000]						X								X	
8	[de Weck et al. 2003]						X									
9	[Maier & Fadel 2001]											X				
10	[Gonzalez-Zugasti & Otto 2000]													X[27]		X[28]
11	[Robertson & Ulrich 1998]				X				X	X					X	
12	[McGrath 2001]	X	X	X				X				X			X	
13	[Sudjianto & Otto 2001]					X										
14	[Farrell & Simpson 2001]													X		

Based on the findings summarised in Table 3.6, Kristjansson et al. (2004) have defined platform in the following way, capturing the accepted body of definitions as the lowest common denominator:

*“**Platform** is a collection of core assets that are reused to achieve a competitive advantage.”*

Kristjansson et al. (2004) further define that *core* is essential for the product to be competitive, *assets* are components, processes, knowledge or people and relationship and *competitive advantage* can be created by differentiation, cost leadership or focusing on a specific market niches.

Ulrich & Eppinger (2008) has made a high level presentation of how platforms are designed and used in product development. This has been presented in Figure 3.34. They discuss the fact that research and development experiences enable the development of product platforms, which can be used in creating product releases utilising a certain platform.

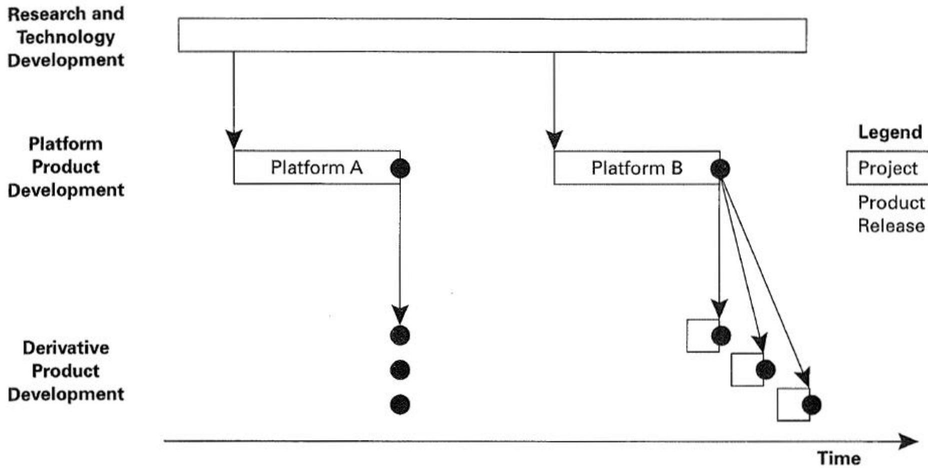


Figure 3.34. *Ulrich & Eppinger (2008) explain that a product platform is used in the development of platform derivative products. (Ulrich & Eppinger 2008)*

As can be seen from Figure 3.34, Ulrich & Eppinger have recognised that different platforms are valid only for a certain time. This issue has also been studied by Riitahuhta & Andreasen (1998) and Lehtonen et al. (2003). They discuss the Dynamic Modularisation approach, which is explained in Chapter 3.8.1. In this context, Lehtonen et al. (2003) define product platform and product family in the following way:

*"A **product platform** enables launching a **product family** that consists of modules developed in the platform development level and that corresponds to certain market needs now and in predictable future."*

Thus the above definition has similarities with ideas discussed by Ulrich & Eppinger (2008). Referring to Figure 3.34, a product family would include products at the level of 'Derivative Product Development'.

To conclude based on the discussed references, a product family can be understood to be based on the product platform that includes re-usable assets, which can be used in the creation of product variants for certain needs. All the product variants that use the product platform comprise a product family.

3.5.8 Configuration

When discussing configuration, several definitions can be found. Configuration is a topic near to standardisation, modularisation and the development of product families and platforms. Pulkkinen (2007) discusses the idea that configuration has two meanings:

- activity: configuring or a configuration task
- object/result: a configuration or a product individual

Thus the first definition considers configuration as an activity. In that case, terms of configuring, configuration task and also configuration processes are often used. The result of these activities is a configuration; thus, it can be said that the activity defines the object. Brown (1998) discusses the idea that **configuring** includes the choosing of components, the establishment of abstract and specific relationships between components and the testing of compatibility and goal satisfaction. Martio (2007) has explained that a **configuration process** is enabled by a common product family structure, of which different variants can be defined by using a configuration process based on the needs of the project, as presented in Figure 3.35. Haug (2007) discusses the fact that definitions of configuring typically focus only on physical products. He has given a definition which also considers non-physical products:

*"**To configure** means to combine predefined entities (physical or non-physical) and define their variable properties, while obeying constraints and legal interface combinations, in a way that satisfies given requirements."*

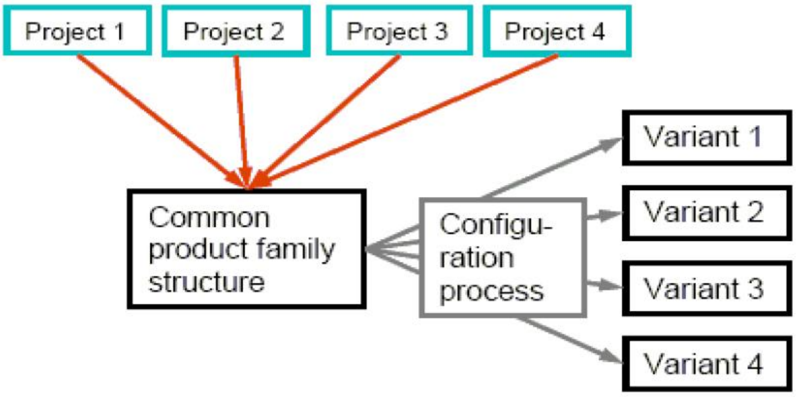


Figure 3.35. *Framework of configuration process according to Martio (2007).*

A variant, as shown in the above Figure 3.35, is understood as a synonym for a configuration in this thesis. Variants or configurations are results of configuring, configuration tasks or configuration processes depending on what definition of the activity is used. Pulkkinen (2007) has defined a configuration as follows:

"***A configuration*** *is the definition of a product individual which is a member of a product family. Configurations consist of a group of components and their relations. Usually configurations are supposed to differ from each other; thus, a configuration is a special arrangement of the set of possible arrangements. Configurations have a purpose that is somewhat similar to the purposes of configurations of the same kind."*

Tiihonen et al. (1996; 1998), Pulkkinen et al. (1999) and Pulkkinen (2007) state that configurable products have the following properties:

- *"Each delivered product individual is fitted to the specific needs of a customer."*
- *"Each product individual is specified as a combination of the pre-designed components or modules. Thus, no new components are designed as a part of the sales-delivery process."*
- *"There is a pre-designed general product structure and it has been pre-designed to meet a given range of specific requirements."*
- *"The sales-delivery process requires only systematic variant design, not adaptive or original design in the sense of Pahl & Beitz (1996)."*
- *"Since the delivered product individuals are based on the common general structure, we consider the combination of them as a product family."*

Pulkkinen (2007) discusses the fact that there are three main categories in configuring, as presented in Figure 3.36. He explains that activities, product structures and information technology (IT) support are important viewpoints of product configuration. Pulkkinen summarises these categories in the following way:

1. *"The activities of configuring include modelling the configuration knowledge, the utilisation of the knowledge in sales-delivery process and maintaining the configuration knowledge."*
2. *"The development of the generic product structures for configurable product families."*
3. *"The utilisation of IT support for configuration as a specific set of information technologies technology."*

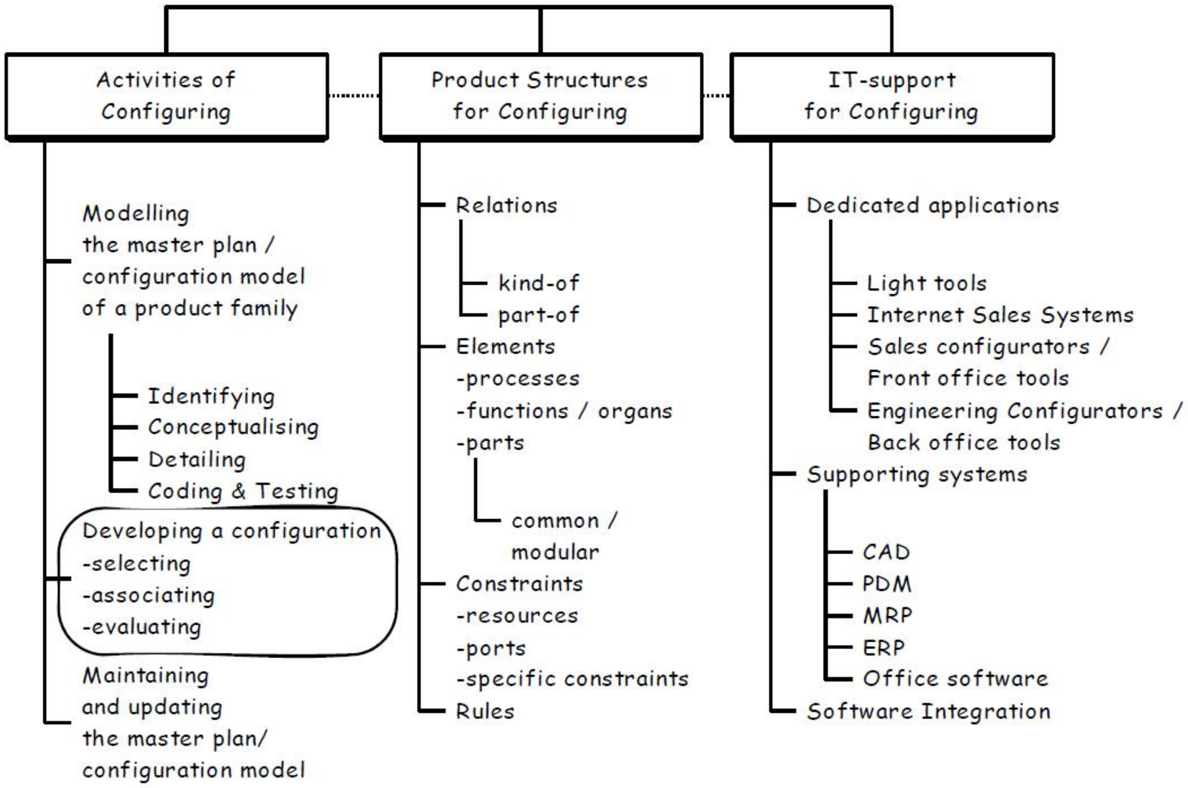


Figure 3.36. *The framework of product configuration. (Pulkkinen 2007)*

Referring to **activities of configuring,** as shown in Figure 3.36, definitions of product families were discussed in Chapter 3.5.7 in general detail, and approaches to development of product families are discussed in the state-of-the-art section of this thesis (Chapter 3.7). Approaches for modelling the configuration knowledge are also discussed in the state-of-the-art section.

In developing a configuration, there are four generic ways to create variety between configurations (or variants, as discussed in Figure 3.35) according to Pulkkinen (2007):

1. *"varying of the number of similar elements"*
2. *"varying of the type of an element (a module in part domain)"*
3. *"varying of the (horizontal) relations of elements"*
4. *"varying of the attribute of an element (module characteristics)"*

Pulkkinen (2007) presents how modularity is a characteristic of a product family architecture and can facilitate the varying of a product, referring to different types of modularity as also shown in Figure 3.25 in this thesis.

Referring to **product structures for configuring**, as shown in Figure 3.36, there is also research that considers this category. Pulkkinen et al. (2000) and Juuti & Lehtonen (2006) discuss how a **configuration task** is performed during the order-delivery process when the product elements are selected from a number of options to modify the product to meet the needs of a customer. They highlight that this definition excludes any design work to be done in the order-delivery process because it was found to be a best practice in companies benefitting financially from configurable products. It is also explained that the design was done in a separate development process beforehand, enabling configuring.

Juuti & Lehtonen (2006) discuss that in the order-delivery process of mass products, the most suitable standard product is selected, whereas in the order-delivery process of mass customised products, the most suitable parts are selected for the product. Engineering is not needed in these product types. In the order-delivery process of one-of-a-kind (or in other words unique or novel) products, some unique designing is always needed according to Juuti & Lehtonen (2006). The latter kinds of products include design for unique characteristics and not design for re-use. Juuti & Lehtonen point out that the goal in design for re-use is to solve unique situations with standard solutions. They also discuss the issues in paradigms by recalling that in mass customisation the objective is to maximise the amount of design reuse but that in a projecting environment, delivery specific elements are often made. For measuring the amount of re-use, a classification of product elements has been made. Standard, configurable, one-of-a-kind and partly configurable parts are recognised by Juuti & Lehtonen. Juuti (2008) discusses the fact that these elements form a partly configurable product structure, as shown in Figure 3.37. Juuti & Lehtonen (2006) and Juuti (2008) have defined these product structure types, consisting of different types of parts, in the following way:

- *"**Standard product structure** has two goals: mass production and product synthesis. Standard product structure contains standard parts which can be re-used within one product, across products within the company or in multiple industries and value chains. Designing of a standard part is done outside the order-delivery process."*

- *"**Configurable product structure** has three goals: enabling variety by modularisation or configuration, enabling commonality by re-use and product synthesis. Configurable product structure contains standard parts and configurable parts. Variability is achieved via configurations: re-using a particular combination of standards parts, modular parts, and/or module system parts. Depending on the customisation method, variability can be achieved by using standardisation (sectional modularity, bus modularity), interchangeable parts and parameter-based modularity. Variability involves that no engineering is needed in the order-delivery process."*

- *"**Partly configurable product structure** has three goals: product-level synthesis, commonality by re-use and variety by configuring or modularisation. Partly configurable product structure can contain standard parts, configurable parts, one-of-a-kind parts and partly configurable parts thus it is a combination of other product structure types presented above."*

- *"**One-of-a-kind product structure** has one goal: a unique synthesis that meets the needs. It is designed for one particular instance and the objective is to achieve a technical system that meets the needs. One-of-a-kind product structure can contain standard parts and unique parts. Manufacturing of unique parts might be possible by using existing equipment but benefits of mass production are not achieved."*

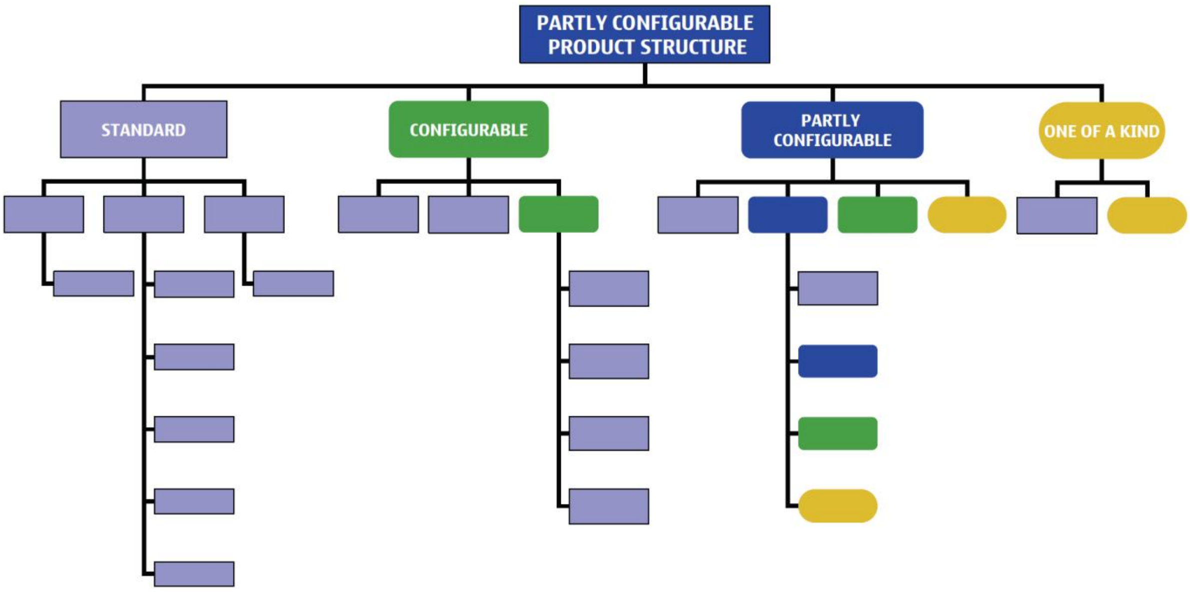


Figure 3.37. *Partly configurable product structure includes standard, configurable, partly configurable and one-of-a-kind elements (Juuti 2008). Juuti & Lehtonen (2006) discuss how structures with these kinds of elements are beneficial in delivering complex products.*

Juuti (2008) has studied potential goals relevant to variability and commonality, which are discussed in Figure 3.38 and Table 3.4. He explains that at first it should be asked if there is engineering in the order-delivery process. If there is not engineering in the order-delivery process, the presumption is that interchangeable modules exist and options are selected from it. This means that the product structure type must be configurable. If there is a need to do engineering in the order-delivery process, the situation is more complex. Juuti (2008) suggests that it should then be defined so that the design process considers design for re-use. As Duffy et al. (1995) and Duffy & Ferns (1998) explain, design for re-use means that new product elements are designed in a way that enables re-using of these elements in other deliveries in the future. Referring back to Figure 3.38, whether design for re-use is considered or not, the next issue to analyse is design by re-use. This means that when it was analysed earlier that engineering is needed in the order-delivery process; now it should be considered whether or not existing design work done earlier can be re-used in the order-delivery process. The next thing to discuss is the need for variability. In this phase it should be considered whether there is need for variability or not. The last question is to think about commonality. This means determining whether or not the product structure should have anything in common with other products.

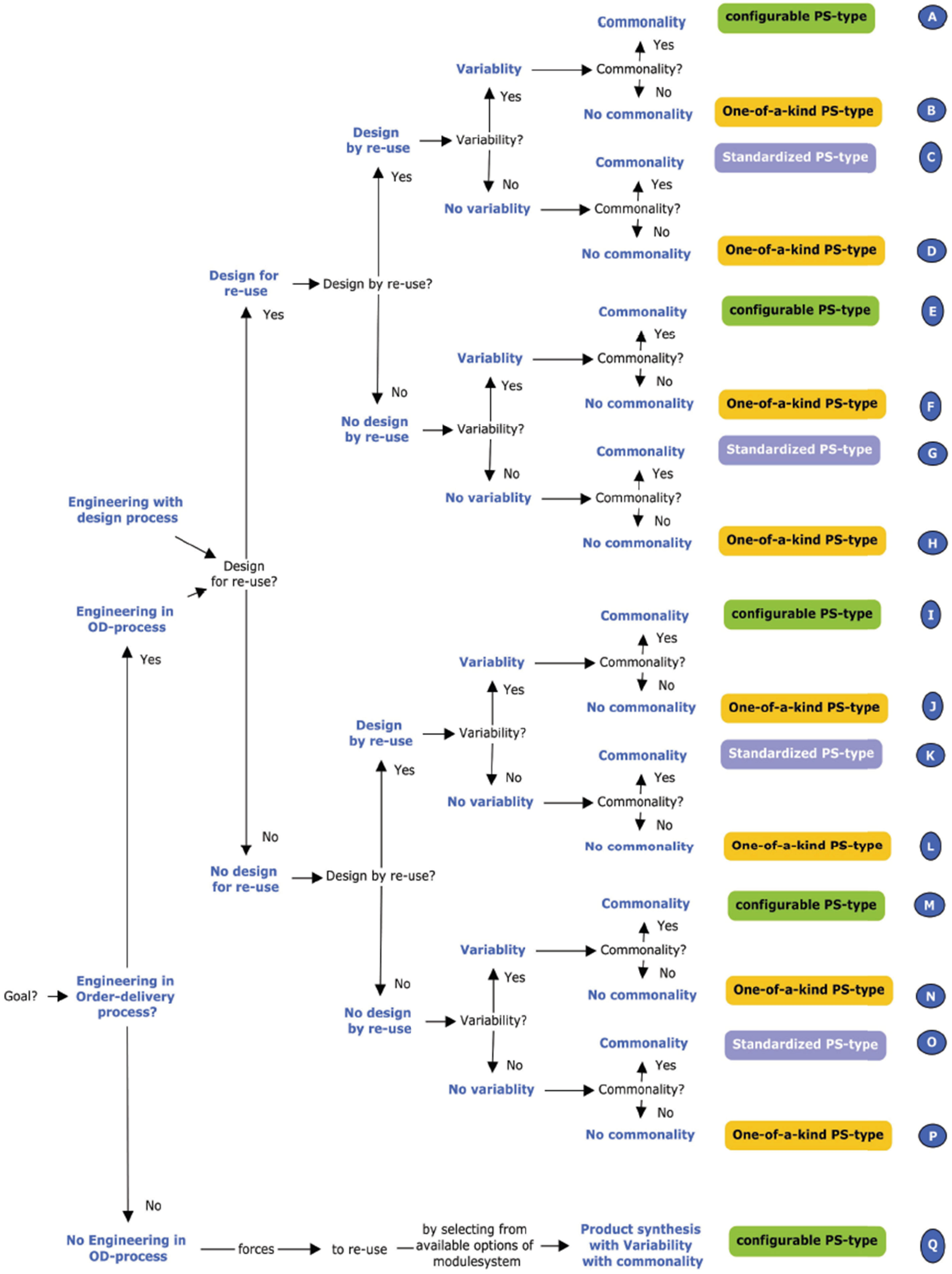
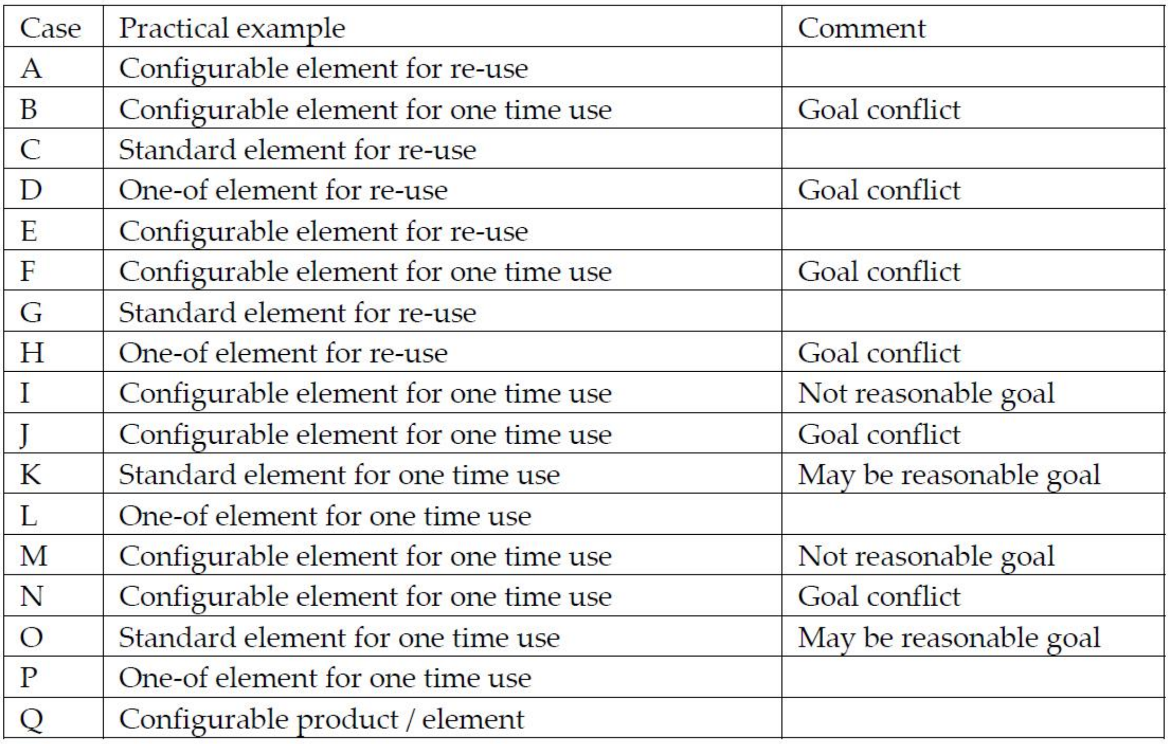


Figure 3.38. *Juuti (2008) explains that by answering questions related to a need for design in the order-delivery process, design for re-use, design by re-use, variability and commonality, it is possible to determine the possible product structure type to consider. In Table 3.7, Juuti (2008) discusses how some of the paths shown in this figure are not reasonable.*

Juuti (2008) has analysed the different paths as shown in Figure 3.37. The results of his analysis are discussed in Table 3.7. Juuti explains that only some of the paths are reasonable.

Table 3.7. *Evaluation of goal combinations referring to Figure 38. (Juuti 2008)*



Case	Practical example	Comment
A	Configurable element for re-use	
B	Configurable element for one time use	Goal conflict
C	Standard element for re-use	
D	One-of element for re-use	Goal conflict
E	Configurable element for re-use	
F	Configurable element for one time use	Goal conflict
G	Standard element for re-use	
H	One-of element for re-use	Goal conflict
I	Configurable element for one time use	Not reasonable goal
J	Configurable element for one time use	Goal conflict
K	Standard element for one time use	May be reasonable goal
L	One-of element for one time use	
M	Configurable element for one time use	Not reasonable goal
N	Configurable element for one time use	Goal conflict
O	Standard element for one time use	May be reasonable goal
P	One-of element for one time use	
Q	Configurable product / element	

By studying the content of Table 3.4 the paths which do not have conflicts, and thus are reasonable, can be listed below. To conclude, by analysing the issues discussed in Figure 3.38, one can get a proposal of product structure type that describes the chosen goals.

Standard element for re-use

- Case C: Engineering in order-delivery process AND design for re-use AND design by re-use AND no variability AND commonality
- Case G: Engineering in order-delivery process AND design for re-use AND no design by re-use AND no variability AND commonality

Configurable element for re-use

- Case Q: No engineering in order-delivery process AND variability AND commonality
- Case A: Engineering in order-delivery process AND design for re-use AND design by re-use AND variability AND commonality
- Case E: Engineering in order-delivery process AND design for re-use AND no design by re-use AND variability AND commonality

Standard element for one time use:

- Case K: Engineering in order-delivery process AND no design for re-use AND design by re-use AND variability AND commonality
- Case O: Engineering in order-delivery process AND no design for re-use AND no design by re-use AND no variability AND commonality

One-of-a-kind element for one time use

- Case L: Engineering in order-delivery process AND no design for re-use AND design by re-use AND no variability AND no commonality
- Case P: Engineering in order-delivery process AND no design for re-use AND no design by re-use AND no variability AND no commonality

Juuti & Lehtonen (2006) and Juuti (2008) have presented a model for different design processes based on the type of product structure. Generic activities in this model, as shown in Figure 3.39, are based on systems engineering practice. This is because the selected phases better reflected the cases discussed by Juuti & Lehtonen (2006) and Juuti (2008), compared to the phases presented in the systematic design process. Figure 3.39 explains what process activities are needed for the designing and delivery of partly configurable products. Partly configurable product structure considers all product element types, as shown in Figure 3.37. When the delivery type is partly configurable, needs and architecture are specified first. After that there is enough knowledge to continue with parallel sessions in the specifying of components. Some components are fully configurable, but partly configurable and one-of-a-kind elements are also needed. Configurable, partly configurable and one-of-a-kind elements needs to be manufactured, but standard elements do not need activities related to the creating of element and thus this is highlighted as “in-use activity,” as shown in Figure 3.39. This approach thus considers standard elements as elements that can be procured commercially. After this, a partly configurable product is integrated according to Juuti & Lehtonen. Figure 3.39 explains how partly configurable products need to be verified and validated in the same way as one-of-a-kind products. (Juuti & Lehtonen 2006; Juuti 2008)

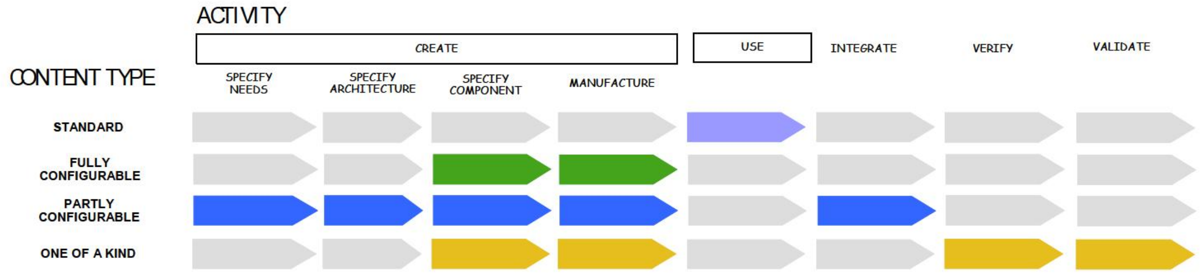


Figure 3.39. *Activity elements needed in partly configurable product structure. (Juuti & Lehtonen 2006)*

Perttula (2004) explains that the purpose of verification and validation is to estimate the maturity of the product, to detect errors and to provide evidence that the requirements for the product have been achieved. According to Perttula, verification proves that general requirements such as standards, safety and type approvals and delivery specific requirements or specifications are considered for the product. He also explains that validation proves that true customer needs and expectations at time of delivery are considered in the product. The difference between verification and validation is summarised in Figure 3.40.

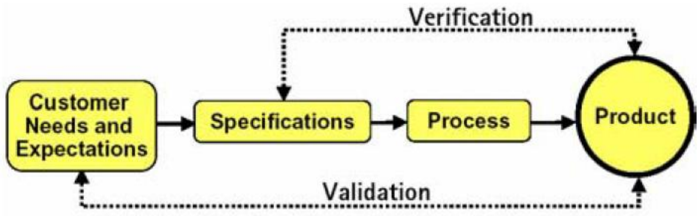


Figure 3.40. *Verification compares the product with the specifications, whereas validation secures proof that the end user is satisfied with the product. (Perttula 2004)*

Referring to **IT support for configuring**, as shown in Figure 3.36, Victor & Boynton (1999) defined a configurator as a human- or computer-driven facilitator for controlling the dynamic network in which new individualised products are defined from modules in a CTO order-delivery environment. Soininen (2000) has described the configuration process based on a configurator, as shown in Figure 3.41. He explains that the configuration process is facilitated by a configuration engine. This engine is based on customer requirements and the configuration model. The configuration model explains the possible combinations of elements needed in the defining of individual products by using the configurator.

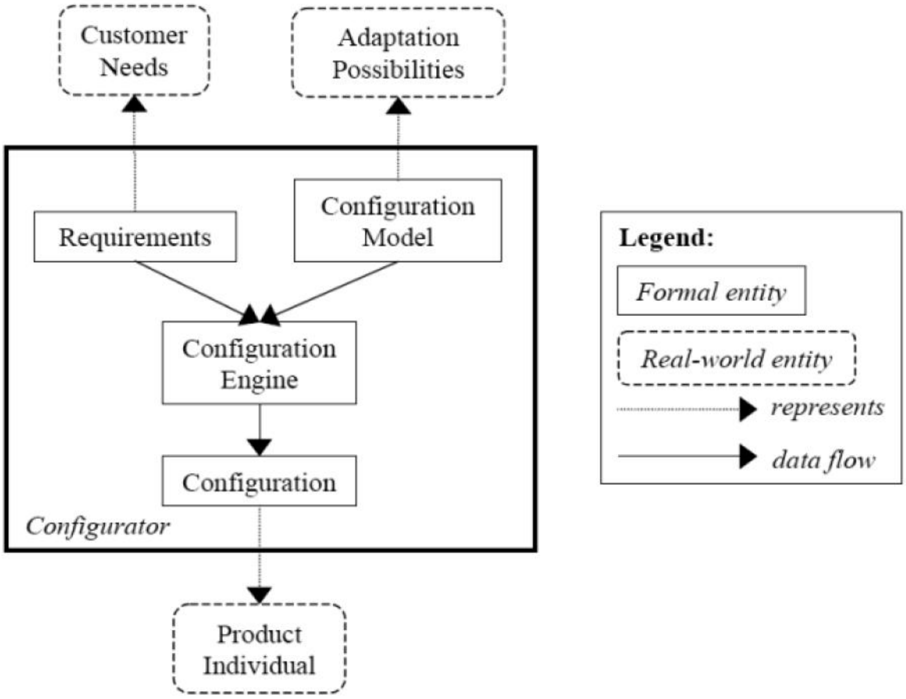


Figure 3.41. *Elements of a configurator. (Soininen 2000)*

Haug (2007) defines a configurator as "*a software-based expert system that supports the user in the creation of product specifications by restricting how different components and properties may be combined*". Haug has come up with a summary of the possible benefits of using a configurator. He explains that a configurator may enable shorter lead times, improved quality of product specifications, preservation of knowledge, use of fewer resources for specifying products, optimized products, less routine work, improved certainty of delivery, and less time needed for training new employees. Haug (2007) and Haug et al. (2012) discuss how even if there are multiple benefits related to configurators, it is still common for the implementation projects of configurators to be very challenging and many of the projects can lead to failures. Haug et al. (2012) add that a project with similar focus on a configurator but with different organisation, scope, or choice of software can succeed later.

Haug (2007) discusses how the quality of methods, techniques and tools applied in extracting, representing and documenting relevant domain knowledge facilitates the implementation project of a configurator. There are three types of configurators from a software perspective according to him: stand-alone software shells, enterprise resource planning (ERP) systems modules and company specific developed software. An ERP system is a generic, off-the-shelf software package, which is aligned to the specific needs of an enterprise for supporting most of the key functions in the company (Soffer et al. 2003).

Haug et al. (2012) have proposed a process for configurator development as represented in Figure 3.42. The process includes five steps and the content of each step is, according to Haug et al. (2012), defined in the following:

1. **Elicitation**: Retrieving of the agreed information related to the product in question from the relevant persons, documents or IT systems.
2. **Translation**: Translating the retrieved information in analysis models for discussing and decision making of the product information to be included in the configurator. If the information is not agreed with persons who should use the configurator, risk of implementation project to fail increases. In many cases graphical models are useful. In this phase, there might be need to create new information because some rules may not have been explicitly defined before the implementation project of a configurator. During this phase, product optimisation can occur if for instance rarely used solution principles and component are eliminated or substituted.
3. **Formalisation**: Transforming of analysis models into a more suitable format for implementation in a configurator. There might be also need to define other configurator aspects such as integrations to other systems and user interfaces.
4. **Documentation**: Documentation is necessary if persons other than the ones that have the information have to use or evaluate it. External knowledge representations (made with programs such as MS Visio, Excel, Word or CAD programs etc.) are necessary if domain / product experts do not understand the modelling environment of configurators.
5. **Implementation**: The design models are implemented in the selected configurator. During the implementation, changes to the design models and thus new information may occur. Complexity of implementation depends on the configurator.
6. **Synchronization**: Updating of external information if changes in the knowledge base of the configurator occur. If there is no external documentation, it is very difficult or even impossible to overview the knowledge implemented. (Haug et al. 2012)

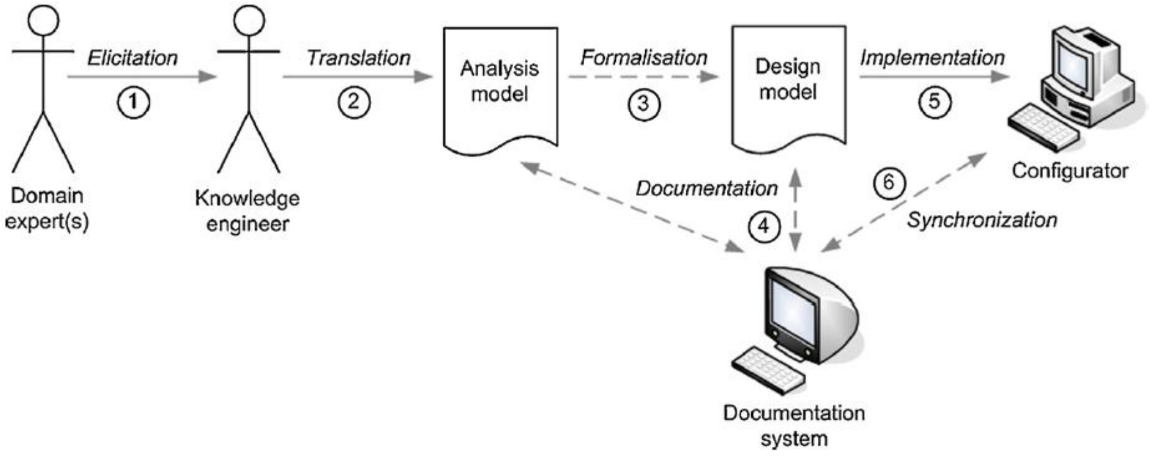


***Figure 3.42.** The process of creating product configurators. (Haug 2007; Haug et al. 2012)*

However, regarding the described process in Figure 3.42, Haug et al. (2012) explain that there are different strategies in configurator development. These are represented in Figure 3.43. The difference in these strategies lies in a) how product, knowledge representation and configuration experts participate in passing on, formalising, implementation and evaluation of product information and b) whether an external (of product configurator) knowledge representation is made or not. In strategy 1, each task is done by a specialist in one specific area. In strategy 2, persons who represent the product information also implement it in the product configurator. In strategy 3, conceptual models (external knowledge representation) are not made and evaluation can be done only by testing the product configurator. (Haug et al. 2012)

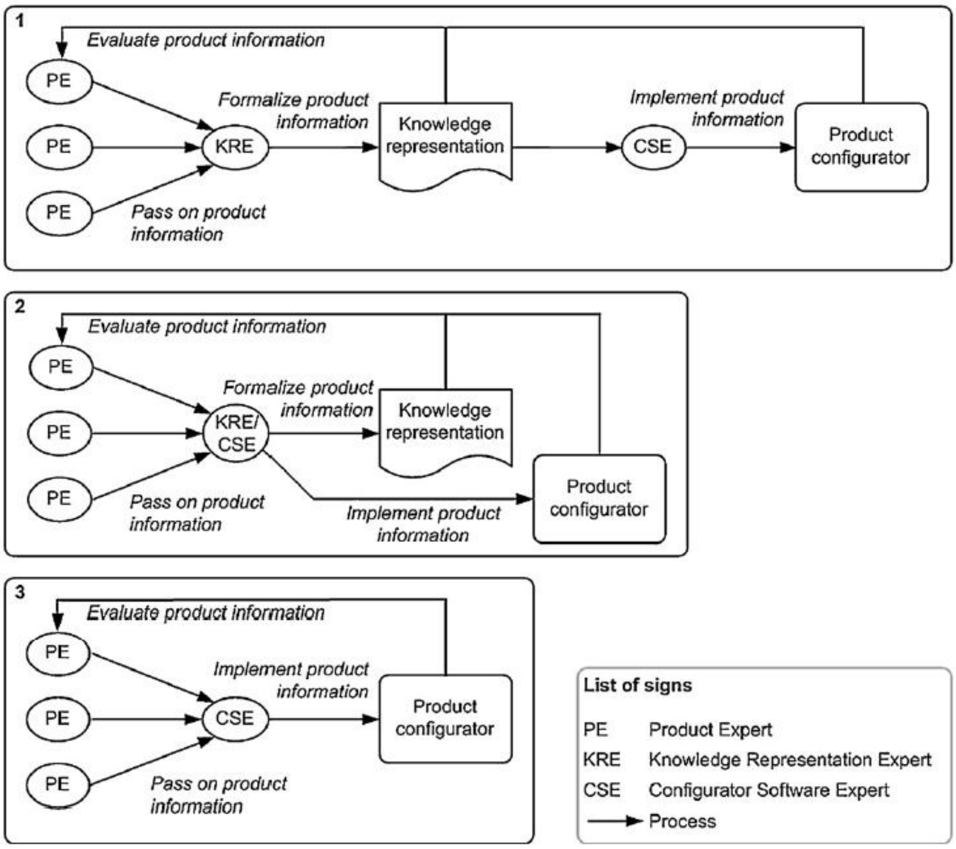


Figure 3.43. *The three main configurator development strategies. (Haug et al. 2012)*

Haug et al. (2012) evaluated these three strategies using the seven dimensions discussed in Table 3.8.

Table 3.8. *Comparison of configurator development strategies. Strategies are shown in Figure 3.43. (Haug et al. 2012)*

	Relative advantages (+) and drawbacks (–)	S1	S2	S3
1	Evaluating gathered product information before implementation	+	+	–
2	Ease of altering implemented product information	+	+	–
3	Ease of changing configurator software	+	+	–
4	Facilitation of the communication between product experts and configurator software experts	+	–	–
5	Minimising use of resources on documentation work	–	–	+
6	Minimising handovers of information, i.e., less chance of misunderstandings and errors	–	+	+
7	Rapid implementation of gathered information, i.e., faster process	–	+	+

They explain that **the first dimension** is fulfilled best in strategies 1 and 2 because in those strategies the evaluation can be done before implementation, and thus errors and misunderstandings can be reduced in later phases. **The second dimension** is critical if results of the configurator don't match the reality. Haug et al. explain that the external knowledge representation that the product experts understand is beneficial for pointing out the problems. **The third dimension** considers the changing of configuration software. In this situation, external descriptions of what have been implemented in the existing configurator are useful again because the different configurators are typically incompatible with each other, according to Haug et al. **The fourth dimension** highlights that the knowledge representation expert could focus on the product understanding rather than IT skills. Haug et al. have found that, in several industrial configurator cases, the knowledge representation expert has been performing the optimisation work for product designs until implementation of product information in the configurator, and that software experts are typically not competent in that task. Thus strategy 1 fulfils the fourth criterion. **The fifth dimension** is relevant if use of the resources on documentation is critical. Haug et al. state that strategy 3 fulfils this best because external documentation is not done. Thus, as discussed in previous criterions, focusing on this criterion and forgetting external documentation creates several risks. **The sixth and seventh dimensions** can be seen best in strategies 2 and 3 because the persons who implement the product information are also the persons who discuss it with the product experts. The result of the previous can be seen in decreased communication time and errors and project costs compared to strategy 1, according to Haug et al. (2012).

Haug et al. (2012) conclude that strategy 1 is appropriate in complex cases in which it is beneficial to have persons with three kinds of properties: 1) can understand the product, 2) can bring product experts into agreement on the product information to implement in the configurator and 3) can represent product information so that the product experts understand it. The challenge is to find single persons with good product understanding, knowledge representation skills and also software skills (Haug et al. 2012). Strategy 2 is appropriate if responsibilities for conceptual modelling of product information and configurator development are desired to be close to each other in order to reduce information handovers and to shorten the duration of configurator project (Haug et al. 2012). Strategy 3 is suitable for projects of little product complexity in which the use of resources needs to be low and the schedule of the configurator project is tight, according to Haug et al. (2012). If product complexity increases and modifications are needed to the configurator, this strategy will prove difficult because a summary of what has been implemented to the configurator is not available (Haug et al. 2012).

Why have these configurator issues been discussed in this thesis with this kind of emphasis? The focus of this dissertation is on the rationalising of product variety towards a modular product family. Thus the issues surrounding the development of configurators should be recognised; however, this thesis does not focus on configurators in detail. The process steps, strategies and problems related to the development of configurators should be considered when developing modular and configurable products because, as discussed earlier, it is possible to realise several benefits by using a configurator in the task of defining product variants in the order-delivery process. Basically this means that if a company designs its products so that they are configurable, there are then possibilities that the company will also strive towards using a product configurator in its operations, such as in a facilitator of sales. Consequently issues in configurator development should be considered in the defining of rationalisation processes or methods of modular product structures. Discussion of configurator strategies revealed that in order to manage and avoid the risks it is wise to define configuration knowledge as separate information before it is implemented in the configurator (presuming that configurator is used). In the state-of-the-art approach and method section of this thesis (Chapter 3.8), approaches for defining and representing configuration knowledge are also discussed in greater detail.

To conclude, this chapter discussed the configuration of products. The main contribution of the chapter to this thesis is that it is important to recognise what kinds of elements the product structure has and for which elements or areas of the product the variety is needed. It was discussed how in introducing variety, configurable structures that can be realised with principles of modularisation can be used. This chapter highlighted also that if configurators are developed, it is wise to make an external representation of the product information which is discussed as configuration knowledge.

3.5.9 Conclusions of product structuring

This chapter discussed product structuring that considers different tactics and approaches regarding how the product is built. The product structuring section first explained that the product can be defined from several viewpoints, including **synthesis-oriented**, **function**, **life phase and product assortment views,** as defined by Andreasen et al. (1996). It was also presented how these different views of the product are overlapping.

The **synthesis-oriented view** was explained using Domain Theory, in which the product is described using activity, organ and part domains. Each domain serves a different purpose and has a different level of abstraction from a physical product viewpoint.

The **function view** of a product can focus on different phenomena by concentrating on having the function descriptions include what the product does from a certain viewpoint.

Product life was also studied. It was explained how when decisions related to a certain activity are made, dispositions to further activities in product life phases might take place, according to Olesen (1992). Basically this means that when designing a product, phases of the product life cycle that the product goes through should be taken into account. Seven universal virtues by Olesen are presented as an example for analysing the influence of design decisions. Thus the approach of Olesen also considers other topics besides quality, cost, delivery and flexibility. These were presented by Fujimoto (2007) (see Chapter 3.3.). These figures follow the suggestions given in DRM. Olesen doesn’t discuss delivery but his list also considers time, efficiency, risk and environment. The challenge lies in performing an analysis using all of these virtues, which might be very difficult because not all of them can necessarily be discussed using quantitative values; however, these virtues might be helpful in order to get at least rough estimations of the product’s suitability to its life phases. There are also other approaches that can be classified below this “life phase” view on product structuring seen by Andreasen. The CSL framework suggests that when designing a product structure, requirements for the product should, in particular, be analysed by concentrating on process, value chain, strategy and organisational structures of the company.

The **product assortment view** was discussed using several topics, such as product variety and commonality, standardisation, modularisation, product platforms and product families and configuration. Based on the studied literature, it can be said that product variety has increased in several industries. The term product variety can be used to illustrate the product assortment that a company offers to the market during a specific time period. Figure 3.44 presents a combined reference and impact model of factors related to product variety. This, as well as other figures in this section (Figures 3.45-3.49), present direct impacts that have been discussed in the literature. Only some assumptions have been drawn from these figures. Increased product variety has brought challenges to the company if re-use of different assets in order-delivery processes could not have been achieved. Possibilities for re-use of once designed assets has been identified to improve productivity in various ways (as for instance described by Juuti ((2008)) and to make a company more competitive against the competitors in the same market. It can also be said that it is critical that the product variety is offered to the market in a way that it is commercially rational for the company providing the variety. Different product structuring techniques and approaches are presented in the literature for increasing the re-use of design assets. Figure 3.45 summarises aspects related to re-use according to different references discussed in this Chapter 3.5.

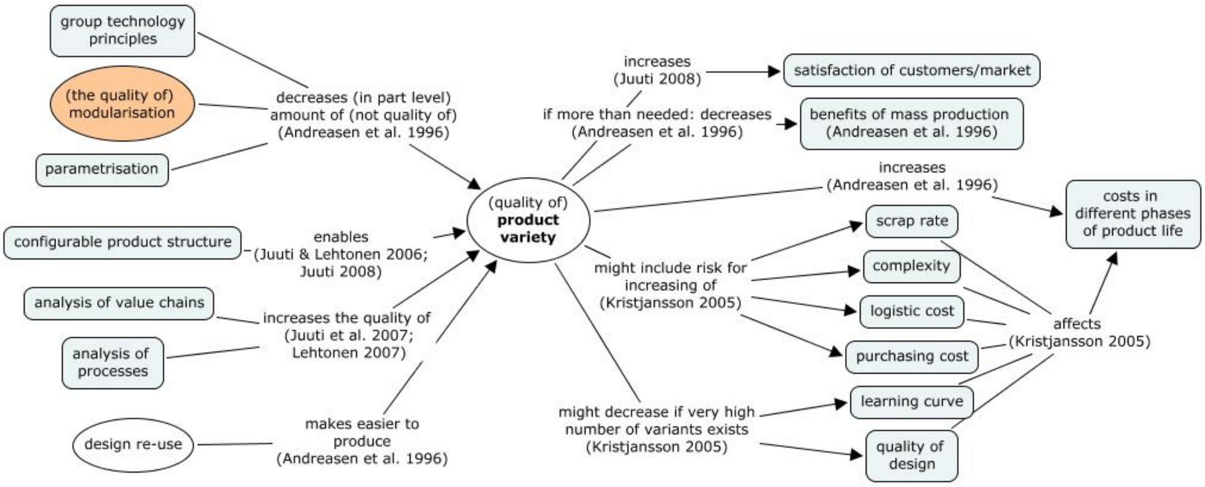


Figure 3.44. *Product variety related factors according to different publications.*

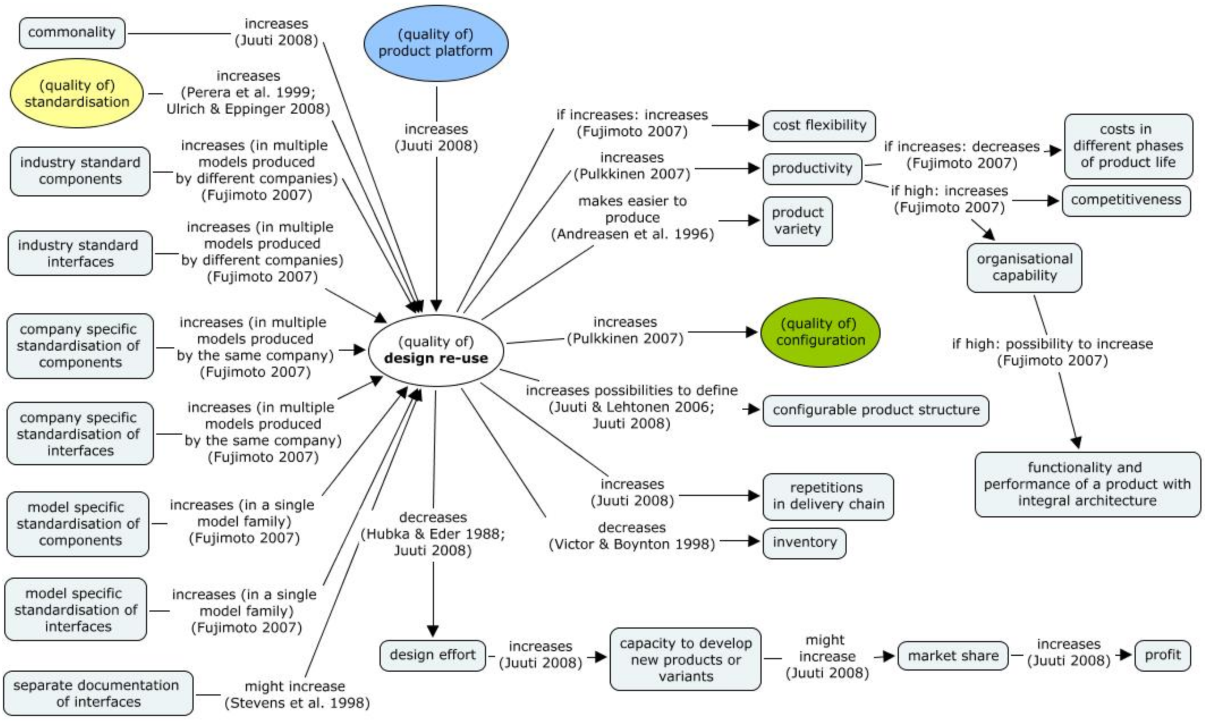


Figure 3.45. *Design re-use related factors according to different publications.*

Standardisation is seen as a starting point in reaching the benefits of re-use. Standardisation may enable several possible benefits in different life cycle phases, but negative effects can be also found (see Figure 3.23). Several kinds of levels of standardisation (such as industry standard, company standard, model specific standard (Fujimoto 2007)) were proposed for analysing the level of standardisation of a specific product. This kind of categorising can be helpful in order to analyse the breadth of standardisation benefits or disadvantages in the company and to help in the selection of focus areas for design in future product development projects. Standardisation of interfaces between the parts was also discussed in the literature. It is one of the most important things in modularisation because standardised interfaces enable effective configuration of a product variant. Figure 3.46 includes a combined reference and impact model from a standardisation viewpoint.

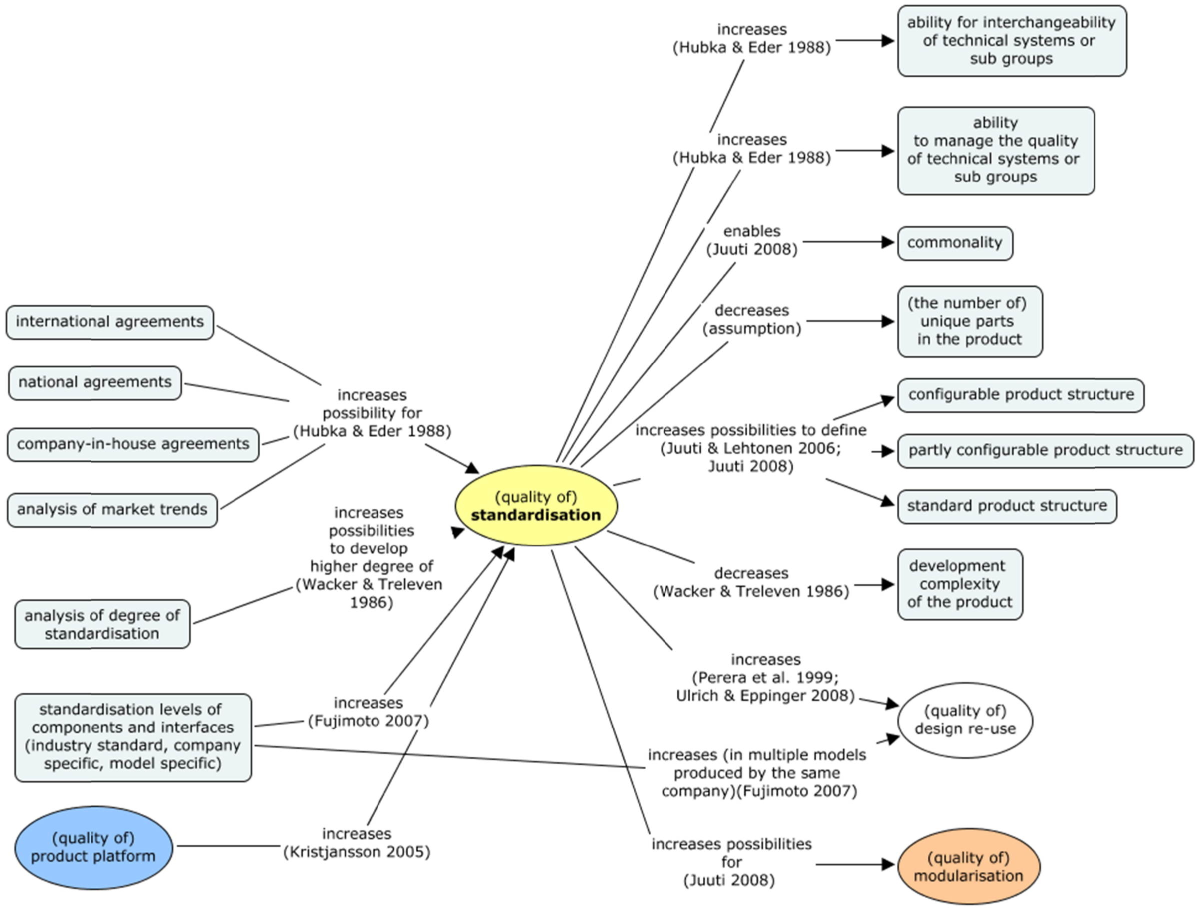


Figure 3.46. *Standardisation related factors according to different publications.*

Modularisation is considered as a good product structuring strategy if benefits realised by repetition in the operations of the company are pursued while the competitive capability to offer different product variants to the market is desired to be maintained. Based on the analysed publications, it can be seen that a different type of modularity has been presented. When aiming at modular products, the deduction can be made from the literature that the possible benefits of modularity and objectives for the modular product should be analysed until the selection of certain modularity types or approaches or methods for designing the modular product is made. For instance, Lehtonen (2007) noted that the function-oriented way to modularise the product does not give the best results in every case, even though it was one possible approach in all of the cases he studied. Thus it can be said that benefits and objectives for a modular product structure have to be analysed from a wider perspective in each case and there is no single solution or driver that would give good results in every case.

Although highlighting the case specific nature of modularisation activities, some generic design elements related to modularisation activities can be identified from the literature. **Partitioning logic, product architecture, modules, interfaces and configuration knowledge** were suggested as important design information elements of modular products aiming for product configuration. It was stated that this kind of division might be helpful in the structuring of the designing of a modular product family. But how does the designing of a new modular product differ from the utilisation of existing products in the developing (re-designing) of a modular product? For instance, Hubka & Eder (1996) discussed this issue in Design Science without modularisation aspects (see Chapter 3.4). They explained that a re-design situation differs in the availability of existing knowledge. This means that there is no need to do all of the early design tasks, or that the content of these design tasks can be different if compared to designing completely new products because inputs to the design tasks can be used from existing knowledge. The same issue can be seen in, for instance, the research of Lehtonen (2007), in which the design process for a new modular product architecture is proposed (this is presented later on in Chapter 3.8.2). This process includes the drafting of module concepts and preliminary layouts in the early phases of the process. When doing re-designing or rationalisation of an existing product assortment, the starting point is not an empty table, but it should still be taken into consideration as to which areas of the product can be maintained as they are and which areas of the product need changes made in order to achieve good modular product architecture. Figure 3.47 includes a combined reference and impact model of modularisation.

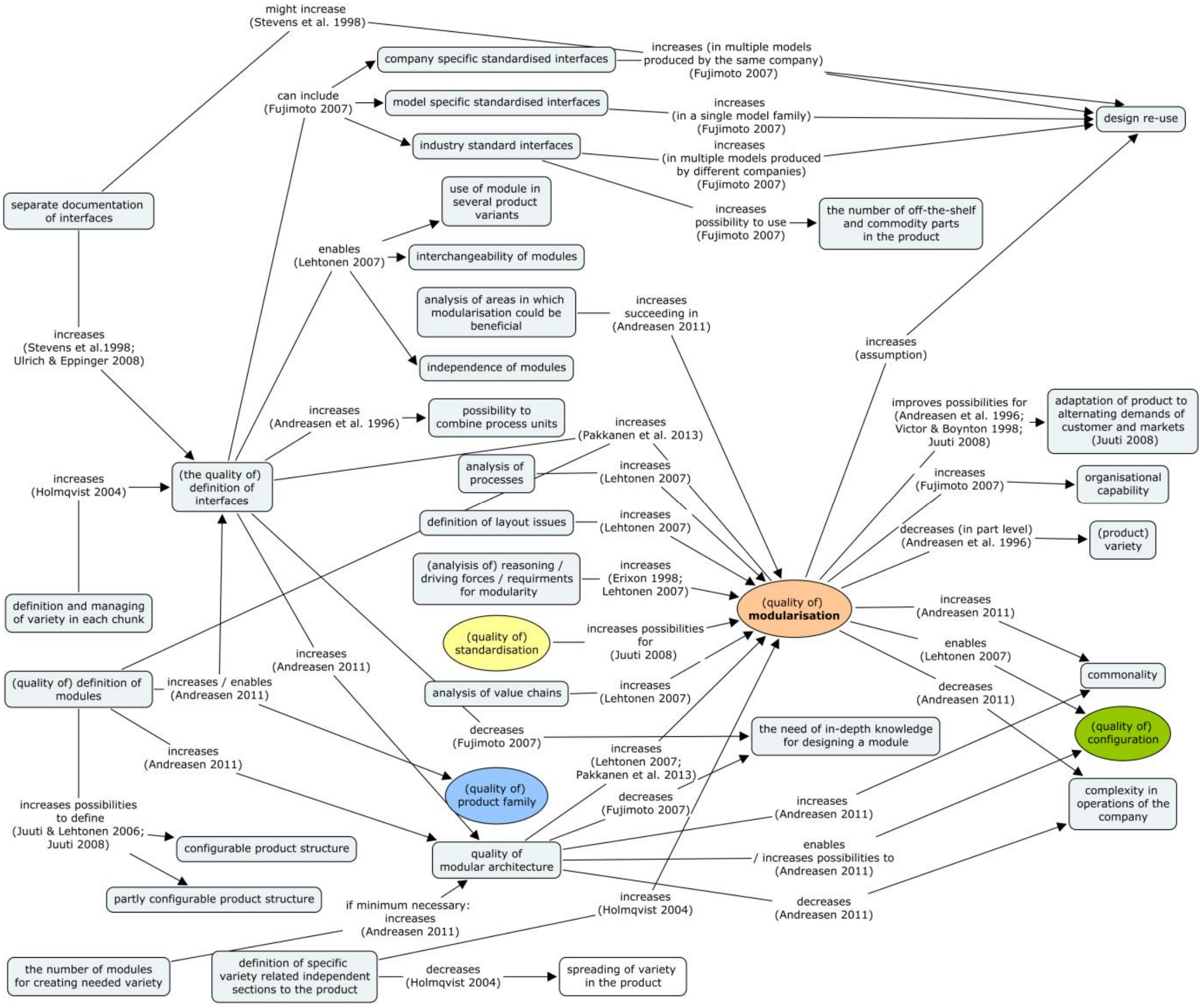


Figure 3.47. *Modularisation related factors according to different publications.*

Platforms and product families were also discussed in this chapter. Several different definitions of the term platform are presented. Typically it is understood to define those assets that are used in several products; thus re-usable assets. These assets can be only parts but the definition of platform can be wider depending on what is desired to belong under the term in each case. Platform definition and modularisation are linked in a way that the platform can be understood including re-usable standard structure that is supplemented with interchangeable modules or unique elements in order to enable variation in a modular product family. Thus unique elements would not be considered as a part of a platform. Consequently these different product variants that have some elements in common with each other (assets from the platform) form a product family. Statements related to the quality of a product platform and product family have been presented in Figure 3.48.

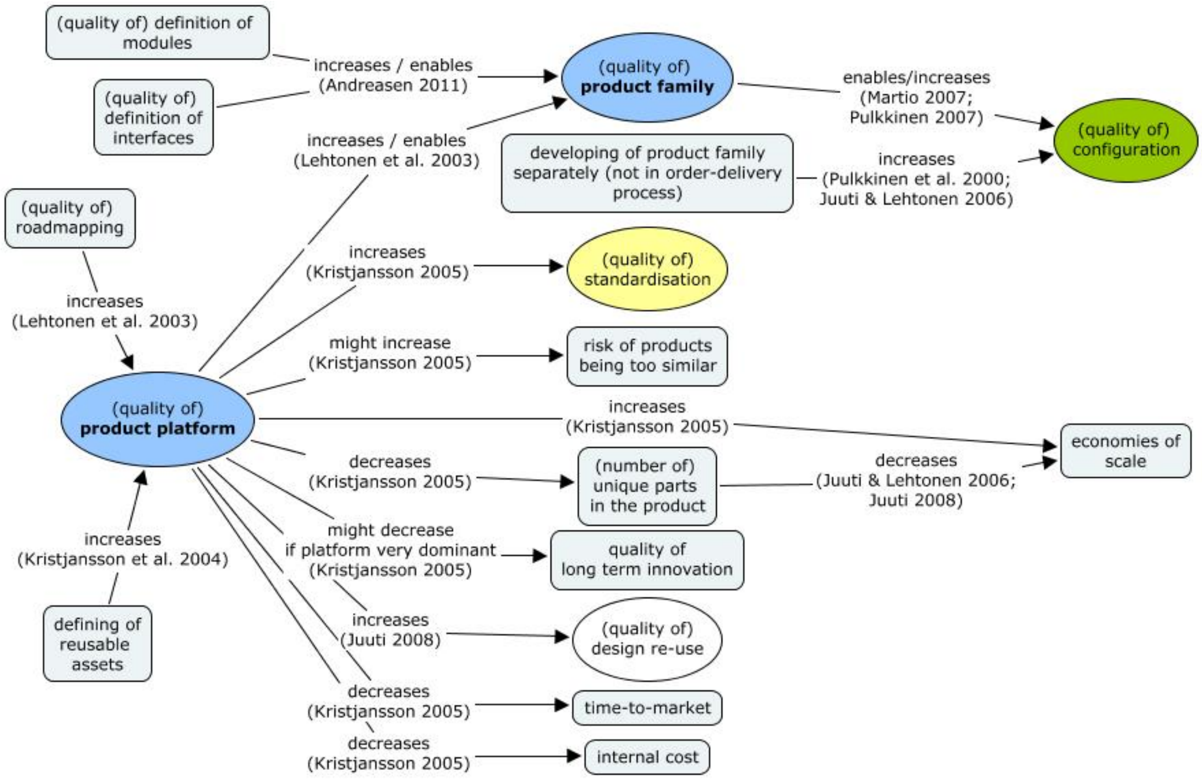


__Figure 3.48.__ Product platform and product family related factors according to different publications.

The product assortment view also includes **configuration** aspects. There are several definitions of configuration. It can mean either the activity of configuring or a product instance as, for instance, Pulkkinen (2007) explained. He proposed a framework for important issues in configuration consisting of activity, product structure and IT support viewpoints. The changing of either the number of similar elements, the type of element, the relations between elements or the attribute of elements was considered as a main activity of configuration. When considering product structures for configuring, the literature revealed that it is important to define that what kind of elements the product consists of. Here Juuti (2008) explained that a product can include standard, configurable, partly-configurable and/or one-of-a-kind elements. Publications on the mass customisation paradigm highlight the importance of modularisation and configuration. It has to be understood that strict configuration that uses only predefined standard and fully-configurable elements might be too difficult and costly to design in order to fulfil the needs of the customer or market. This is because the developing and maintaining of a wide product assortment utilising standard and modular structures for a large quantity of different requirements that might not even be realised in product orders can be very expensive. Thus it can be more beneficial to recognise the areas in the product that are designed against customer-specific requirements, but most of the product is based on the standard or fully configurable structures. Consequently, this kind of modularisation and configuration might not completely fulfil the ideal concepts of mass customisation paradigm in reality. IT support for configuring considers the design and use of configurators, which are typically based on customer requirements and configuration models. It was found from the literature that the defining of the configuration knowledge in a way that the product experts understand it and can refer to it easily can be beneficial when implementing a product configurator. Thus this also supports the highlighting of configuration knowledge as one of the most important design elements of the module system. Figure 3.49 presents the reference and impact model of configuration.

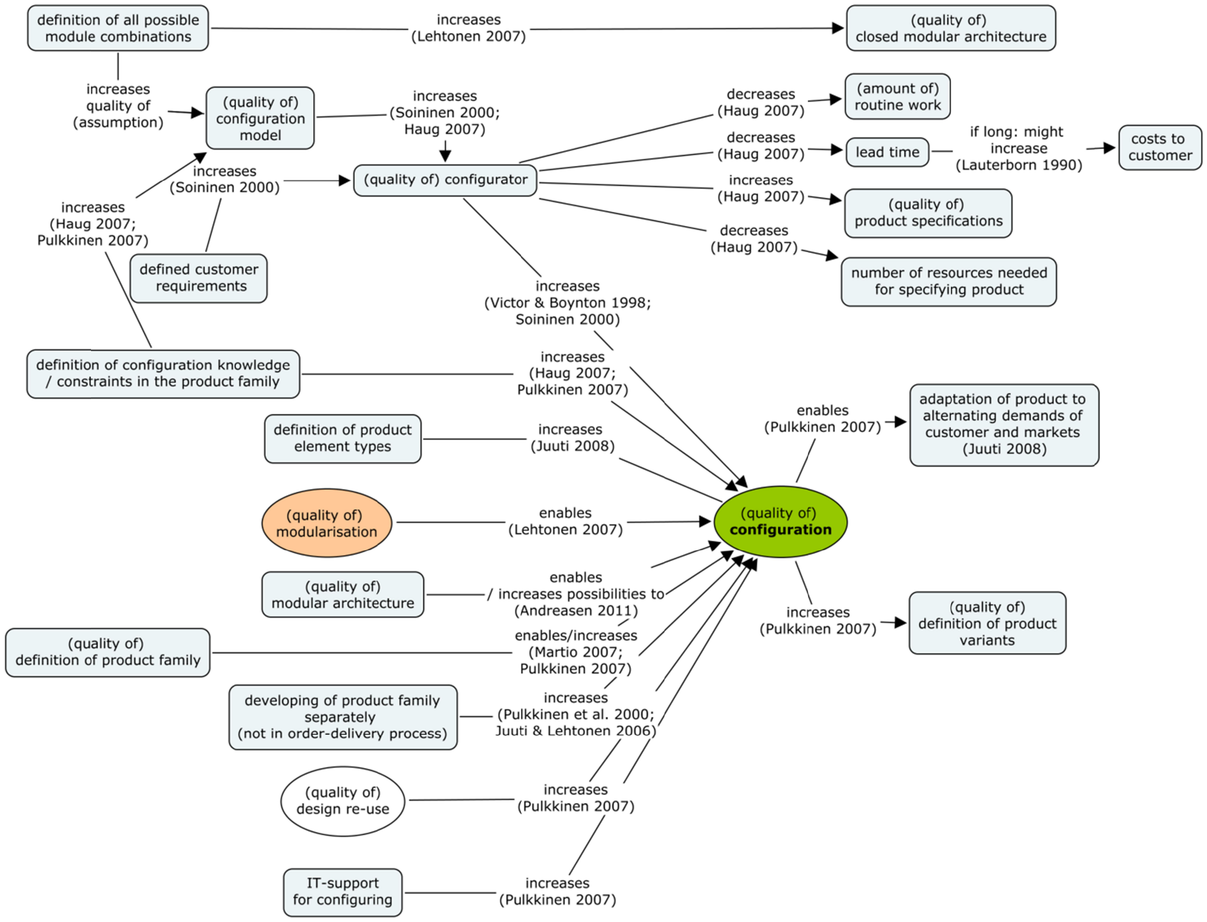


Figure 3.49. *Configuration related factors according to different publications.*

As can be seen, the content of this third chapter focuses mostly on life phase and product assortment views from a product structuring perspective. The following chapter discusses generic design processes. The aim of that chapter is to analyse the content of those processes and to discuss how product-structuring tactics and issues discussed in this chapter are covered in those generic design processes.

3.6 Engineering design processes

In this chapter, an overview of design processes is made. Based on the literature (Cross 2007; Geis et al. 2008; Howard et al. 2008; Geis & Birkhofer 2010; Gericke & Blessing 2011; Lehtonen et al. 2011a; Gericke & Blessing 2012), the following “bill of materials” for this section on design processes can be made. The below topics are briefly gone through in this chapter.

- History of design processes
- Benefits of using design processes
- Understanding design processes
- Generic stages of design processes
- Categorisation and comparison of design processes and similarities and differences of design processes
- Rational behind design processes
- Criticism against design processes
- Industry view on design processes
- Applying of design processes

Cross (2007) has discussed the **history** of design research. He explains that several new design methods and related publications appeared in the 1960’s but in the 1970’s there was a great deal of criticism towards design methods and their usability. This even led to the abandoning of design methods by some of the early pioneers in the field, according to him. Cross explains that the situation got much better when it was proposed in publications that those methods designed in the 1960’s were only first-generation versions and thus a necessary beginning in the field and discussions about the future generation of the methods was then opened up. At the present time, there have also been research and publications available in which different design processes and their similarities, differences and fits to certain needs has been discussed. These are discussed in this section.

When discussing the **“why” of using** design processes, several advantages have been recognised. Howard et al. (2008) and Gericke & Blessing (2011) have listed the benefits of design processes and design methodologies related to the following issues:

1. Design processes facilitate the managing of design activities.
2. Design processes help in the rationalisation of creative work.
3. Design processes facilitate the remembering of the essential issues in designing.
4. Design processes enable the teaching and transferring of designing and they are a foundation for design research.
5. Design processes facilitate actual designing.
6. Design processes improve communication among people related to designing.

There is also discussion about **how design processes are understood** in general. Gericke & Blessing (2011) have noticed that different design processes are understood inadequately. Similarities and differences between design processes are often not understood. Geis & Birkhofer (2010) state that there is lack of approaches that combine all existing models and define interactions and interfaces between different design theories. This kind of approach could improve understanding of the design processes, according to them.

A number of different design processes or theories have been represented in a product design context. Howard et al. (2008) and Gericke & Blessing (2011) discuss how a **generic core of**

stages can be identified from procedural models, although not all of the models consider the phases to the same extent. Howard et al. (2008) and Gericke & Blessing (2012) have summarised these generic stages based on an analysis of different design process models:

1. Establishing a need (driver for the design; product idea or a need or a problem)
2. Analysis of task (additional information)
3. Conceptual design (abstract/principle solutions / concepts)
4. Embodiment design (detailing the concept)
5. Detailed design (refinement and finalisation)
6. Implementation (integration, manufacturing, installation, test, approval, launch of the product)

Howard et al. (2008) do not state from which publication these definitions of stages have been taken. They just note that these stages are generally agreed upon by design authors. Of the above six generic stages, it can be seen, however, that some of them have a clear similarity to, for instance, the systematic design process model presented by Pahl & Beitz (1996). Gericke & Blessing (2012) complemented these stages with two more life cycle phases:

7. Use (operation, monitoring, maintenance)
8. Closeout (recycling, disposal, update/evolution)

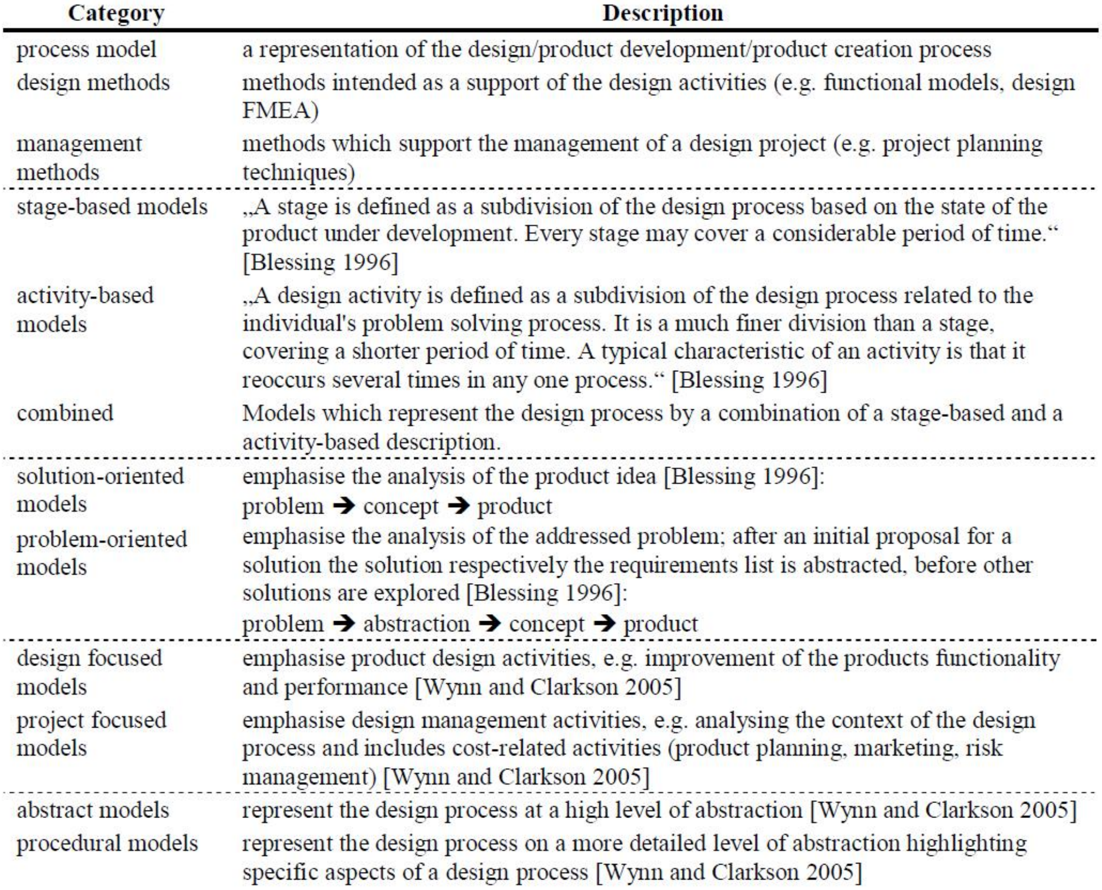
As can be seen from the above generic phases, not all of them are actual design process phases but also include other life cycle phases (phases 6-8). For example, Gericke & Blessing want to highlight the entire life cycle that should be considered in the designing.

There also exist **categorisations of product development models**. These categories have been presented in order to aid with comparison of the models, but based on the analysis performed by, for instance, Gericke & Blessing (2011), several challenges arise related to the categorising work. A scheme for the categorisation of design process models by Gericke & Blessing (2011) is shown in Table 3.9. When carrying out the analysis they found that categorisation into prescriptive and descriptive models was difficult because the models often included both elements. For this reason, they do not consider this aspect. Gericke & Blessing have also made other observations, but these are discussed later on in this chapter.

Thus the categories shown in Table 3.9 explain how design processes can be analysed and categorised from different perspectives. Howard et al. (2008) analysed 23 design process models and how they consider the above-mentioned six generic stages of design process. A summary of their research can be seen in Table 3.10 (complete references discussed in the table can be found in their paper). Howard et al. discuss the fact that nearly all of the processes they analysed are market driven (not technology driven). Thus this would be another possible categorisation option.

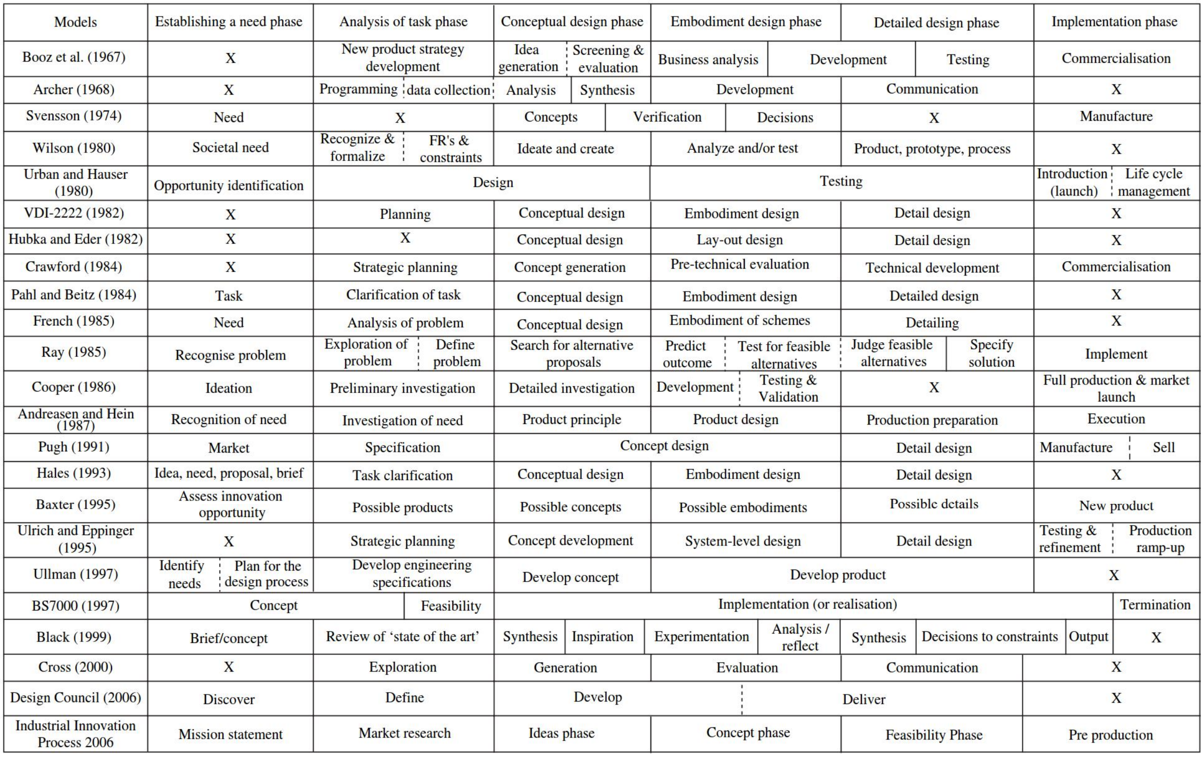
Process models as presented by various authors handle different phases differently, as can be seen from Table 3.10. For instance, certain stages are not considered at all (mainly the first or last phase) in some models, but clear similarities can also be found at least at the term level.

Table 3.9. *Categorisation scheme of design process models according to Gericke & Blessing (2011; 2012).*



Category	Description
process model	a representation of the design/product development/product creation process
design methods	methods intended as a support of the design activities (e.g. functional models, design FMEA)
management methods	methods which support the management of a design project (e.g. project planning techniques)
stage-based models	„A stage is defined as a subdivision of the design process based on the state of the product under development. Every stage may cover a considerable period of time.“ [Blessing 1996]
activity-based models	„A design activity is defined as a subdivision of the design process related to the individual's problem solving process. It is a much finer division than a stage, covering a shorter period of time. A typical characteristic of an activity is that it reoccurs several times in any one process.“ [Blessing 1996]
combined	Models which represent the design process by a combination of a stage-based and a activity-based description.
solution-oriented models	emphasise the analysis of the product idea [Blessing 1996]: problem ➔ concept ➔ product
problem-oriented models	emphasise the analysis of the addressed problem; after an initial proposal for a solution the solution respectively the requirements list is abstracted, before other solutions are explored [Blessing 1996]: problem ➔ abstraction ➔ concept ➔ product
design focused models	emphasise product design activities, e.g. improvement of the products functionality and performance [Wynn and Clarkson 2005]
project focused models	emphasise design management activities, e.g. analysing the context of the design process and includes cost-related activities (product planning, marketing, risk management) [Wynn and Clarkson 2005]
abstract models	represent the design process at a high level of abstraction [Wynn and Clarkson 2005]
procedural models	represent the design process on a more detailed level of abstraction highlighting specific aspects of a design process [Wynn and Clarkson 2005]

Table 3.10. *A summary made by Howard et al. (2008) about how different process models discussed by different authors consider typical stages of product development.*



Models	Establishing a need phase	Analysis of task phase	Conceptual design phase	Embodiment design phase	Detailed design phase	Implementation phase
Booz et al. (1967)	X	New product strategy development	Idea generation Screening & evaluation	Business analysis Development	Testing	Commercialisation
Archer (1968)	X	Programming data collection	Analysis Synthesis	Development	Communication	X
Svensson (1974)	Need	X	Concepts Verification	Decisions	X	Manufacture
Wilson (1980)	Societal need	Recognize & formalize FR's & constraints	Ideate and create	Analyze and/or test	Product, prototype, process	X
Urban and Hauser (1980)	Opportunity identification	Design		Testing		Introduction (launch) Life cycle management
VDI-2222 (1982)	X	Planning	Conceptual design	Embodiment design	Detail design	X
Hubka and Eder (1982)	X	X	Conceptual design	Lay-out design	Detail design	X
Crawford (1984)	X	Strategic planning	Concept generation	Pre-technical evaluation	Technical development	Commercialisation
Pahl and Beitz (1984)	Task	Clarification of task	Conceptual design	Embodiment design	Detailed design	X
French (1985)	Need	Analysis of problem	Conceptual design	Embodiment of schemes	Detailing	X
Ray (1985)	Recognise problem	Exploration of problem Define problem	Search for alternative proposals	Predict outcome Test for feasible alternatives	Judge feasible alternatives Specify solution	Implement
Cooper (1986)	Ideation	Preliminary investigation	Detailed investigation	Development Testing & Validation	X	Full production & market launch
Andreasen and Hein (1987)	Recognition of need	Investigation of need	Product principle	Product design	Production preparation	Execution
Pugh (1991)	Market	Specification	Concept design		Detail design	Manufacture Sell
Hales (1993)	Idea, need, proposal, brief	Task clarification	Conceptual design	Embodiment design	Detail design	X
Baxter (1995)	Assess innovation opportunity	Possible products	Possible concepts	Possible embodiments	Possible details	New product
Ulrich and Eppinger (1995)	X	Strategic planning	Concept development	System-level design	Detail design	Testing & refinement Production ramp-up
Ullman (1997)	Identify needs Plan for the design process	Develop engineering specifications	Develop concept	Develop product		X
BS7000 (1997)	Concept	Feasibility	Implementation (or realisation)			Termination
Black (1999)	Brief/concept	Review of 'state of the art'	Synthesis Inspiration	Experimentation Analysis / reflect	Synthesis Decisions to constraints Output	X
Cross (2000)	X	Exploration	Generation	Evaluation	Communication	X
Design Council (2006)	Discover	Define	Develop	Deliver		X
Industrial Innovation Process 2006	Mission statement	Market research	Ideas phase	Concept phase	Feasibility Phase	Pre production

In addition to Howard et al., Gericke & Blessing (2011) discuss how similarities and differences can be found from design methodologies. They explain that the perspective of analysis affects how much the process models look similar to each other. Gericke & Blessing explain that on an abstract level, the same stages can mainly be identified from design process models. If analysis is made on a deeper level, differences can be found. They add that even if process models seem to be similar, designers probably work differently. According to Gericke & Blessing (2011), the main reason for this is that generally speaking, in process models the sequence of intermediate results are given but how those results are achieved is not explained. Thus these processes also have method-like properties, which Newell (1983) discussed. Gericke & Blessing (2012) continue by stating that the level of given detail is often low and that many of the models are abstract. This makes it harder to compare the models to each other. Gericke & Blessing have observed that project-focused and design managements models (see categorisation in Table 3.9) typically have more similarities than design- and engineering- focused process models. Gericke & Blessing (2011) discuss the fact that there is no consensus as to how detailed design process models should be or can be. Abstract models cover a wider area but they do not provide specific context-based support, whereas specific models are suitable only for a certain group of designers.

In their newer paper (Gericke & Blessing 2012) they represent the results of an extensive analysis of 82 design process models. The contribution of these models to different generic stages is shown in Figure 3.50. In this paper, they highlight the fact that all of the models are rather abstract representations of the design process. They also noticed that categorisation as an abstract or procedural model was difficult to do because, for instance, abstract graphic representations were supported by explanatory text and methods which actually makes them procedural models. Gericke & Blessing discovered that despite the fact that some models had stages, the supporting information for using the model was limited or else details were provided only for a specific stage. This made the categorisation as abstract and procedural models unacceptable, according to them.

Gericke & Blessing (2012) explain that, based on their analysis as shown in Figure 3.50, most of the process models cover the core stages, which are analysis of task, conceptual design, embodiment design and detail design. They add that design-focused publications focus mainly on these previously mentioned stages, but project-focused approaches cover the process from establishing a need to implementation or beyond.

Most of the design process models are sequential, linear or waterfall models, including a sequence of stages (Gericke & Blessing 2012). They add that the amount of spiral models (a recurring sequence of similar activities is done in each of the subsequent stages) or V-form models (where the design problem is decomposed in the initial design stages and developed solutions are integrated stepwise and evaluated in the later stages) is low. Authors have also noticed that there are processes which do not fit into previously mentioned categories. In these models, the design process is represented as, for instance, a network of activities without a specific sequence.

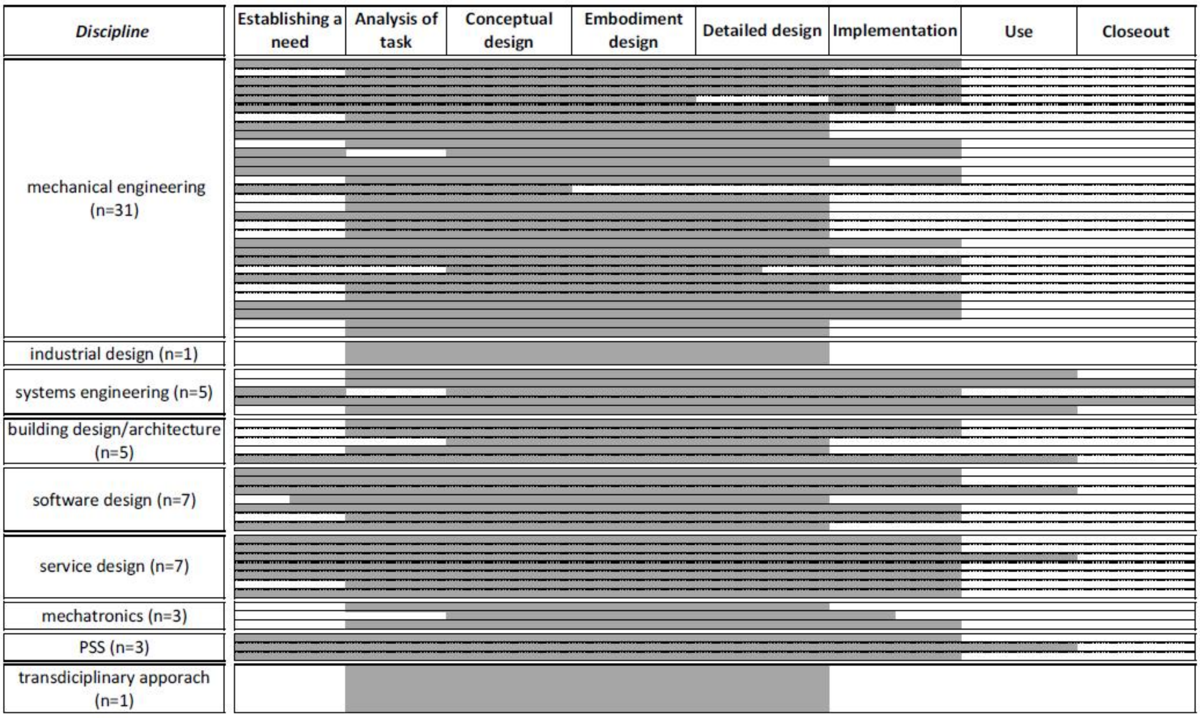


Figure 3.50. *Analysed design process models by Gericke & Blessing (2012) show that most of the models cover the main stages presented by Howard et al. (2008). Based on this study, it can be said that the models in systems engineering have the widest coverage.*

As Howard et al. (2008) and Gericke & Blessing (2012) have presented a summary of different design processes and their contents by stages, so Lehtonen et al. (2011a) have presented a different framework for analysing and comparing design processes. In this framework, as shown in Figure 3.51, design processes are analysed according to how much knowledge of the design artefact (product or service) is assumed at the beginning of the designing. According to Lehtonen et al., on the left side of the framework the starting point is fuzzy and the design process needs to consider facilitating the understanding and definition of the design goals, the extent of the design artefact (e.g. production line, supply network, product) and the actual design solutions. In the middle of the framework, design knowledge enables the defining of the design goals, but relations to the product structure and functionality need to be clarified in the design process. On the right side of the framework, design goals are known and defined in detail and priorities of the design goals are explicit.

The bottom of the framework describes the level of predetermination of the design process according to Lehtonen et al. (2011a). The level of predetermination of the design process relates directly to the level of clarity in the design goals and the understanding of the relative importance between them. On the left side in the framework in Figure 3.51, the design process is not fixed and the process is designed during the actual project, according to Lehtonen et al. Thus the situation in the left side in the framework can be defined as opportunistic. When moving towards the right side of the framework, the next level of predetermination of the design process considers processes with levels of abstraction. This also relates directly to the level of clarity on the design goals and their importance. Because relations of the goals to the product are not completely explicit, the design process has to also consider possible abstract issues that are not yet explicit. The next level of predetermination of the design process includes predetermined processes in which iteration possibilities are highlighted. Predetermined processes are located on the right side of the framework. No iteration is needed because all the goals and their importance are well known at the beginning of the designing.

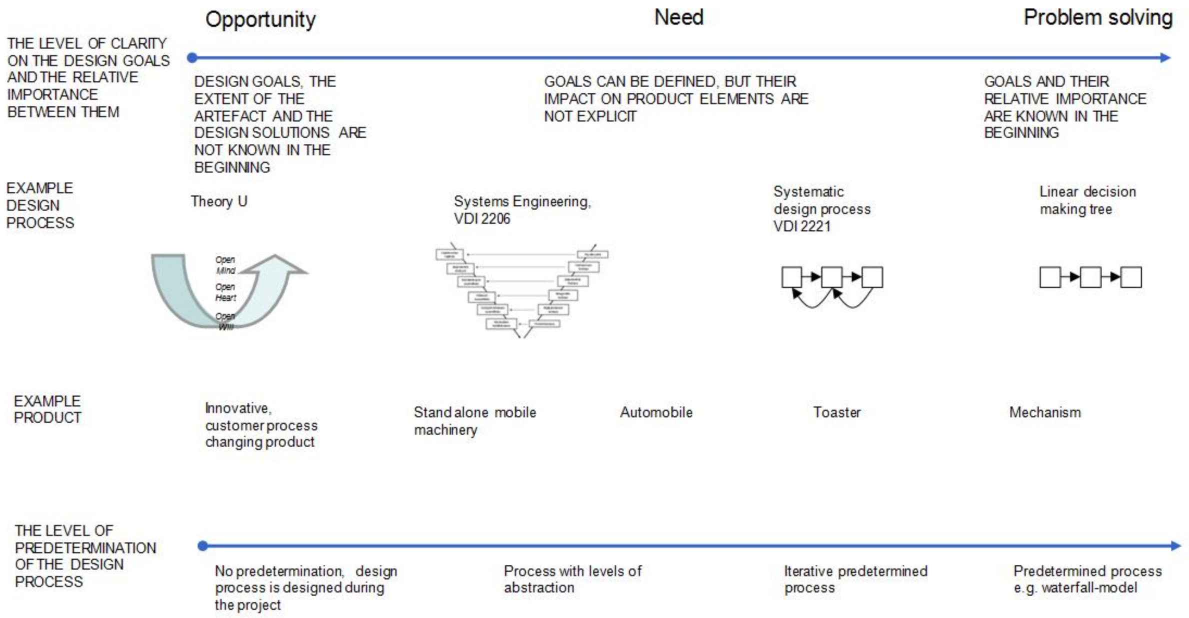


Figure 3.51. *The framework for analysis and comparison of design processes according to Lehtonen et al. (2011a). Four examples of design process models and also some example products have been positioned to the framework by Lehtonen et al. Holistic processes are presented on the left side of the framework whereas the right side focuses on detail-oriented and single-discipline processes.*

The framework shown in Figure 3.51 emphasises how different design situations exist in which one process can be more suitable than another. Similar conclusions about **rational behind design processes** can be found. Geis & Birkhofer (2010) note that all of the models were developed with a specific intention in mind, as they portray designing from different perspectives. Lehtonen et al. (2011a) continue by also reminding us that every design process is designed against particular drivers and objectives and thus different design processes might not aim for the same objectives as the product development project would want to proceed in reality. Gericke & Blessing (2012) also discuss how although the intention is to define process models in a branch independent way, it can be seen that the authors have some specific context on their mind that is not explained in the usual way. If the rationale behind the process is not explained, it makes it harder to evaluate which exact situations the design process, which is intended as a generic process by a specific author, would fit best.

A great deal of **criticism** has been published related to design methodologies. Howard et al. (2008) state that generic design processes are poor as regards representing creative processes and linking creative tools and processes. They also add that the elements of a generic creative process model, including stages of analysis, generation and evaluation, should be linked with the engineering design process. This is said to be important in order to better use creativity tools, methods and techniques in designing. Howard et al. also mentions that understanding the linkages between engineering design and creative processes can reveal where and when resources should be used to facilitate designing, although they do not consider the type of the resource at all.

Gericke & Blessing (2011) explain several issues related to design process models. They state that different disciplines should be taken into greater consideration and designing should be more integrated. Gericke & Blessing also think that most of the models are too generic and too much interpretation is needed in order to use a specific method or process model. The result of this is that the design process models might not facilitate the designing of projects at all and do not guide the daily decision making. The critique of current design methodologies and process models (mostly in mechanical engineering and architecture) is summarised below by Gericke & Blessing (2011; 2012):

- Design processes focus on original design, although most design tasks are based on existing designs.
- Design processes focus on market pull situations. Technology push is not appropriately considered.
- Design processes usually focus either on design or on management. Both viewpoints have to be considered in order to provide an improved support.
- Design processes do not explain how to perform design activities, only what to do.
- Design processes do not explain the rationale of the proposed processes.
- Design processes do not represent the creative process sufficiently.
- Design processes do not support transdisciplinary team-work sufficiently.
- Design processes do not consider goal iteration sufficiently.

Lehtonen et al. (2011a) have similar criticism towards academic design processes:

- Design processes assume that design goals are clear and that a valid requirement list can be made at the beginning of the process.
- Design processes poorly consider the sequence of the emergence of new knowledge.
- Design processes discard the role of existing knowledge, ability and skill level of the actual design team. Design processes do not address learning aspects during the designing.

According to Lehtonen et al. (2011a), **product development in industry** typically considers the partial re-designing of functions, incremental designing, by implementing alternative concepts or new technology with the products. According to Oja (2008), radical innovations are rare, mainly because most product concepts are of the dominant design type and incremental innovation or development may provide just enough advantage against competitors. Incremental designing is discussed further in Chapter 3.7. It is mentioned by Gericke & Blessing (2012) that most of the process models they analysed focus mainly on original design (new product development). They explain that the number of modified process models for adaptive or variant design is low. Gericke & Blessing have noticed that these kinds of models usually exclude either partly or wholly the early stages of the design process. In industry, the whole design process as presented in publications is rarely gone through on a full scale, according to Lehtonen et al. (2011a). Another statement found in the paper by Lehtonen et al. is that the reasoning for how the product is being developed in the industry depends upon the life cycle phase (maturity and detail level) in which the product resides.

Lehtonen et al. (2011a) explain that a business situation in industry is typically not product-oriented and an optimal product is not the only success factor. According to Lehtonen et al., there are several constraints for the number of resources and competencies available in the development process. For instance, the manufacturer of the product has to have the ability to manufacture the product using available resources if investments cannot be made. Communication possibilities with the clients also have to be considered because, although it would be possible to develop a new radical product, it might not garner the market interest or attain acceptance, as stated by Lehtonen et al. (2011a).

Thus Lehtonen et al. (2011a) summarised the challenges for using design processes in industry. They found four main problem factors:

1. The extent of the design artefact. Challenges can arise if there are no explicit boundaries in the technical system.
2. The capability to state and share the design goals during the design process. This can be a problem, especially if the design artefact has no history (new product) and the developer network is large.
3. The ability to "design the designing process" during the design process. This was found to be a possible problem in large, multi-organisation projects with several technologies and disciplines involved in the design process.
4. The capability of the design process to clarify the needed organising, roles, responsibilities and power. Different organisations and their different design processes and design philosophies can become a challenge unless the design process is not able to deal with several different design processes and practises.

One major area of discussion in the research field of design processes is the **applying of design processes**. Gericke & Blessing (2011) highlight that there is not one generic approach that could be applied to all cases, but process models often need adaptation to the case.

Generally speaking about the design process models, Lehtonen et al. (2011a) state that several of the processes aim to cover the product development cycle in one staged process with predetermined inputs and outputs for each stage. Lehtonen et al. (2011a) and Gericke & Blessing (2012) have recognised that almost all of the models include iterative or feedback loops to earlier stages to evaluate if the current results fulfil the original objectives, some more intensively than others. It is also mentioned by Lehtonen et al. that the practical iteration can only take place between the stages because the output of the previous stage acts as the input for the next stage. Basically this means that the larger the work content of the stages is, the higher the risks are for a lot of possible re-work to be done if the results do not fulfil the original goals. Thus this argument suggests dividing designing into rational pieces.

The design process seems to be presented often as an isolated process, according to Gericke & Blessing (2012), and most of the design processes do not consider the other processes which contribute to the creation of the final product. They give an example of how only some of the authors link business processes with design processes, although the design process should address all the functions and disciplines related to the product. It is also stated that the process models do not fully explain designing and because of this discipline-specific cultures, communication (terms and design models) and management styles are not typically considered in design processes, according to Gericke & Blessing (2011).

The same kinds of suggestions are made by Lehtonen et al. (2011a). They explain that in order to apply the design process successfully, the surrounding culture with belief systems, norms and constraints needs to be considered in relation to design intent, design object, amount of preset technical solutions and the level of knowledge of the technical system. One approach that emphasises the thinking of the surrounding culture originates from researchers of human behaviour. Vygotsky (1987) formulated cultural-historical activity theory to understand human behaviour. In this theory, the relationship between human and objects of the environment is mediated by the culture, tools and signs. Leontjev (1981) continued to develop this theory by separating the insight of activity into individual and group activity. Another significant result of his research was the separation of activity, action and operation from each other. These separated issues described different hierarchy levels. For instance, activity: take a part from a box; action: assemble the product so it can be used; operation: deliver the product to the customer and make a profit for the company. Leontjev highlights that transitions occur between the action levels. For instance, actions become activities when one advances and becomes accustomed with some actions. Engeström (1998) has done research in work research and the work study context. He adopted the research results of Vygotsky (1987) and Leontjev (1981) and developed a common structure for presenting human activity, which is called cultural-historical activity theory. The model of the theory is presented in Figure 3.52. The original objective of the model was to present the relation between the individual and the community in work. All factors of this operation system are connected to each other.

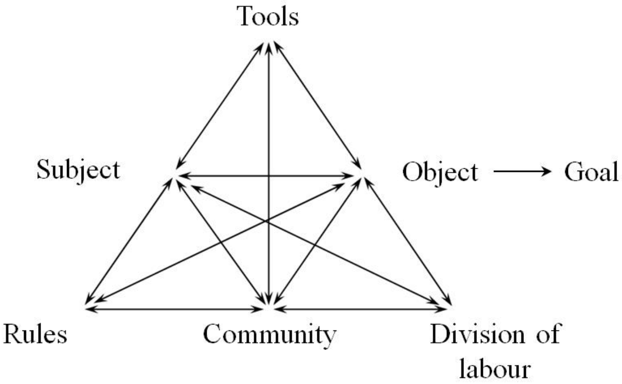


Figure 3.52. *Common structure of human operation (Activity System) (Engeström 1998).*

Referring to Figure 3.52, this could be one approach for facilitating descriptions of discipline-specific cultures, which Gericke & Blessing (2011) discussed. The subject can be a single worker or group of workers. Community refers to all who share the same object. For example, a community can be all the people of an organisation who are participating in the production of the product. Division of labour refers to division of tasks, decision making and benefits amongst the community. Rules include collective rituals, traditions and rules which affect operation between subject and community. The human multiplies physical and mental possibilities by using tools. Tools give subject and community possibilities of having an influence on something.

Related to these elements shown in the model by Engerström in Figure 3.52 (especially community and division of labour), in order to successfully choose and apply design methods (tools in Figure 3.52) in daily work, Geis et al. (2008) state that methodological competence is the most important skill. They discuss how the methodological competence of designers consists of five main elements:

1. Expert knowledge of methods, tasks and processes and their scope and experience in problem-solving actions.
2. Choice of appropriate methods, including the analysis of situation and interrelations.
3. Adaptation of methods, including analysis, organisation and adaptation of methods and proceeding.

4. Execution of methods referring to problem-solving behaviour and control of actions, including dealing with uncertainty and fuzzy data, appropriate balancing between concreteness and abstraction and continuous focus on the goals.
5. Reflection on actions as a measure to improve own actions and knowledge and thus to improve own methodological competence.

Based on the literature discussed above, there are clear signs that the same kinds of issues as were prevalent approximately fifty years ago, which Cross (2007) discussed, are on the table. The usability of the existing design processes occupies the minds of several researchers, and a great deal of criticism concerning, for instance, the level of detail of the processes has been given, although clear benefits have also been recognised as being related to the use of the processes. Several attempts to put different processes into the same picture have been presented in the publications. An improvement in the understanding of the processes and the facilitating of selecting the most suitable process to be applied by making a holistic view of different design processes has been a major objective of these categorising and analysing approaches. Design projects are often considered as incremental or re-design situations in industry, as was discussed earlier in this chapter. Thus it has been explained in publications that the design process and all its stages are typically not gone through on a full scale in industrial product development. Although studied summaries of design processes do not consider product structuring aspects such as re-design, modularisation and product family matters in depth, they give a good overview of the current state of affairs in design processes and their research.

The scope of the thesis relates to the situation in product development in which existing product designs should be considered in the designing of a modular product family. Thus certain viewpoints that relate to the objectives of this thesis can be recognised, and these viewpoints would be worth studying from the perspective of generic product development processes in more detail:

1. **How are objectives for the product derived in generic design processes?**
2. **How is the need for product variants considered in generic design processes?**
3. **How are design re-use and re-design considered in generic design processes?**
4. **How are standardisation, modularisation, configuration, platform and product family aspects considered in generic design processes?**

The first question is important because in modularisation, objectives for the modular structure also need to be defined until designing. For this reason, target setting of generic design processes is interesting topic.

The second question is related more deeply to the objectives of this thesis. This thesis is not about designing a single product but rather about the application context demands for product variants. Thus the studied generic processes are also analysed from product variant perspective.

The third question discusses design re-use and re-designing topics. In Chapter 3.5.4, design re-use was divided into design for re-use and design by re-use. In this part of the thesis, the focus is in both categories. The aim is to clarify how an existing product assortment or variety should be designed towards a structure that could be re-used in the sales/order-delivery process.

The fourth question relates directly to product structuring tactics. This question aims to find an answer regarding how these generic design processes consider these issues.

Based on these questions, some selected design processes are studied in the next sub-sections and answers to the previously mentioned questions are sought.

3.6.1 Pahl & Beitz

Pahl & Beitz (1996) have presented the systematic product development process with four main phases, including planning and clarifying the task, conceptual design, embodiment design and detail design. The whole process is shown in Figure 3.53 and discussed in this chapter. Although the cited book is from the 1990's, Pahl & Beitz had already published works related to these topics in the 1960's (Pahl & Beitz 1996).

Functions and function structures are often linked to this process. Pahl & Beitz define **modular products** as machines, assemblies and components that fulfil various overall functions by combining distinct building blocks or modules. They discuss the fact that products that have already been marketed are often redesigned as a modular system. Pahl & Beitz mention that predetermined products might have disadvantages, but that they also have advantages, such as the fact that they have already been tested and the stage of expensive new development can be bypassed. Moreover, Pahl & Beitz do not only discuss **function modules** that help to implement technical functions independently or in combination with others. They also discuss **production modules**. Production modules consider only production aspects and do not highlight function considerations at all, according to them. Pahl & Beitz have classified function modules in more detail as shown in Figure 3.54. As can be seen from this figure, a modular system has been defined as a possible collection of different modules, but it is recognised that the product can also include non-modules. These non-modules reflect customer-specific issues and are developed separately.

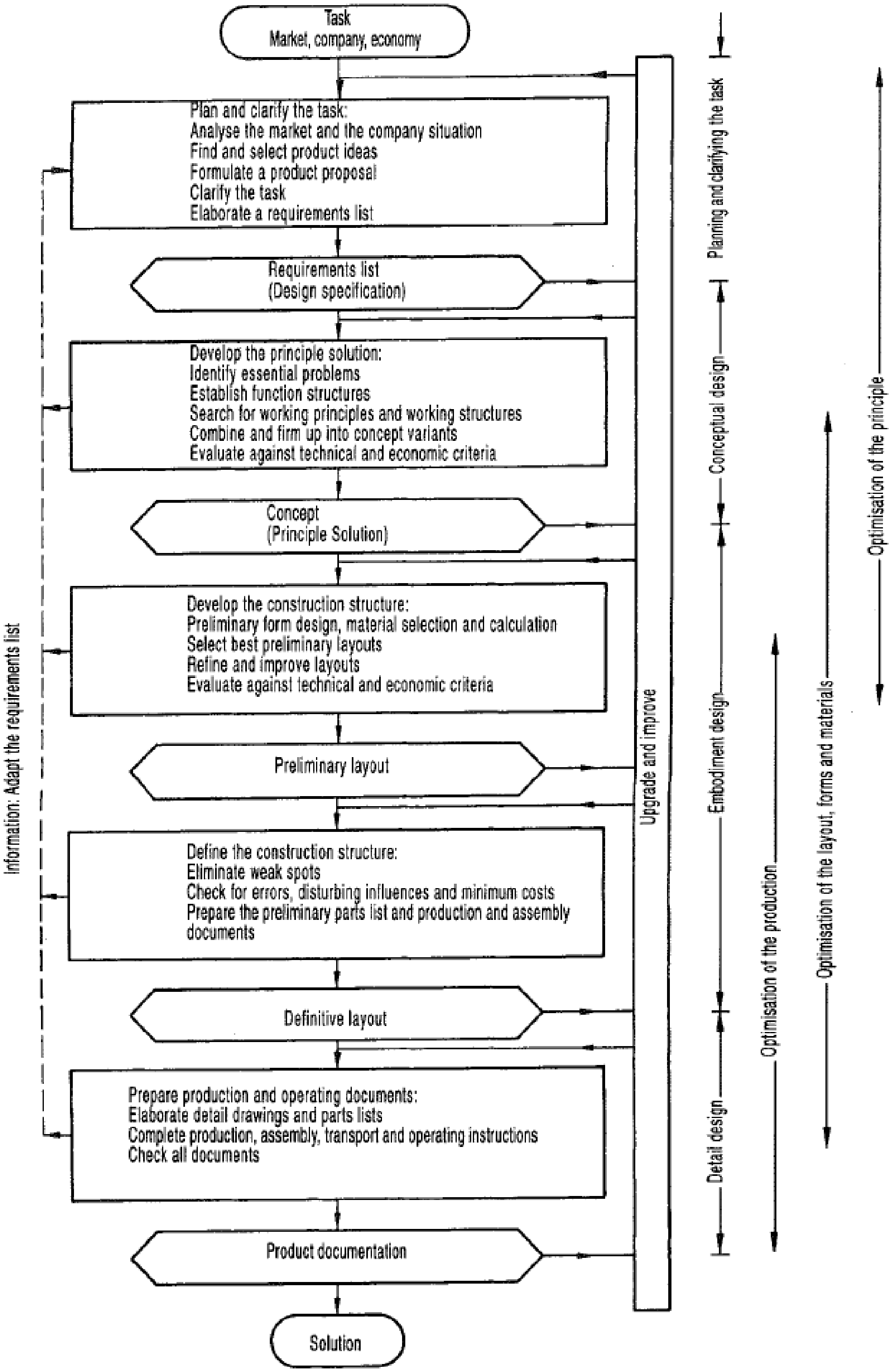


__Figure 3.53.__ Product development process according to Pahl & Beitz (1996).

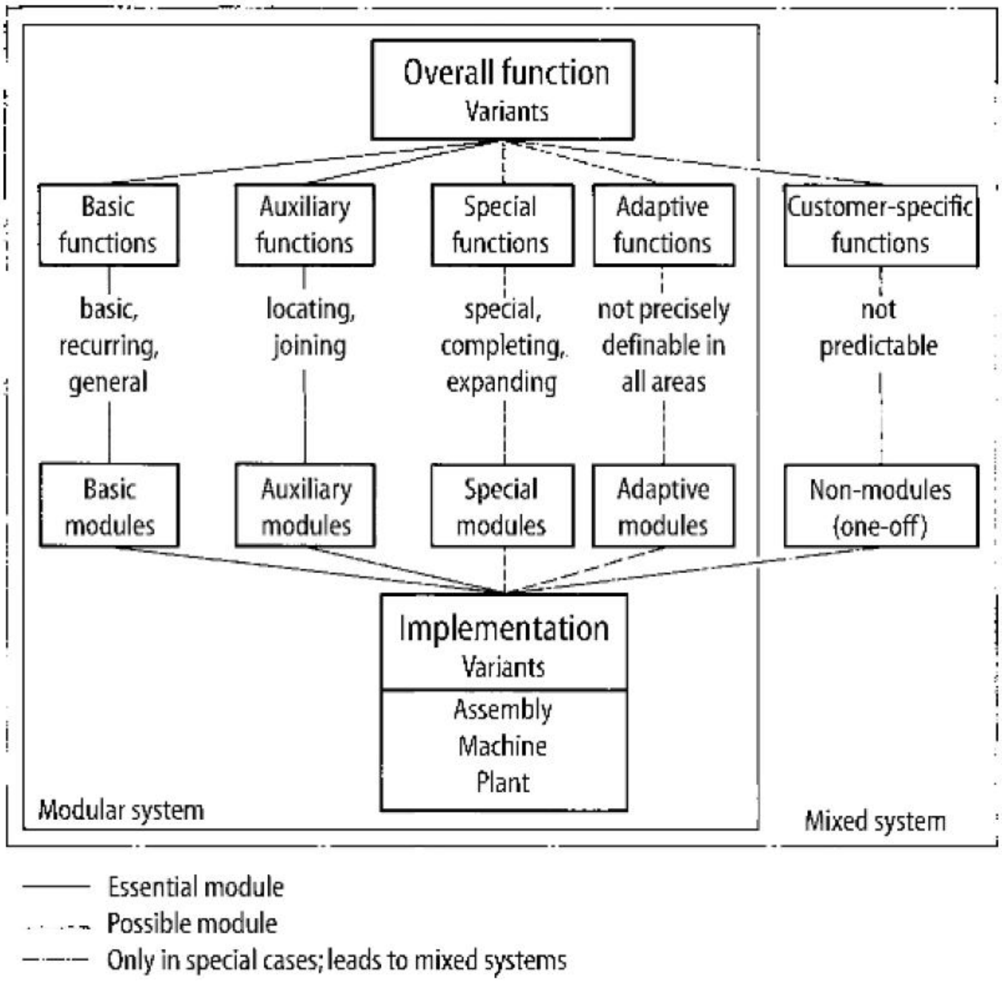


Figure 3.54. *Pahl & Beitz (1996) discuss how the product system can include different functions and related modules or non-modules.*

The process model, as shown in Figure 3.53, concentrates mainly on the designing of a new single product, but issues related to variants, modularisation and re-designing have also been introduced in regard to this process. In the following, the four main phases of the process and the previously mentioned interesting issues from the viewpoint of this thesis are explained.

In the first phase, **product planning and clarifying the task**, information is collected concerning the requirements that have to be fulfilled by the product and about the existing constraints and their importance. Pahl & Beitz (1996) explain that a driver for product planning can arise from market, company or from other sources, such as economic or political changes. Pahl & Beitz discuss how rationalisation of product range and production can be one starting point for product planning. They represent five steps which take place after the driver for the designing is clarified:

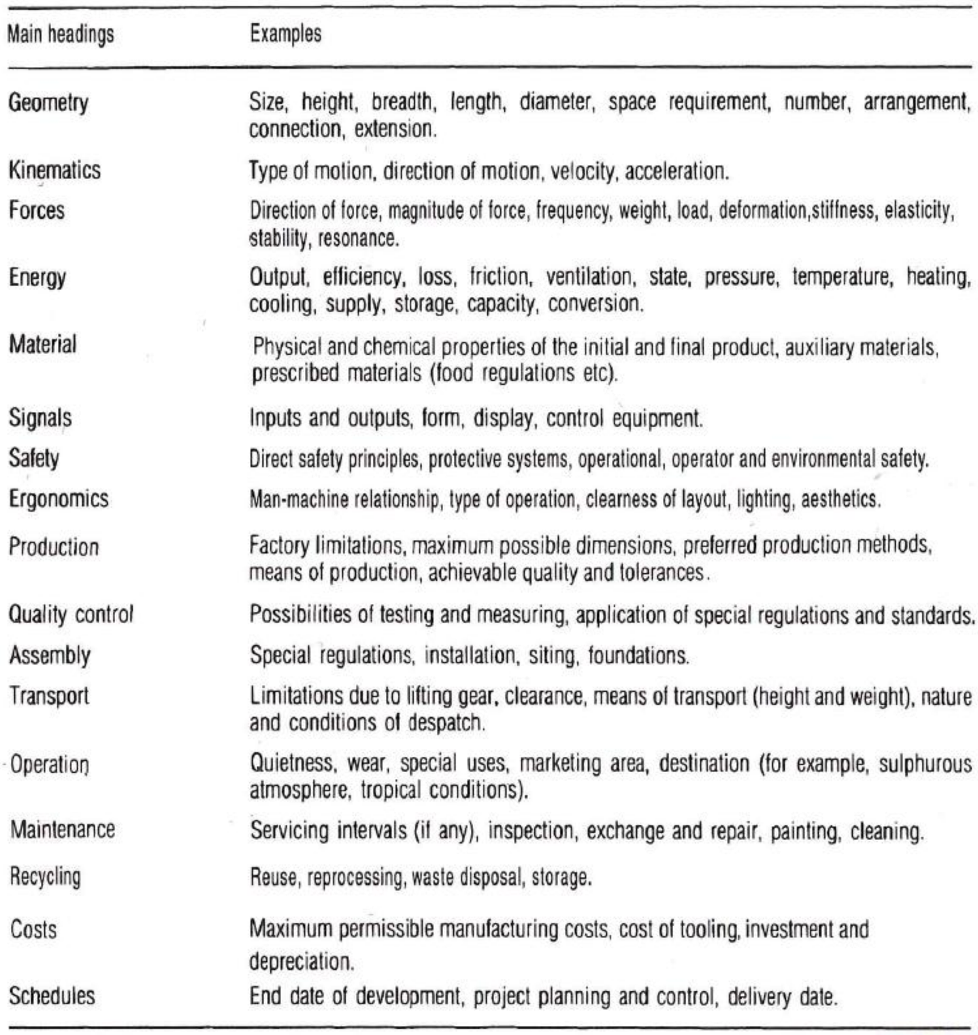
1. Analysing the situation by assessing, for instance, the own competence of the company, status of technologies and future developments.
2. Formulating search strategies considering opportunities, needs and trends and company goals and strengths.
3. Finding product ideas with, for instance, the aid of considering changing of functions, working principles or embodiment.
4. Selecting promising product ideas.

5. Defining product with a multidisciplinary team by creating a product proposal that includes and defines functions, a preliminary requirement list, cost target and budget and company goals. Only those product proposals that fit in with the goals and strength of the company will enter the actual development steps.

Pahl & Beitz (1996) note that if product planning focuses on existing product lines (further development or systematic variation), the original development department or members of that department responsible for the product line can observe the designing of the new product or product line. The first main phase of this product development process results in a requirement list. Pahl & Beitz state that one should pay attention to the main headings shown in Table 3.11 while defining the list. They write that a requirement list is valuable for storing information for further developments or negotiations, for example.

According to Pahl & Beitz, the designing of a modular system is justified if the variants for the overall function are needed. Pahl & Beitz note that market expectations for particular variants have an important role because of economic analysis and application of modules. They suggest that rarely demanded variants that increase the overall cost of the modular system should be removed if reliable cost information is available. According to Pahl & Beitz, this can happen even as late as when the concept or embodiment design is defined.

Table 3.11. *Pahl & Beitz (1996) have presented a check list for drawing up a requirement list.*



Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension.
Kinematics	Type of motion, direction of motion, velocity, acceleration.
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation,stiffness, elasticity, stability, resonance.
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc).
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct safety principles, protective systems, operational, operator and environmental safety.
Ergonomics	Man-machine relationship, type of operation, clearness of layout, lighting, aesthetics.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of despatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Recycling	Reuse, reprocessing, waste disposal, storage.
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date.

The second phase focuses on **conceptual design**, in which the principle of a solution is determined. This phase includes abstraction of the design problem, establishment of function structures, defining of working principles and suitable combinations and evaluation of variants against technical and economic criteria. The result of the phase is a concept to be developed further. Pahl & Beitz explain that if the case is one of adaptive design, the function structure can be obtained by analysing the product with its known components and assemblies. When speaking about conceptual design, Pahl & Beitz highlight that both technical and economic characteristics should be considered as early as possible. They suggest that the main headings presented in Table 3.11 should also be taken into consideration in this phase (and also in the embodiment design phase) when selecting the most promising concept. Thus it can be said that the approach suggested by Pahl & Beitz (1996) is not only customer-oriented but also includes business-oriented aspects in setting the objectives and analysis of the results.

From a modularisation and variant perspective, Pahl & Beitz point out that the function structure defines the structure of the product in principle. They also propose that designers should divide the overall function variants into a minimum number of similar and recurring sub-functions. These sub-functions should be interchangeable. Pahl & Beitz discuss the fact that it is often cheaper to combine several functions into one complex function. For instance, the same module can include both basic and adaptive functions from production reasons, thus being a production module in the way Pahl & Beitz have defined it earlier. The same authors also remind us that a product should be designed in a way that variants in high demand should be able to be built-up mostly with basic functions and more rarely bought variants with additional special and adaptive functions. A mixed system, as shown in Figure 3.54, should be considered only when a modular system cannot fulfil the need. In searching for solution principles, Pahl & Beitz discuss how the technical and economic factors are so complex that it is hard to set definitive rules for modularisation.

The selection and evaluation of solution principles is done in the same way when developing a modular product using technical and economic criteria. Based on their experience, Pahl & Beitz state that in this phase variants are usually incomplete and thus selections are difficult to make. Pahl & Beitz explain that designers must estimate the production costs of each individual module and analyse their relative effect on the cost of the whole modular system. Usually these are only rough estimates, according to these same authors. They explain that, in particular, the basic modules that can be found from most of the product variants should consider cost-effectiveness and that the layout of these modules must be adapted to the expected demand. It is also suggested that it is often more economical to make individual adaptations in rare special cases or use a mixed system with one-of-a-kind solutions as shown in Figure 3.54 than to consider these in terms of the whole modular system.

Embodiment design is the third phase in the process presented by Pahl & Beitz. In this phase, the overall layout design (general arrangement and spatial compatibility), the preliminary form designs (component shapes and materials), the production process and solutions for any auxiliary functions are determined. Besides new product development, Pahl & Beitz also discuss situations in which existing products are developed further or improved based on new requirements and experiences; thus, product development does not start from scratch in these cases. They suggest that it is useful to analyse the failures and disturbing factors for the existing solution and then to develop a new requirements list. After that, it should be considered whether or not it is sufficient to modify the existing embodiment or rather if new principle solutions are required. Pahl & Beitz explain that steps that have to be completed in embodiment design in this situation that depend on the analysis of failures and disturbing factors.

As was discussed in the chapter on modularisation, interfaces are essential enablers of benefits with modularity. Pahl & Beitz provide guidelines for the designing of interfaces between connecting product elements in order to make assembly work easier. Reducing, standardising and simplifying of interfaces are considered as objectives in the designing of interfaces for assemblies.

Some generic guidelines for actual module designing can also be found in the book by Pahl & Beitz, where it is stated that modules should be developed while keeping in mind functions and production, assembly handling and distribution requirements from an economic perspective. The aim is to maximise the number of similar and recurring parts. Pahl & Beitz also discuss how the most common modules should be designed for equal wear and tear and for easy replacement. In the examples found from their book it can be seen that the final modular structure differs from the function structure; several functions are fulfilled by a single module or its variants, as explained by Pahl & Beitz.

Detail design is the fourth and the last phase in the design process. This phase includes completing the embodiment of the product with final instructions and documents about the layout, forms, dimensions and surface properties of components, selection of materials and final consideration of the production methods, operating procedures and costs, according to Pahl & Beitz (1996). These instructions and documents should consider different life cycle phases such as production, assembly, transportation, quality control, operating, maintenance and repairing. Suggestions for modular products can also be found. Combining of individual modules into product variants must be considered in the part list, according to Pahl & Beitz. The distinction between essential and possible modules and the classification of modules is also suggested in documenting. This is particularly recommended in order to facilitate production and assembly work.

As several benefits (for instance, reduced design effort in the order-delivery process) related to modular products have already been discussed earlier in this thesis, Pahl & Beitz have also recognised limitations that the modular product offering can create. From a manufacturer point of view they list the following challenges:

- more difficult adaptation to special customer needs
- possible lack of drawings for variants that have not been delivered
- longer intervals for product changes (redesigning of the whole modular system is needed)
- dominant role of the modular system in terms of technical features and the shape of product variants
- increased production costs because of, for instance, the need for accurate locating surfaces
- increased assembly effort and care required
- difficult designing of an optimal modular system because of different interests of users and producers
- costs of rare combinations instead of tailor-made designs

From the user point of view they discuss the following challenges:

- more difficult to meet special wishes
- special-purpose designs can have better quality characteristics in some areas of the product
- weights and structural volumes can be greater because of space requirements

Apparently one concern discussed by Pahl & Beitz is that the modular system cannot fulfil the requirements of the customer and it dominates the content of the product too much. Non-modules (customer specific product elements) have been introduced for this problem but by using these, the economic benefits of modularity are reduced from a company viewpoint.

Lack of drawings for variants might affect, for instance, the quality of customer service if a customer wants to know the details of the product before ordering a product. One solution for this could be a product configurator that would produce the needed documents based on the customer selections that define the product variant. This requires that the modular system be able to fulfil all the needs of the relevant customers and no customer-specific non-modules are needed because the defining of these needs more time.

Longer intervals of product changes can be a problem if market or customer requirements and expectations change rapidly. In the chapter on product platforms and product families, the literature suggests that one solution is to use product platforms that consider specific requirements, and these platforms can then be updated over time. Management of different versions of the modular systems is discussed e.g. in the Dynamic Modularisation approach (Riitahuhta & Andreasen 1998) in which roadmaps for product and module changes were suggested in order to manage the product architecture. This will be discussed in Chapter 3.8.1. Harlou (2006) suggests considering future designs when product architecture for the product family is designed.

Increased production and assembly costs and the amount of effort needed are also highly case specific. This issue, discussed by Pahl & Beitz, relates mainly to interfaces and interchangeability of the modules.

Design of an optimal modular system is probably impossible but several cases discussed in the literature have shown that better results are achieved if compared to the starting points of those projects. These kinds of examples can be found in, for example, dissertations by Erixon (1998), Harlou (2006) and Juuti (2008). Modularisation might include compromises from both company and customer viewpoints and it must be analysed in every case to determine what possible benefits would be realised by modularising the product assortment, as suggested earlier by Andreasen (2011).

The costs of rare combinations of product instances are one challenge in designing a modular system. It must be decided as to what extent the modular system serves possible customer requirements. For instance, it might be beneficial to analyse the requirements of the most important customer segments and to develop modular architecture while keeping these in mind and leaving rare modules or product elements outside the modular system.

It can be stated that special-purpose designs with integral architecture can be more difficult to realise than solutions that use modular systems, due to, for instance, the lack of design re-use (even though the designing of a modular system is a costly activity if compared to the designing of a single product). These special-purpose products might have better properties from a customer viewpoint. One often-seen approach from the company viewpoint is to highlight the choice between a standard/modular product and a customer-specific product in the price. Thus these are different value chains in companies. Uniqueness costs more. For instance, in the modularisation process based on the V model discussed by Lehtonen (2007), it is suggested that testing should be done on a different complexity level for a modular system in order to guarantee the quality. When designing fully customer-specific designs, the need for testing can be even more extensive if needed solutions for the product are completely unfamiliar to the company.

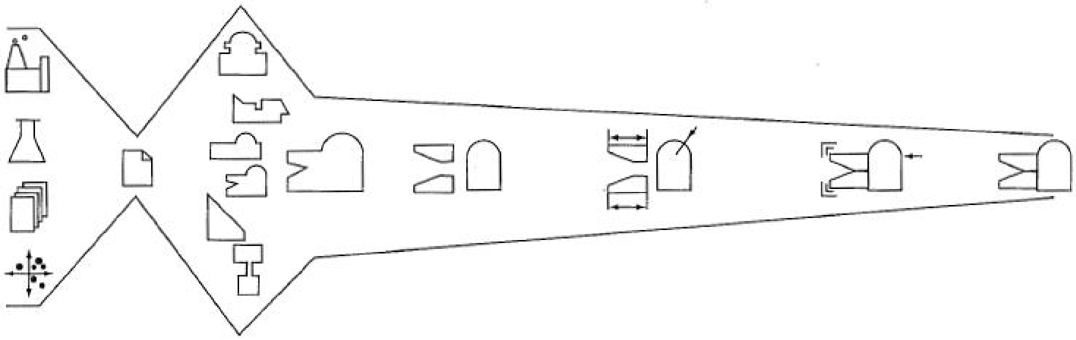
Pahl & Beitz also state that the weights and volumes of modular products can be greater if compared to a single product that does not use any product platform. The same kind of critique was discussed in relation to standardisation by Perera et al. (1999) (see Chapter 3.5.5). The architecture of the modular product family has to consider all the possible variants derived from it. This can be seen in, for instance, the example discussed by Holmqvist (2004), in which a truck frame had freezing areas for separating the variable elements. The way in which a product is built and its interfaces defined affects whether or not the weight or volume of the product increases.

It is also explained in the book by Pahl & Beitz that the approaches discussed in the book have been hardly introduced at all in practice for adaptive and variant design. It is believed that the reason for this is the focus of methods on working with functions and function structures. In the book it is explained that these are not the most important tasks in these types of designs. As was discussed in the modularisation chapter, it is not obvious that modularisation based on the function structure leads to good results in every case (Lehtonen 2007), thus the suitability of this function-based approach should be considered critically.

3.6.2 Ulrich & Eppinger

Ulrich & Eppinger (2008) present the generic product development process using six phases, including planning, concept development, system-level design, detail design, testing and refinement and production ramp-up. The main content of the process can be seen in Figure 3.55.

Defining the objectives for the product concentrates highly on the identification of customer needs, which is discussed as a task for marketing. Ulrich & Eppinger state that customer needs and specifications have to be technically and economically realisable. Customer-need activities belong to the concept development phase, in which concepts are generated and finally one is selected for further development in more detail. Several of the selection criteria are related to customer needs, but Ulrich & Eppinger also discuss ease of manufacturing, production costs and use of existing parts in the examples presented in the book. Thus economic analysis also belongs to the concept development phase. The purpose of the economic analysis is to make sure that the concept is appropriate from, for example, a development and manufacturing costs perspective. Ulrich & Eppinger also note that there might be other stakeholders who are important from an economic success viewpoint, but they do not explain this issue in detail. (Ulrich & Eppinger 2008)



	Phase 0: Planning	Phase 1: Concept Development	Phase 2: System-Level Design	Phase 3: Detail Design	Phase 4: Testing and Refinement	Phase 5: Production Ramp-Up
Marketing	• Articulate market opportunity. • Define market segments.	• Collect customer needs. • Identify lead users. • Identify competitive products.	• Develop plan for product options and extended product family. • Set target sales price point(s).	• Develop marketing plan.	• Develop promotion and launch materials. • Facilitate field testing.	• Place early production with key customers.
Design	• Consider product platform and architecture. • Assess new technologies.	• Investigate feasibility of product concepts. • Develop industrial design concepts. • Build and test experimental prototypes.	• Generate alternative product architectures. • Define major subsystems and interfaces. • Refine industrial design.	• Define part geometry. • Choose materials. • Assign tolerances. • Complete industrial design control documentation.	• Reliability testing. • Life testing. • Performance testing. • Obtain regulatory approvals. • Implement design changes.	• Evaluate early production output.
Manufacturing	• Identify production constraints. • Set supply chain strategy.	• Estimate manufacturing cost. • Assess production feasibility.	• Identify suppliers for key components. • Perform make-buy analysis. • Define final assembly scheme. • Set target costs.	• Define piece-part production processes. • Design tooling. • Define quality assurance processes. • Begin procurement of long-lead tooling.	• Facilitate supplier ramp-up. • Refine fabrication and assembly processes. • Train work force. • Refine quality assurance processes.	• Begin operation of entire production system.
Other Functions	• Research: Demonstrate available technologies. • Finance: Provide planning goals. • General Management: Allocate project resources.	• Finance: Facilitate economic analysis. • Legal: Investigate patent issues.	• Finance: Facilitate make-buy analysis. • Service: Identify service issues.		• Sales: Develop sales plan.	

Figure 3.55. *Product development process according to Ulrich & Eppinger (2008).*

Ulrich & Eppinger discuss how their process can be adapted to different situations based on the product type. Ulrich and Eppinger present the generic market-pull product development process with the assumption that the design organisation works in an environment conducive to success. It is explained that this is not always possible in reality. For example, inadequate resources lead to non-optimal solutions. In addition to the generic market-pull process, other approaches are recognized. They have presented a total of eight different product types with different foci:

- Generic (market-pull) products: Finding of market opportunity and then developing of a product.
- Technology-push products: Finding of market for product with new technology.
- Platform products: Taking technology platform into account in concept development.
- Process-intensive products: Developing of production process and product together.
- Customized products: Taking similarity of projects into account in the structuring of development process.
- High-risk products: Taking greatest risks or uncertainties into account in the early phases of design process.
- Quick-build products: Taking advantages of fast prototyping cycle in the design process.
- Complex systems: Considering the architecture of the entire system by breaking the system down into subsystems and then further breaking these down into components that can be designed in parallel.

If analysis should be made of some example product, it can be challenging to decide on only one group that it belongs to. For instance, platform products can also be highly process-intensive products if existing production process must be used in production of platform products because of resource limitations.

Ulrich & Eppinger (2008) also present another classification of product development projects based on the novelty of product platform or product:

- **New product platforms**: creating a new family of products based on a new common platform addressing familiar markets and product categories.
- **Derivatives of existing product platforms**: extending an existing product platform to better address familiar markets with one or more new products.
- **Incremental improvements to existing products**: adding or modifying some features of existing products in order to keep the product line current and competitive.
- **Fundamentally new products**: developing radically different product or production technologies addressing possibly new and unfamiliar markets.

One objective of this thesis is to reveal what kinds of approaches can be found from the literature as far as addressing the development of platforms that use modular product architecture; thus, the above platform classifications and development steps of architecture interesting.

Ulrich & Eppinger represent four steps that result in **estimation of the geometric product layout, architecture**. Architecture describes the most important chunks of the product and the most important interactions between the chunks. The four steps are discussed below. The result of these steps can be used in guiding early system-level design activities, according to Ulrich & Eppinger.

1. Create a schematic of the product
2. Cluster the elements of the schematic
3. Create a rough geometric layout
4. Identify the fundamental and incidental interactions

Ulrich & Eppinger discuss that the schematic in **the first step** can include both physical and functional elements. They argue that some of the elements can be defined functionally because not all of the product elements may have been developed into physical concepts or parts yet. Ulrich & Eppinger explain that the number of elements in this schematic should be under 30 but they do not give any reasons for this particular number. They simply state that if the product is more complex, areas which are not relevant during the development occasion can be described on a more abstract level. These kinds of areas can, for instance, include secondary systems related to power, status, safety or structural support, according to Ulrich & Eppinger. Ulrich & Eppinger conclude that the choices described in the schematic of the product create a base for the architecture.

In **the second step**, all the elements of the schematic are assigned into chunks. Ulrich & Eppinger suggest that at first each element would be separate chunks and then those elements would be clustered in a way which is beneficial. They suggest that the following issues be considered in the decision-making phase of clustering:

- Geometric integration and precision: Managing of physical relations can be easier when the parts which need to be accurately positioned to each other are located within the same chunk.
- Sharing of functions: If several functions are related to one part, functional elements should be put together.
- Capabilities of vendors: The same kinds of technologies can be implemented within the same chunk if a vendor has the capabilities for a specific technology.
- Design or production similarities: If designing or production of elements is made using the same technique (for instance, electric parts), elements could be assigned into the same chunk.
- Localisation of change: Elements of the product could be isolated into their own modular chunks if the product includes areas which are likely to include a need for variety.
- Accommodating variety: Elements could be clustered in a way that enables the company to change them in order to create value for the customer.
- Enabling standardisation: Elements that can be used in other products should be clustered within the same chunk in order to enable economies of scale in production.
- Portability of the interfaces: Some elements, such as electronic elements with interactions with other electronic elements, can be easily separated from one another.

The objective of **the third step** is to create a rough geometric layout of the product. This can be, for instance, a 2D or 3D drawing, computer model or physical model. The feasibility of the geometric interfaces in chunks should be considered during this step, according to Ulrich & Eppinger. They also highlight the importance of participants with different backgrounds, such as industrial designers and human interface specialists, in this step.

In **the fourth step**, interactions between chunks are recognised in order to facilitate designing. Interactions can be both intended and unintended. Ulrich & Eppinger discuss the fact that intended interactions need to be designed and understood and described explicitly. Unintended interactions should also be documented somehow. Ulrich & Eppinger suggest that graphs and matrices can be used when representing relations. This representing facilitates the managing of designing. If interactions can be defined using a clearly defined interface that will handle the fundamental interactions, independent designing of chunks is then enabled, according to Ulrich & Eppinger. They add that knowledge of interactions develops when system-level and detail designing proceeds.

Ulrich & Eppinger conclude that product architecture starts to develop with the help of sketches, function diagrams and early prototypes in the **concept development step**. They add that the basic product technology determines how well the product architecture can be defined in this step. When dealing with a completely new product, concept development focuses on basic solution principles and technologies on which the product is based. In this situation, the product architecture is in a relevant part in system-level designing. If designing involves incremental development to an existing product, product architecture is usually determined in this concept development step. According to Ulrich & Eppinger, the reason for this is that basic technologies and solution principles are predetermined, so design effort concentrates on the improvement of an existing concept. When a product category matures, supply chain and product variety issues become relevant. This leads to a situation in which the product architecture also becomes a central element among the capabilities of the company to offer product variety efficiently. Thus the architecture defines how well the product can be adapted to different needs, according to Ulrich & Eppinger. They also explain that modular architecture can respond to product changes that can arise from several reasons, such as the need for upgrades, add-ons, adaptation, wear and flexibility in use or re-use, more efficiently than the integral architecture.

To conclude, Ulrich & Eppinger discuss how the objectives for the product emerge mainly from customer needs, but they also consider other requirements emerging from the company. The role of these, however, is not highlighted outstandingly in the process and its explanations.

The need for product variants is questioned in the concept evaluation phase. The issue is whether or not one concept can fulfil all the relevant objectives or if there is instead a need for selecting more than one concept to be developed further. Ulrich & Eppinger suggest that the architecture of a product is the major enabler of an efficient way to produce product variants.

Modularisation, design re-use and platform issues are covered with varying extent by Ulrich & Eppinger. Ulrich & Eppinger discuss function-oriented modularisation. As already discussed in the modularisation chapter, it is not certain that this kind of modularisation leads to good results. Thus the suitability of the approaches that Ulrich & Eppinger suggest should be analysed until done in each case. Ulrich & Eppinger also explain an approach for the developing of product architecture. This approach with its four steps can help in the developing of architecture and it trusts strongly the expertise of the designers.

3.6.3 Andreasen & Hein

Andreasen & Hein (2000) have presented a generic product development model known as Integrated Product Development (IPD). The authors of the model explain that one of its most important purposes is to link the product development process to business optimisation and to highlight the fact that the IPD process is based on the three parallel but integrated streams of market, product and production. The overall model of IPD is shown in Figure 3.56.

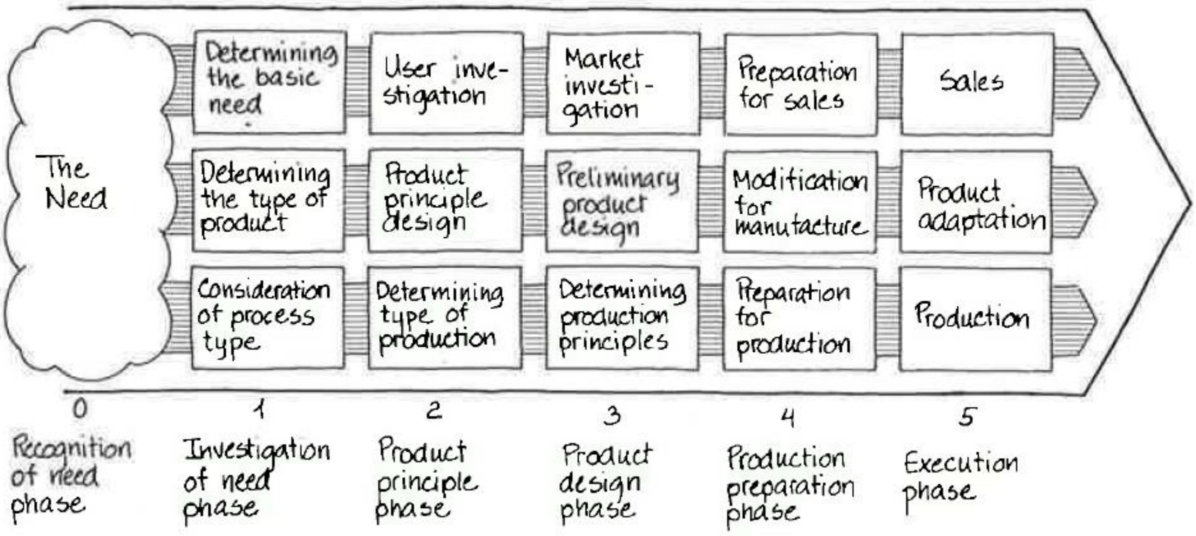


Figure 3.56. *Integrated Product Development model includes three parallel and integrated streams of creation of market, product and production (Andreasen & Hein 2000).*

As shown in Figure 3.56, the IPD model highlights the fact that product development begins with a need. Andreasen & Hein (2000) explain that this need can arise from several sources, including consumer and manufacturer point of views. Andreasen & Hein have summarised the main contents of the phases of the IPD model in the following way:

In the first phase, **investigation of need**, the need is identified. This need is defined by a product type and process type. In this phase, it is also explained at a basic level regarding who actually has the need and who would buy the product and at what price.

In the second phase, **product principle,** it is analysed as to who is the user of the product and how the product will be used and of what type the user-product interaction is. The general principles of the product are also defined and this helps in determining the type of production.

In the third phase, **product design**, the output is a demonstration of the fact that the product works. The product and its technology are defined in more detail and take into consideration the expected size of the market. Feasible production principles are also determined during this phase.

In the fourth phase, **production preparation**, the possibility for manufacturing the product with the desired quality is demonstrated. Andreasen & Hein suggest that the maturity of the product should go hand-in-hand with production and assembly definitions. They also add that the sales system, including prices and the relationship of the sales system to production, should be set up during this phase.

In the fifth and final phase of the IPD model, **execution**, production and sales are ongoing and the product is adapted to the need, if necessary.

If compared, for instance, to the process model discussed by Pahl & Beitz (1996), IPD concentrates more on management issues and project leader perspectives than on actual design and its detailed part- or assembly-level guidelines. IPD covers very little about modularisation, product families, platforms and variants. It is recognised that producing too many or too few variants can be a problem for executives and it is difficult to develop a product range that enables adaptability to customer needs and is rational from a production viewpoint. Despite this, the model is relevant because it shows that in the designing of a product different viewpoints must be considered in order to create a successful product, whether it is only a single product or a product family, and this model also highlights simultaneous tasks of different functions.

3.6.4 Conclusions of generic design processes

In this section, design processes were discussed in order to gain an overview of the quality of these processes and how they consider different issues that are relevant for this thesis. Some basics of the design processes were already presented in the section on Design Science in Chapter 3.4, but this Chapter 3.6 reveals that in the field of product development, several different design processes have been presented. It was also found that by analysing these processes, generic main phases can be identified.

Models that give an overview of different design processes and categorise them have been presented in the publications. In these models, generic product development stages have been recognised. It can be seen that these generic stages are very similar, as has been presented in a few main publications, such as in the book by Pahl & Beitz (1996). Some of the design processes have design focus and some of the processes concentrate more on, for example, management viewpoints. Discussion of the usefulness of design processes has also been a topic for several decades. Several advantages and disadvantages have been recognised and, for instance, there is no consensus about how detailed the generic design processes should be. Research results of many authors show that several of the processes focus on new product development and the utilisation of existing products, and knowledge as a starting point in design processes is rarer. The rationale behind design processes is often not described. It has been noted that many of the design processes have some background beliefs that would, for instance, describe design situations in which the design process in question would suit most of them, but these are not documented. Thus, although the processes have been described as generic design processes, the suitability of those processes to different design tasks varies. Criticism of design processes concentrates also on the lack of creativity viewpoints.

Industrial viewpoints from the literature revealed that the development of completely new products is not so common because product concepts have become dominant designs in several industries and thus incremental development can be enough in order to stay competitive in an industry. As discussed, the number of design processes that focus on adaptive and variant designs is low, and in these processes early stages are not gone through at the same level as in design processes that focus on the designing of a completely new product.

To gain more insight into generic design processes, three generic design process models were analysed in more detail, keeping in mind the objectives of this thesis. These three process models were systematic design process by Pahl & Beitz, product development process by Ulrich & Eppinger and the integrated product development process model by Andreasen & Hein. Why were these selected? Selection was done by estimating their recognition in the research field. This was subjective interpretation, performed by the author of this thesis. The aim was to select those processes to be analysed in more detail which are generally well known in the field such as, for instance, those publications that are often taught in universities. Processes were analysed by considering how the objectives for product development are set and how product structuring issues such as design re-use, re-designing, standardisation modularisation, variants, product family and platform issues are covered in the models. One can see that these three design processes are very different. One of the process models is design-oriented (Pahl & Beitz 1996) than other two (Andreasen & Hein 2000; Ulrich & Eppinger 2008) which have more of a focus on managerial issues.

Pahl & Beitz (1996) presented a design oriented process model with four main stages. It was explained that a systematic process has seldom been used in an adaptive and variant design environment. In the first stage, **product planning and clarifying the task**, objective setting focuses on the requirement list, and considers product and life cycle issues. The second stage, **concept design**, highlights technical and economic considerations. From a modularisation perspective, it is said that it might be cheaper to combine several functions into one function. Thus, even though Pahl & Beitz highlight function modules, they also mention that modules can be defined from production viewpoints. In the latter, a module includes several functions. It is noted that no seldom-demanded variants should be included in the modular system (the modular system defined by Pahl & Beitz has a different meaning than that of the Module System discussed in modularisation chapter). Thus this guideline by Pahl & Beitz has similarities with different types of product elements (standard, fully configurable, partly configurable, one-of-a-kind) that were discussed in Chapter 3.5.8 of configuration. Pahl & Beitz noted that the most important variants should be able to be produced using basic modules and that a mixed system that includes unique design should be used only if a modular system cannot fulfil the requirements. **Embodiment design** is the third stage in the process by Pahl & Beitz. It was explained in this stage that if the design situation is re-designing, then current problems of the product should be analysed and a new requirement list developed, along with considerations regarding whether or not a better product can be achieved by re-designing the existing product. From a modularisation point of view, one interesting topic was guidelines for the designing of interfaces and modules. These guidelines appeared to be, however, on a generic level and highlighting the importance of reducing, standardising and simplifying interfaces between different sections of the product and maximising the number of similar and recurring parts and enabling easy replacement of the modules. **Detail design** is the last stage of the process model. The consideration of product variants in the part list was mentioned as an important step of this stage because it helps production and assembly; however, for instance configuration knowledge including customer requirements was not discussed.

Ulrich & Eppinger (2008) explained that customer needs should be technically and economically feasible. In their section on solutions, they suggested that several factors must be considered, such as development and manufacturing costs. Ulrich & Eppinger have recognised different product types, such as platform products, but they have not presented a process that goes deeply into detail when designing these kinds of products. They merely explain that a platform must be taken into consideration in conceptual designing. Ulrich & Eppinger emphasised more in regard to product architectures. They explained steps that can facilitate the designing of architecture and gave the approximation that 30 elements maximum should be considered when defining architecture because otherwise the development might turn out to be too complex. This means that some areas of the product, such as secondary systems, must be described on a more abstract level than others, according to them. Ulrich & Eppinger also noted that the documenting of interactions between product elements is important. This relates to the definition of interfaces. Ulrich & Eppinger stated that the architecture of the product fixes the capabilities to efficiently provide variants. At worst, this can cause large modifications to existing designs in re-design situations in which basic technologies and solution principles are pre-defined and when in the current architectures of product assortment, variability viewpoints are considered inadequately.

Andreasen & Hein explained in Integrated Product Development the importance of considering market, product and production activities in parallel and integrated streams in product development. They explained that the main stages of product development are the defining of need, product principle, product design, production preparation and execution. This publication explained the topic mostly from a management point of view and the core of this thesis was considered very little in this model and its descriptions.

To conclude this chapter, product development and product structuring issues have been discussed in several publications and a number of generic approaches and suggestions can be found. Design processes were analysed in order to get an overall picture regarding on which level the processes are typically described and what advantages and shortages the current design processes have. A clear approach, which would include definitions of the steps for rationalising existing product assortment to more a homogeneous modular product family, was not considered in these chosen generic design processes. For this reason, there is a need to focus on the individual approaches in modular product family development and incremental product development in more detail. Until that time, incremental designing is discussed because there are publications in which it is stated that this kind of designing is more common in the industry than new product development.

3.7 Incremental designing in industry

This section discusses incremental designing. In the earlier section the generality of new product designing and incremental designing was discussed briefly. It was found that incremental designing is more common in industry. In this section, more insight and discussion about its importance are presented.

Oja (2010) explains that there are several factors that drive companies to engage in product development. He discusses how the main high-level driver is the continuation of the business by improving its capabilities and competence. This driver includes two general aims, according to Oja:

1. Increasing product value by improving product functions and properties that respond to increases in customer requirements and/or separation from the competitors.
2. Decreasing realisation cost of value and product costs.

It is explained that product design is affected by, for instance, cost pressure, market interest, product appearance, product properties and improvements in technology. Customer dissatisfaction is an obvious reason for product development because of missing or dated product property, quality, usability, reliability, maintainability or design, but the driver can also be recognised as an opportunity, according to Oja. Profitability pressures can also lead to product development because of a decrease in market price, inflation or an increase in production costs, as discussed by Oja.

Oja (2010) explains that most of the development activities in industry are done for existing products and product concepts. He presents the idea that companies have a product history and a product portfolio that is being sold and meets specific needs. Oja also explains that customers typically express their need by referring to products, devices, functions or properties that are based on some existing product or experienced event. Business drivers of the companies aim at development of existing products because new product development includes many risks and a need for a larger investment, although it might enable better market position or profitability, according to Oja. For instance, a new product can create more distrust than confidence. Thus there are fewer risks in operating in a well-known field in which a lot of knowledge is available and it is therefore uncommon that the development would start from scratch. Oja continues by discussing how one common objective in industry is where a delivery project would include, as little as possible, activities in which new things are developed or unknown issues are dealt with. This is because iterations take time and affect negatively on strict schedules. From a product-structuring viewpoint this would mean minimising unique elements in the products, as discussed by Juuti (2008), for example. Oja also suggests that it is beneficial to have other parallel processes in the company in which a platform or new product properties are developed and these would not be as strictly affected by delivery schedules as delivery projects, if possible. Thus these suggestions have similarities to, for example, the approach discussed by Ulrich & Eppinger (2008) in Figure 3.34. If engineering activities are needed in delivery projects, those activities are focused mainly on the development or modifications of existing products rather than on the creation of new solutions in industry according to Oja (2010).

Pugh (1991; 1996) and Oja (2010) discuss dynamic and static designs and concepts. They explain that in the early stages of a product class, there are typically several concepts co-existing but eventually one core concept replaces others. They call this a static design. Thus **incremental product development** is about the further development of sub-systems of static designs. Oja expresses the idea that incremental development starts from an existing product or concept and advances towards an idea and finally into a solution. The main activity is to develop an alternative principle solution for existing functions. It is possible to increase the life cycle of the product by engaging in incremental development and development in technology disciplines with small steps. (Oja 2010)

According to Pugh (1996), dynamic concepts, including the finding of new product ideas, are rare in industry. This kind of approach is needed in situations in which similar or existing concepts cannot fulfil the requirements or needs (Pugh 1996). The term “**radical innovation**” is also used when discussing new products, according to Oja. He discusses how radical innovation includes a difference in an overall concept, if compared to earlier products which have been used for the same purpose. Oja also explains that radical innovation can include new technology or else can refer to when a known technology is used in a new field or context.

As was already discussed in TTS, there are multiple ways to classify products (technical systems). Hubka & Eder (1998) have classified technical systems based on their degree of novelty. This classification includes four classes:

- Re-used technical systems: Standardised and non-standardised parts that exist and are available and can be selected and used without modifications to fulfil certain requirements.
- Adapted technical systems: These are existing technical systems which do not fulfil all the requirements without modifications. However, the core concept of technical system remains unaltered but changes in size, power, speed or other dimensions, or material and manufacturing methods must be made.
- Re-designed technical systems: Conceptual changes are needed. Only functions, some of the parameters and working principles remain unaltered. Form, dimensions, material or technology might be modified.

- Original technical systems: There exists no technical system that fulfils the requirements; thus a new solution is needed.

Based on these categories by Hubka & Eder, incremental designing would mainly consider adapted technical systems and re-designed technical systems.

Hubka & Eder (1996) discussed, in design process knowledge (Figure 3.9 and 3.10), a situation where the designing of a new technical system and the re-designing of an existing technical system exists. Re-designing of an existing technical system has a different focus than in the designing of a new technical system. Knowledge of existing solutions (for instance, manufacturing documentation) and component structures is available in a re-design task and this kind of knowledge can then be used in the re-designing of structures. (Hubka & Eder 1996)

According to Oja, different modifications of Stage-Gate processes (Cooper 2001) are often used in an industrial product development context. However, this model supports more in terms of project management than in the defining of a context for product development activities or technical system, according to Oja. This is the reason why this model hasn't been discussed in the earlier chapter on generic design process. This kind of strict project management model brings about a situation where design methodologies in an industry often have a linear nature because certain design issues, such as specifications, are frozen and the model prevents feedback and iteration loops. Oja has defined that one reason for preventing iteration is the adherence to a schedule along with the avoidance of risks that are included in transforming the predetermined concept using alternative solutions. Thus this kind of operation differs highly from the approaches presented in the literature in which feedback loops, which enable iterations between different steps, are often suggested (for instance VDI 2221). When discussing generic design processes, Oja has noted that these processes do not bring enough support for incremental development, especially in those cases in which several disciplines in the product must be considered. Thus he suggests an approach that would consider interactions and impacts between and within disciplines in more detail in incremental designing, in order to avoid problems with partial optimisation. (Oja 2010)

Oja (2010) has presented the incremental innovation method. The main steps of the method are shown in Figure 3.57. He explains that the core of the method is to analyse the function execution event chain and properties which affect each event in different disciplines and what kind of interactions exist. According to Oja, this method is suitable for finding better concepts that go beyond disciplines in static multi-disciplinary products. Oja states that the aim is also to increase the understanding of the overall system and to facilitate the finding of ideas in a more focused and systematic way than with typical creative techniques. He adds that traditional creative techniques can also be used after the starting point for the idea has been analysed or recognised. At that point, creation and intuition can be guided towards technical context. Oja has defined how the incremental innovation method introduces an alternative approach to the product development process and how it complements the generic design processes by concentrating on static concepts. (Oja 2010)

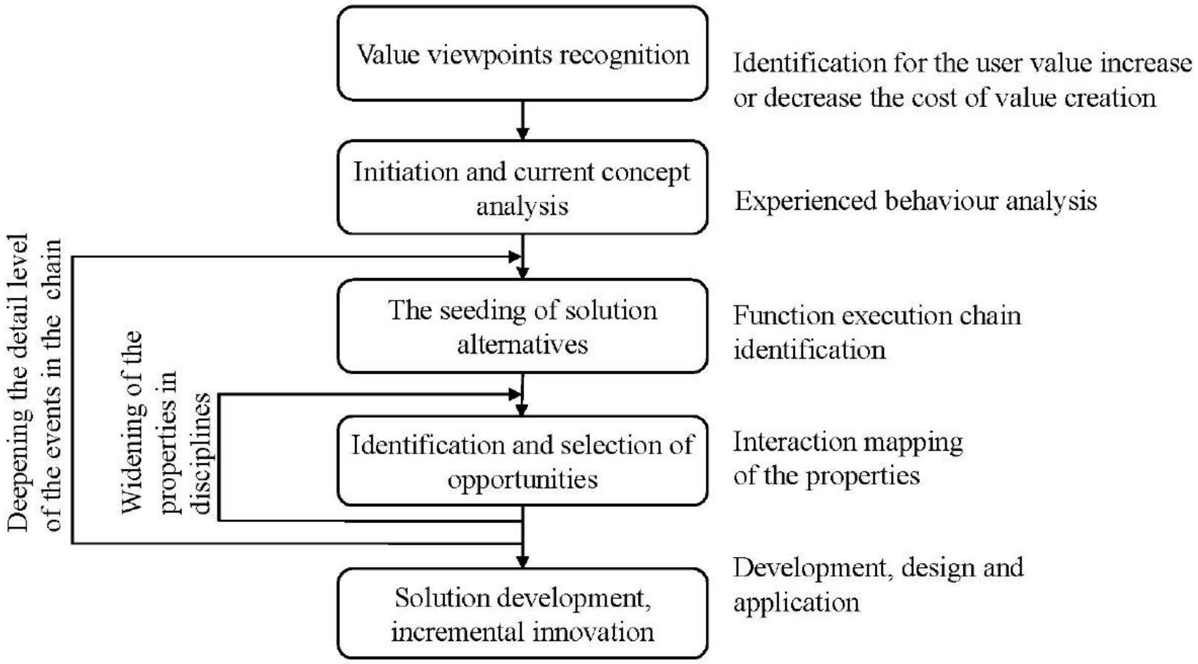


Figure 3.57. *Incremental innovation method (Oja 2010).*

The first step of the method includes recognition of value viewpoints. The aim is to consider value creation. (Oja 2010)

The second step includes analysis of concept. The aim is to gain more understanding about the behaviour of the product in its use environment, according to Oja. The analysis is function oriented. By analysing functional structures, Oja explains that it is easier to recognise opportunities in multi-disciplinary products and in highly integral systems by approaching product development from the direction of sub-systems and their interactions. He also presents this in the analysis; the possible problem of a product is described as its behaviour is experienced. All the systems and technologies that relate to the function execution chain are recognised and analysed. These can include functional structures, mechanical systems with mechanisms, energy and power train systems and control systems, according to Oja (2010).

The third step concentrates on solution alternatives. Oja defines how the function execution chain and events included in the chain and different disciplines are analysed in this step. The aim is also to analyse the types of interactions. These interactions can affect a single specific discipline or else have an effect among several disciplines, according to Oja. The objective of the mapping is to help in deciding whether improvements should be made among different disciplines or if it is enough to only do optimisation in a certain discipline (Oja 2010).

The fourth step of the method presented by Oja discusses identification and the selection of opportunities. Oja suggests that interactions within a concept should be visualised and take into consideration events, disciplines and their properties and type of interactions (within or/and between disciplines). Multidisciplinary mapping should be used in exploring and identifying interactions utilising function execution events and properties in each discipline. The aim of the mapping is to visualise opportunities and indicate interactive properties between two or more disciplines and to help to see possible deviations from an ideal function, according to Oja.

The fifth step considers solution development. It is explained that the development of a different solution principle will happen either by altering the function execution chain or by changing control of events (new sequence). It is also explained that further processing can be done with different concept development methods, such as the 40 inventive principles discussed in TRIZ (Altshuller 2005) or approaches discussed by Pahl & Beitz (1996). Oja also explains that if altering effects only a few organs, properties or control, the term “incremental innovation” can be used. He adds that if the function execution chain changes considerably, then it is radical innovation. (Oja 2010)

The contribution of the incremental innovation method and its background in regard to this thesis is in the recognition of the important role of incremental product development in the industry. For example, Pugh and Oja state that most of the product development activities do not focus on new product development. As discussed in Chapter 3.6 of generic design processes, the quantity of these kinds of approaches focusing on product development; utilisation of existing designs was found to be rather low when compared to approaches focusing on new product development. The method discussed by Oja does not consider directly the issues with variable products such as modularisation, product platforms or product families. Thus the function-orientation of the method is a reasonable approach. Oja states that the aim is to focus on interaction, impact and event chains and to re-design the sub-systems or sub-concepts in areas in which it is beneficial. To conclude, this section supports how design methods in which existing products are used are important and also how the design methods should not focus only on the designing of completely new product families, for example.

3.8 Existing design supports for rationalising of product variety

Different product development and product structuring approaches, tools and methods are discussed in this chapter. The objective is to examine design processes in which existing product designs are used. Furthermore, more emphasis is aimed at product structuring techniques such as modularisation, configuration techniques and product family and platform development. Another objective is to gain more understanding of the state-of-the-art in the core research context of this thesis.

A basic presentation of each approach in Chapters 3.8.1 - 3.8.9 is given and analysis is done concerning how the approach in question contributes to this thesis. In the analysis, the same issues that were already discussed in the chapter on product development processes are considered. Thus, the focus is in analysing how objectives and/or requirements are defined for the products and on what kinds of suggestions have been presented for the designing of product structure utilising variability and commonality. Thus, design re-use, re-designing, standardisation, modularisation, configuration, platform and product family issues are observed in this chapter from the various publications. At the end of the chapter, a conclusion of the current state of methodologies is presented.

3.8.1 Riitahuhta & Andreasen: Dynamic modularisation

Ulrich & Eppinger (2008) discussed the fact that different platforms are valid only for a certain time. This issue has also been studied by Riitahuhta & Andreasen (1998). They discuss Dynamic Modularisation (Dymo) and the importance of the life cycle as a one-dimension in modularisation. With the life cycle they consider adding new modules and leaving out old modules from the module assortment. Lehtonen et al. (2003) also discuss Dymo. The Dymo framework has been presented in Figure 3.58. They explain further that product development can take place at the platform development level (upper level) and at the product creation level (lower level). They state that platform development includes customer requirement management, product architecture management and the development and module creation process. Lehtonen et al. define product platform and product family in the following way in this context:

“A ***product platform*** *enables launching a* ***product family*** *that consists of modules developed in the platform development level and that corresponds to certain market needs now and in predictable future.”*

Lehtonen et al. (2003) explain that one aim in this model is to maximise design re-use and in this way shorten the development time of single products and increase the efficiency of product development. Figure 3.58 shows the principles of how products are made in Dymo. Product creation in Dymo doesn’t include actual development work, according to Lehtonen et al. (2003). They argue that the product creation work is an integration of the modules and does not include the development of completely new designs.

The product creation process in this model starts with defining business and market needs, which can be defined using feature or product roadmaps (plans for/of the future) and can include product categories or portfolios (bottom left corner in Figure 3.58). Lehtonen et al. highlight the fact that requirement management is a continuous process and more complex than in single product development because the requirements must be considered from the perspective of the whole module system.

System-level product architecture is developed next (“A” in Figure 3.58). Lehtonen et al. (2003) state that the architecture considers the modules that can be used and their interfaces. In this way, as defined in Figure 3.58, architecture and its module structure provide the capabilities of the platform and thus enable the defining of the features and other properties, which are available in a specific configuration of a platform release.

Lehtonen et al. (2003) discuss how module releases (“Subsystem” rows in Figure 3.58) are made of this common platform architecture. Thus this framework has similarities with, for example, the suggestion made by Holmqvist (2004). He explains that the same product architecture for all variants simplifies the part sharing between the variants. Lehtonen et al. discuss the fact that modules are developed against business needs and that they serve product programs.

The authors of Dymo explain that the modules should be encapsulated using well-defined interfaces in order to reduce the complexity of managing the platform. Lehtonen et al. (2003) also discuss how the flexibility of the module structure can be increased if interactions between the modules are minimal.

The final products are made by selecting and integrating the suitable modules from the subsystem releases according to customer requirements. Subsystem releases also have architectures of their own, as illustrated in Figure 3.58.

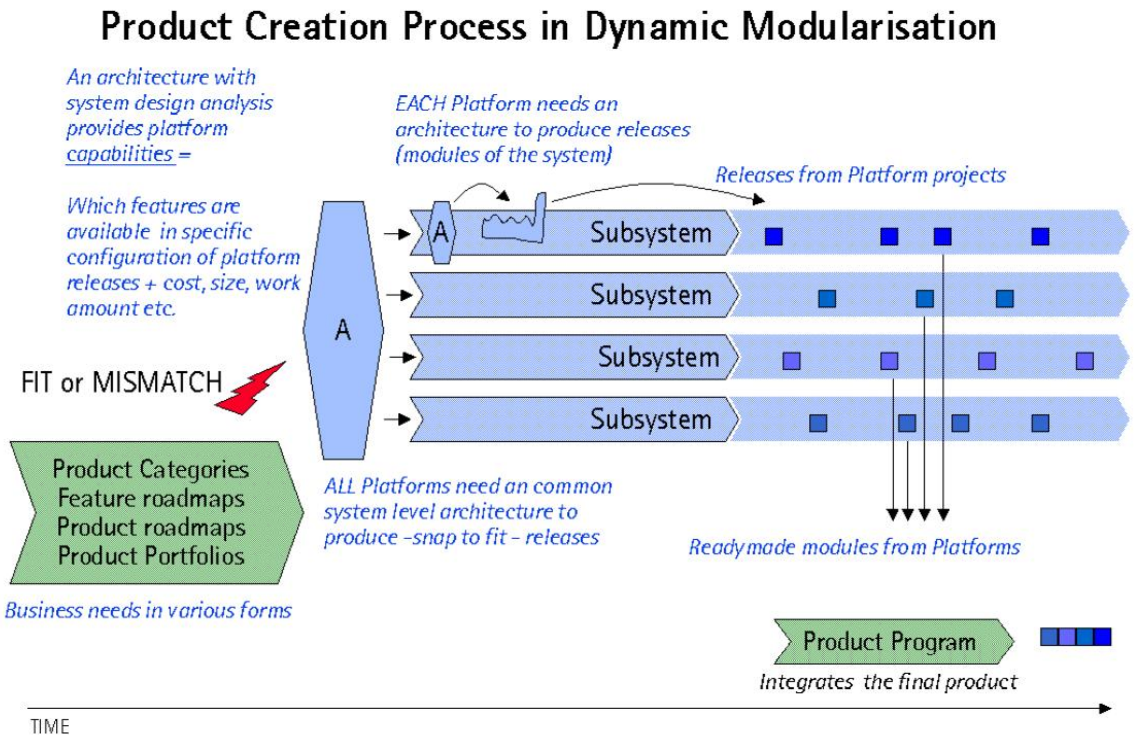


Figure 3.58. An example of the platform-driven product creation process known as Dynamic Modularisation. Dynamic Modularisation illustrates the relationship between business needs, architecture, module development and product creation from the modules. (Lehtonen et al. 2003)

What makes Dymo a non-static model? According to Lehtonen et al. (2003), the module has a life cycle that considers when the module is available and for how long. It is stated by the same authors that the strategic or competitive reasons such as new technology can affect the modules and the architecture. Lehtonen et al. (2003) argue also that the platform module structure doesn’t need to be static in order to be manageable and beneficial to the company, but that the dynamic nature of this kind of modularisation can make verification of the module system challenging. Thus it is stated that Dymo is suitable for only small partitions of companies because of challenges related to processes, communication, competences and product structure.

Lehtonen et al. (2003) explain that there needs to be designers with different kinds of roles in Dymo, such as designers who plan the re-use of modules and their compatibility and define the needed configurations as part of product family level planning. The authors explain that the decisions made in the product family or at the platform level affect multiple people and thus in the decision making process the voice of relative people should be heard.

Lehtonen et al. (2003) discusses that in order to manage the dynamic architecture, support systems must consider the link between business needs (requirements management) and architecture and module development. Support systems should enable working with an imperfect platform product model, considering which modules and structures are ready and which are not. Thus version management is important if dynamic architectures are developed. It should enable the relating of the specific versions of modules to the specific needs. (Lehtonen et al. 2003)

Dymo can be considered as a high-level architecture-oriented framework for product creation. Although Dymo does not have a detailed methodological structure, it gives support in highlighting the importance of architecture as an enabler of effective product creation and the role of platform versions as providers of future elements for product creation. Product creation as discussed in this approach has clear similarities to definitions of configuration. Thus this approach highlights the fact that effective product creation does not include design work in the order or sales-delivery process, but includes only a selection of suitable solutions that the architecture enables.

3.8.2 Lehtonen: Design process for new modular product architecture

Lehtonen (2007) presents a design process for the development of new modular product architecture. The process follows the phases of the V model of Systems Engineering as presented in Figure 3.59.

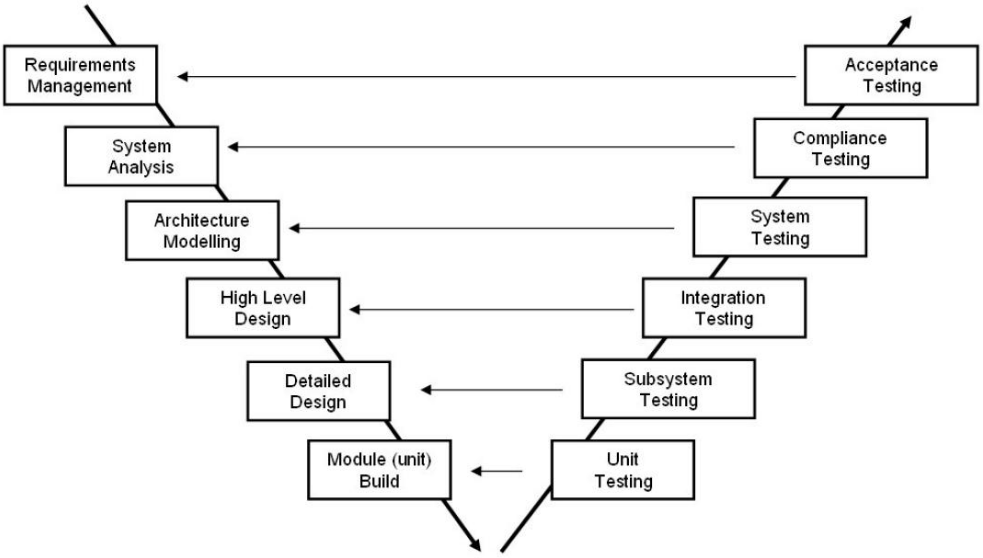


Figure 3.59. *Steps of the V model of Systems Engineering according to Lehtonen (2007).*

Based on the elements presented in the generic V model above, Lehtonen (2007) has described eleven steps of the design process of new modular product as follows. This process model is presented in Figure 3.60.

1. The value chain and production process analysis which produces **the requirements for the modular structure** ("Requirements Management" and "System Analysis" in the original V model shown in Figure 3.59).
2. The system-level description of the modular system to be founded on the requirements stated in the first step. The description is called **the target architecture of the modular system** ("Architecture Modelling" in the original V model). In the next phases **modular architecture** is designed.
3. Development of individual modules according to the process of systematic design. **Concepts and solution principles of modules** are created first ("High Level Design" phase in the original V model).
4. **Module preliminary layouts** are selected for the systematic design ("Detailed Design" phase in the original V model). This phase is critical from an implementation of the modular structure point of view, because the decision in selecting will affect

whether requirements for the modular structure can be fulfilled with the chosen technology or not. Thus there might be a need to return to previous phases.

5. **Module definitive layouts** include structural designing of modules (“Module (unit) Build” phase in the original V model). In this phase, the modularity of the product may be reduced but not increased because of the possible need for adding elements and dividing individual parts into a number of parts, as discussed in analysis of systematic design process from modularisation perspective (phases 5 and 6 in the systematic design process: “Establish Dimensional Layout” and “Detailing, elaboration”).
6. **Module testing** ensures that functionalities of the modules fulfil the requirements (“Unit testing” in the original V model).
7. **Module integration tests** ensure that individual modules can be integrated and meet the requirements (“Subsystem testing” in the original V model).
8. **Product variant test** ensures that the integration of product belongs to a product family (“Integration testing” in the original V model).
9. **Checking the module systems ability to produce the required variants** includes testing related to the module system’s ability to produce other required variations (“System testing” in the original V model).
10. **Validation of module system against business goals** ensures that variants meet the requirements of the business environment (“Compliance testing” in the original V model).
11. **Acceptance** includes decisions of proceedings with the implementation of the product range (possibly as a platform). This is a case-specific task typically done by corporate management. (“Acceptance testing” in the original V model). (Lehtonen 2007)

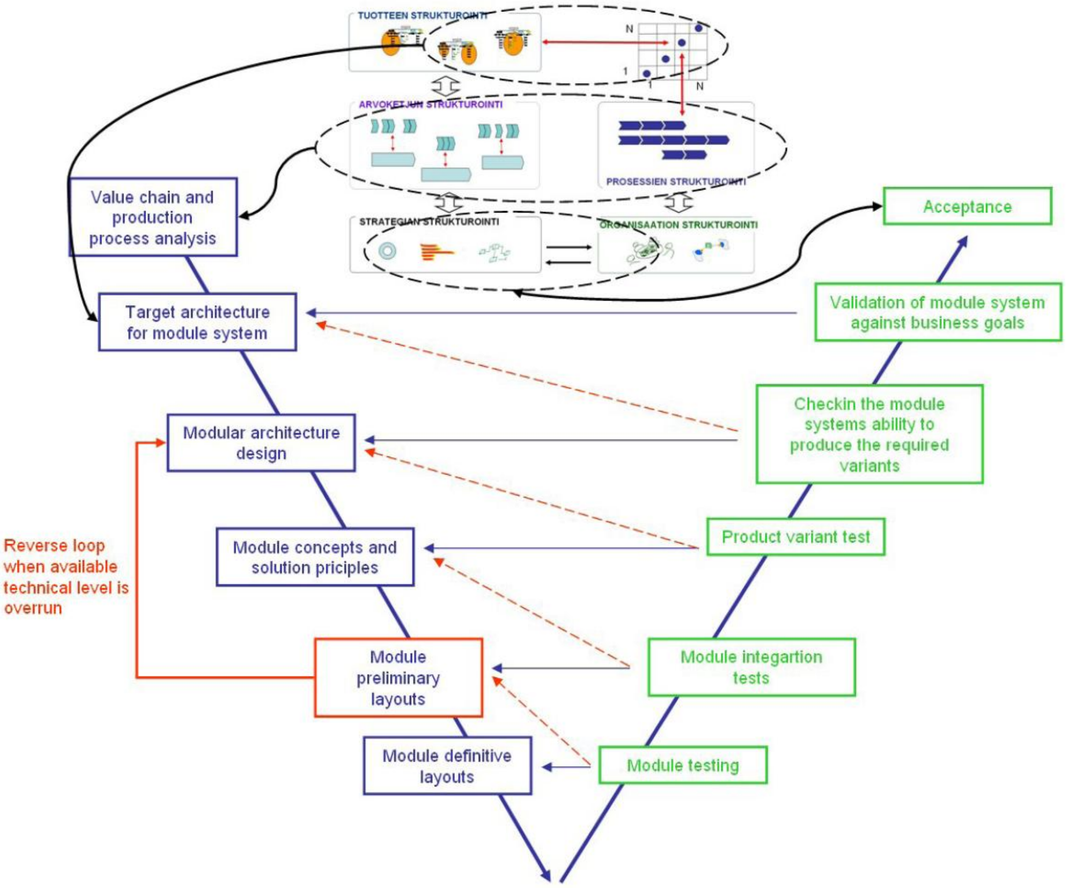


Figure 3.60. *The design process of a new modular product. (Lehtonen 2007)*

As shown in Figure 3.60, Lehtonen (2007) concludes that the first and the last step could be performed using the CSL framework. He also argues that concrete tools are missing for this kind of analysis and also that other working steps in the context of Systems Engineering are lacking usable tools compared to the systematic design process. Thus Lehtonen states that a systematic design process could be used in the micro cycles of the proposed process (macro cycle is the whole V model). Although the process discussed by him aims at developing new modular products, Lehtonen has also discussed issues related to re-use of existing structures in modularisation. This is shown in Figure 3.61.

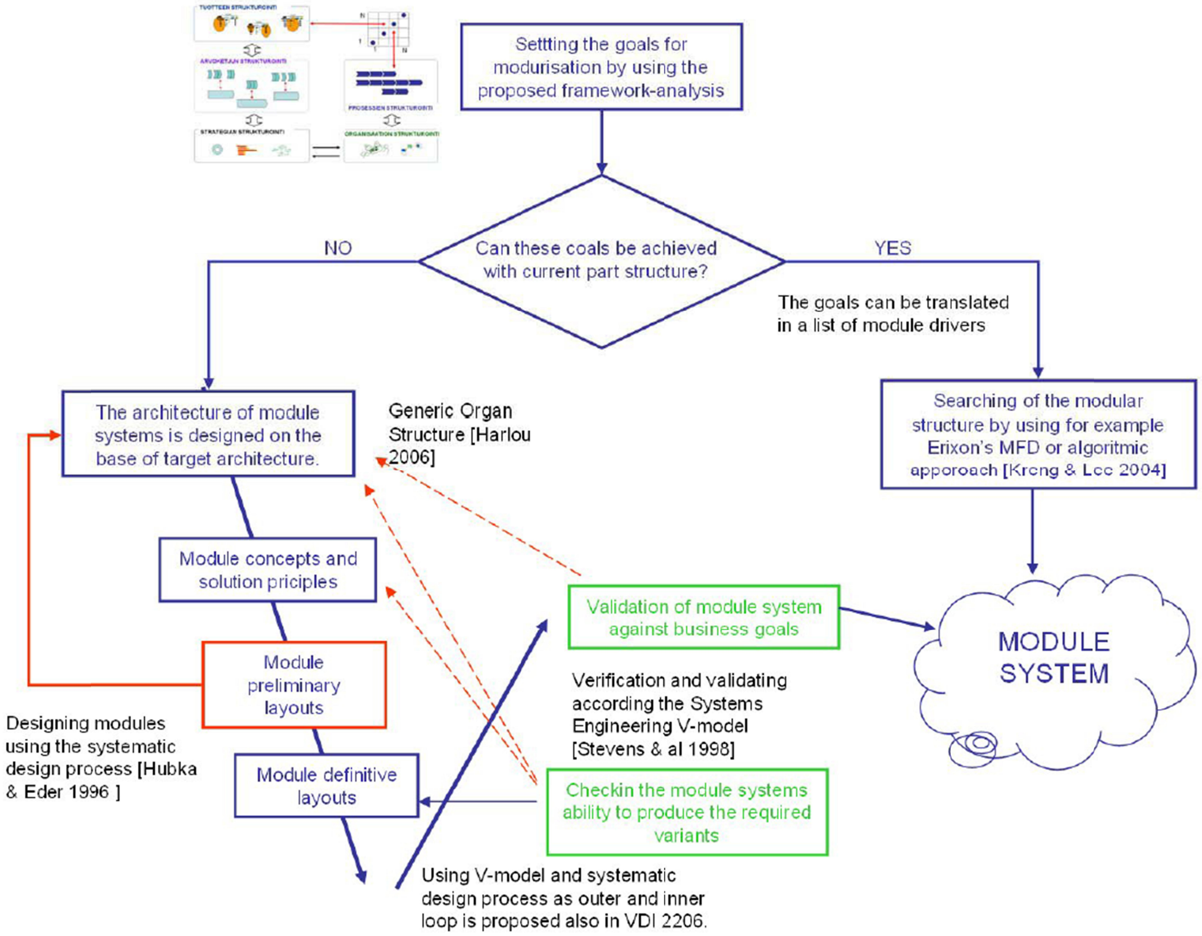


Figure 3.61. *Lehtonen (2007) states that goal setting uncovers whether modularisation can be done utilising current part structure or if completely new solutions are needed. Thus he suggests that the approach presented by him could be used in the latter case and in the former case there could be other approaches, of which Modular Function Deployment is given as an example.*

Lehtonen explains that the designing of a new product using a process that considers functional and organ structures means that in establishing these structures, favouring of a specific method of implementation is avoided. The focus is on seeking out sub-functions for supporting the overall function or transformation and also on seeking out abstract solutions in the organs, as Lehtonen stated. This principle can be seen in, for instance, the books by Hubka et al. (1988) and Pahl & Beitz (1996). To conclude, in a design situation in which the design process of a new modular product is used, the systematic design process can be used in the designing of single modules (but not in the designing of the whole module structure), as presented in Figure 3.61 by Lehtonen. The process steps of the systematic design process emphasises the seeking of several alternative solution principles and then selecting the most suitable one from these alternatives against the criteria based on the requirement list. This can be seen by analysing the explained guidance of tools proposed in the systematic design process. It can be stated that if the design situation focuses on the re-use aspects of current part structures, as discussed on the right hand side of Figure 3.61, there could be alternative methods and tools with guidance to be applied. Thus MFD is discussed in the next section. In the later sections, the role of algorithmic approaches is also discussed.

3.8.3 Ulrich: Designing of modular architecture

Some of the approaches in which Ulrich has been involved were discussed in Chapter 3.5.6 on modularisation and in Chapter 3.6.2, in which the publication on Product Design and Development by Ulrich & Eppinger was studied. Ulrich (1995) discusses key points in the defining of modular architecture. He presents the idea that this process includes three main points:

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

When compared to the discussion presented in Chapter 3.6.2 on the defining of architecture, the suggestions made in this approach by Ulrich (1995) can be seen as more function-oriented. He explains that the result of the first step is function structure. The second step focuses on mapping from functional elements to physical components (parts or sub-assemblies), according to Ulrich. He explains that modular architecture has one-to-one mapping from functional elements to physical components. The third step involves specifying the interfaces. Ulrich explains that interfaces may involve geometrical connections or non-contact interactions such as wireless communication. He continues by explaining how interface specification defines the protocol for the primary interactions of component interfaces and this should explain mating geometry, including dimensions, positions and sizes of the contact surfaces and maximum forces that it must sustain. Ulrich also adds that interfaces can be standardised across many different manufacturers and suggests de-coupling interfaces in order to manage changes if changes to one component are made.

To conclude, the approach by Ulrich is function-oriented and is thus not considered as a solution for the research problem based on the discussions made in Chapter 3.5.6 on modularisation in which a function-oriented starting point was considered possible but not necessarily optimal in every case. Aside from the starting point in the approach by Ulrich, it also includes potential suggestions. Issues related to interface definition are justified and thus applicable for considerations of the design support.

3.8.4 Erixon: Modular Function Deployment

Erixon (1998) presents a systematic method and procedure for product modularisation known as Modular Function Deployment (MFD). The MFD includes five main steps, which are shown in Figure 3.62.

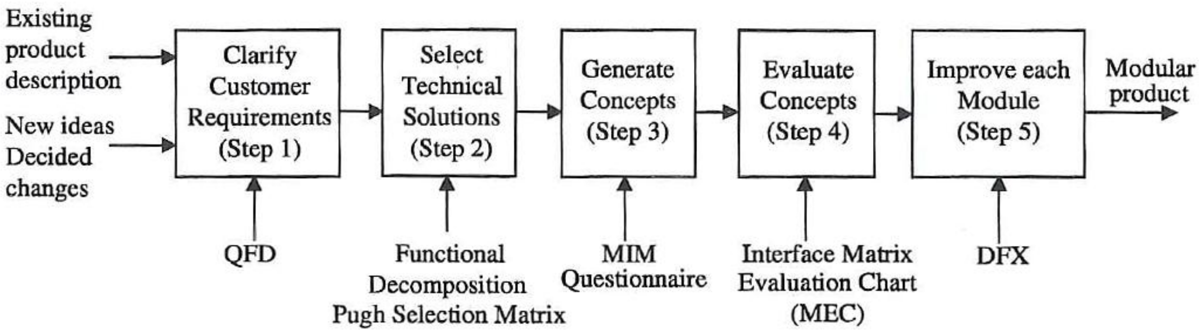
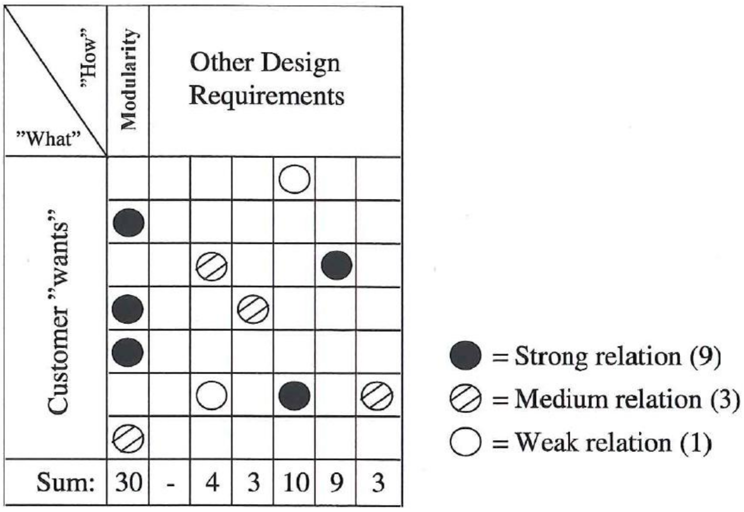


Figure 3.62. *Erixon (1998) discusses the Modular Function Deployment (MFD) method, including five steps.*

As described in Figure 3.62, descriptions of existing products, new ideas and planned changes can be an **input** for the process. The above figure also presents how each step includes tool suggestions. The steps of the process are described as follows, according to Erixon (1998).

Step 1 includes clarification of customer requirements and the formulating of a specification of the product. Erixon suggests Quality Function Deployment (QFD) (see e.g. Hauser & Clausing 1988 for more information about QFD's main tool house of quality) for this step. In the QFD matrix by Erixon, modularity is the first design requirement, in order to remind us of its importance to the design team. This is illustrated in Figure 3.63. Erixon suggests that clarity and measurability should be considered when defining the requirements for the development project. The first step results in relation mapping between customer and design requirements.



"How" / "What"	Modularity	Other Design Requirements					
Customer "wants"					○		
	●						
			▨			●	
	●			▨			
	●						
			○		●		▨
	▨						
Sum:	30	-	4	3	10	9	3

● = Strong relation (9)
▨ = Medium relation (3)
○ = Weak relation (1)

Figure 3.63. *The QFD matrix is used for defining relations between design requirements and customer wants. (Erixon 1998)*

Step 2 includes the selecting of technical solutions. Erixon suggests functional decomposition with the defining of technical solutions. He describes how technical solutions can be understood as function carriers, organs, means, design parameters etc. He also notes that the formulation of functions and solutions must not become a goal in itself. It is explained that prerequisites for robust modular solution are minimal interactions between modules. Erixon explains that there are different tools available that can be used in describing the relations between functions and technical solutions. For instance, matrices and functions and a means tree are noted. Figure 3.64 shows an example of functions and a means tree by Erixon. Thus this approach has clear similarities to approaches discussed by Pahl & Beitz (1996), in which function structure is created and then solution principles are sought for these sub-functions.

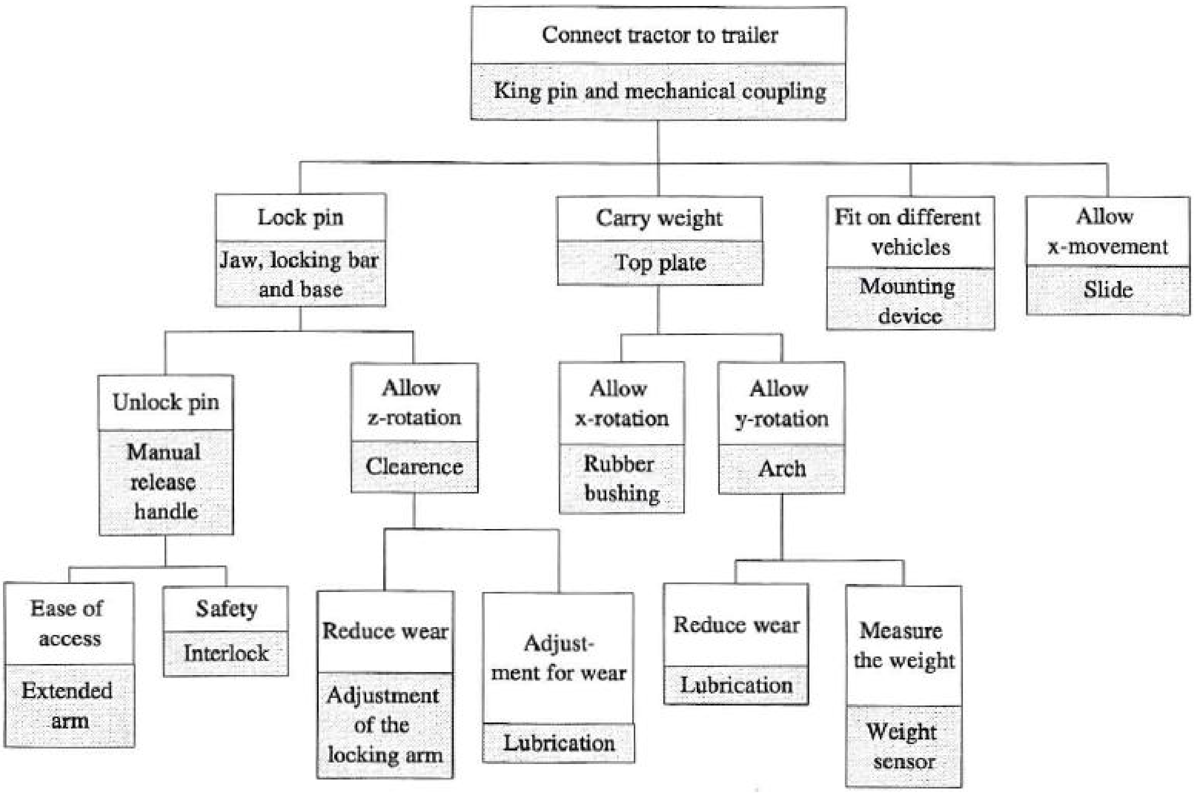
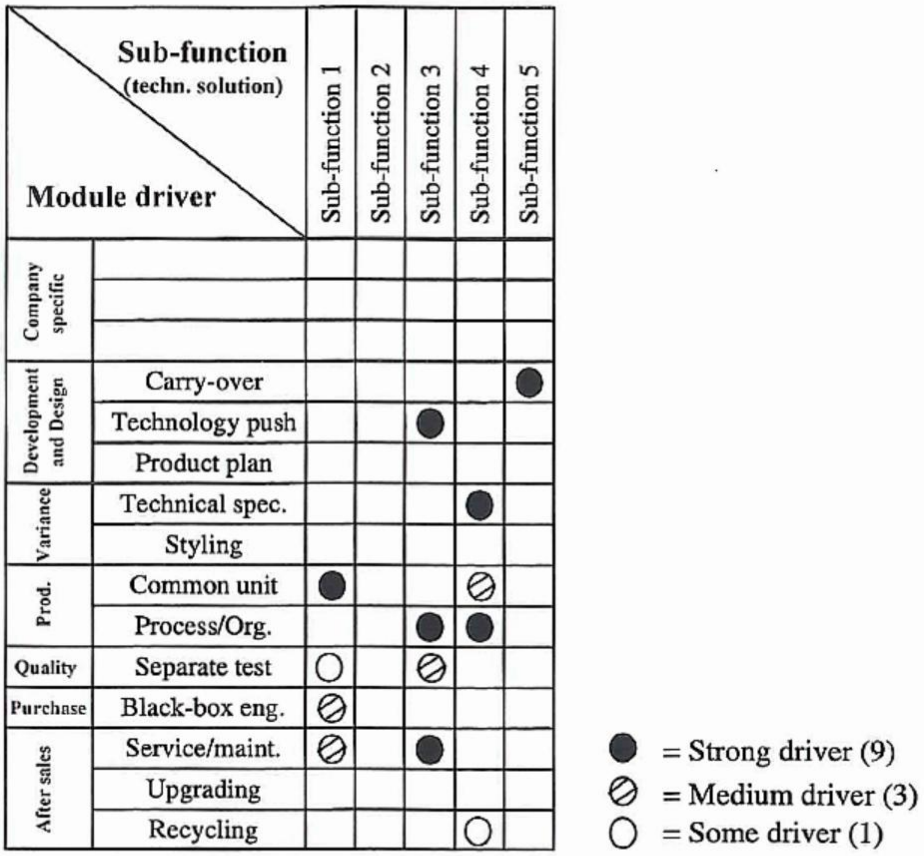


Figure 3.64. *Example of functions and means tree. (Erixon 1998)*

As a guideline, Erixon suggests the identification of sub-functions that all customers want and sub-functions that are not required by every customer. Thus this approach also tries to recognise the section that could be standardised in the products. The integration of one or more sub-functions is not suggested at this step. The reason is that integration is discussed in later steps containing a broader view of modularity, according to Erixon. The Selection Matrix (Pugh 1991) is suggested for evaluation of solution alternatives for different functions. In that matrix, one alternative is chosen as a reference and the rest of the alternatives are compared to the reference. The MFD suggests considering production requirements in the selection of solution alternatives.

Step 3 focuses on the generation of concepts. Module drivers are discussed in this step. These were presented earlier in Chapter 3.5.6 (Modularisation) in this thesis. Erixon presents that module drivers can be used as a basic criteria for the evaluation of sub-functions, as shown in Figure 3.65. As Erixon mentions, sub-functions are already considered in this step as technical solutions. He discusses how this evaluation is independent for each sub-function and shows which of the technical solutions have the urge for modularity and which do not. For facilitating the evaluation, Erixon has presented a questionnaire in which each of the module drivers is gone through by answering a question with three options. This questionnaire can be seen in Table 3.12.



Module driver		Sub-function (techn. solution) Sub-function 1	Sub-function 2	Sub-function 3	Sub-function 4	Sub-function 5
Company specific						
Development and Design	Carry-over					●
	Technology push			●		
	Product plan					
Variance	Technical spec.				●	
	Styling					
Prod.	Common unit	●			⊘	
	Process/Org.			●	●	
Quality	Separate test	○		⊘		
Purchase	Black-box eng.	⊘				
After sales	Service/maint.	⊘		●		
	Upgrading					
	Recycling				○	

● = Strong driver (9)
⊘ = Medium driver (3)
○ = Some driver (1)

Figure 3.65. *Evaluation of sub-functions against the module drivers in Module-Indication-Matrix (MIM). (Erixon 1998)*

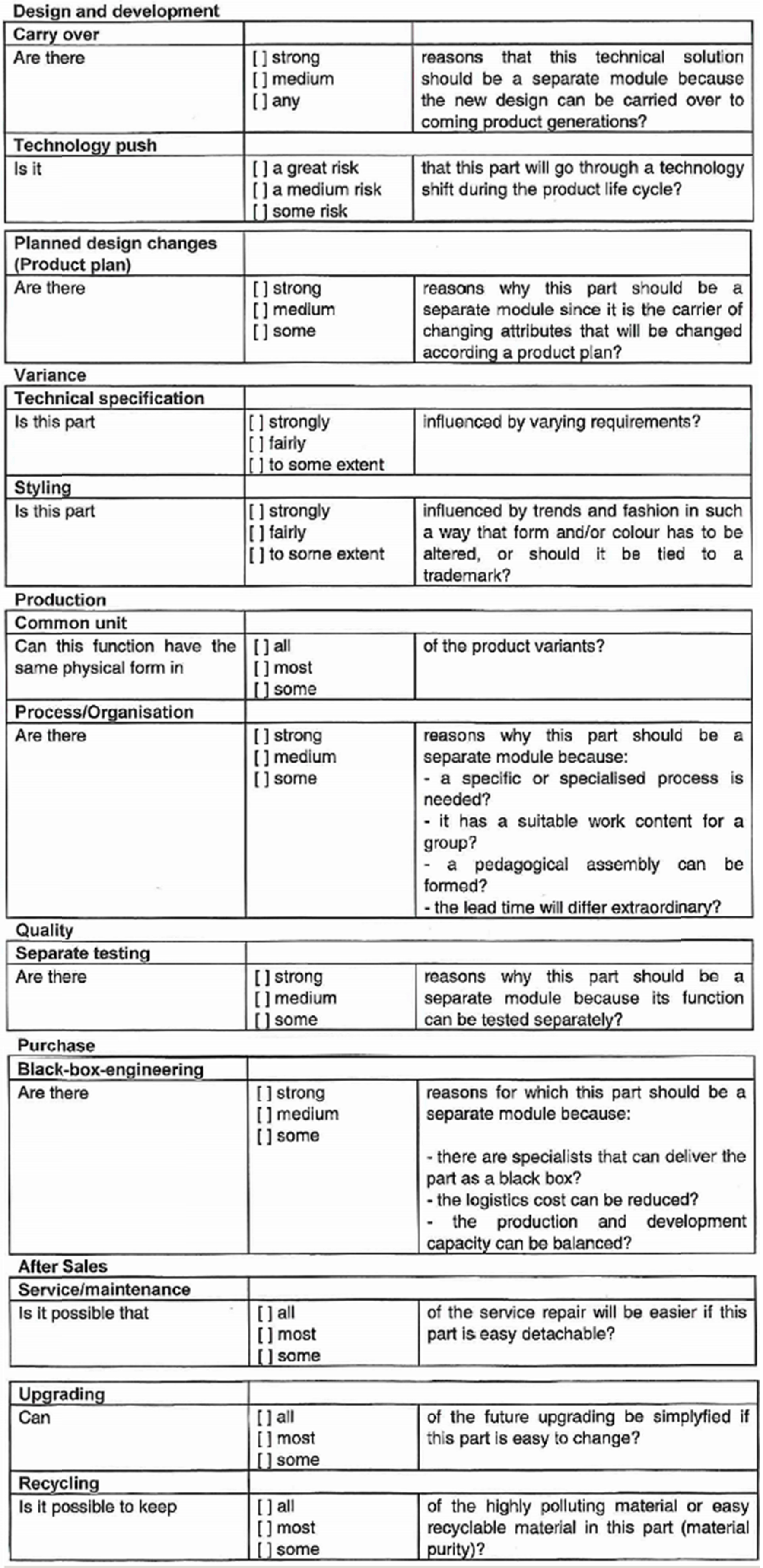
Erixon gives guidelines for interpretation of the evaluation chart from a technical solution viewpoint:

- If there are several highly weighted drivers: Consider technical solution as a likely module or the basis for module.
- If there is unique module driver pattern: Consider technical solution as a single sub-function.
- If there are few and/or low weighted module drivers: Consider technical solution to be integrated or grouped with other sub-functions or technical solutions if there is no module driver, spatial and technical contradictions.

If sub-functions have the same module drivers, an integration or grouping should be thought of. If sub-functions have contradictory module drivers, integration or grouping should be avoided, according to Erixon.

Erixon states that a great deal of knowledge regarding the company and its products is needed in this step. He also reminds us that filling out matrices is not the primary goal but that these can be helpful in decision making for the development team.

Table 3.12. *Supporting questionnaire for the MIM by Erixon (1998).*



Design and development

Carry over		
Are there	[ ] strong [ ] medium [ ] any	reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations?
Technology push		
Is it	[ ] a great risk [ ] a medium risk [ ] some risk	that this part will go through a technology shift during the product life cycle?

Planned design changes (Product plan)		
Are there	[ ] strong [ ] medium [ ] some	reasons why this part should be a separate module since it is the carrier of changing attributes that will be changed according a product plan?

Variance

Technical specification		
Is this part	[ ] strongly [ ] fairly [ ] to some extent	influenced by varying requirements?
Styling		
Is this part	[ ] strongly [ ] fairly [ ] to some extent	influenced by trends and fashion in such a way that form and/or colour has to be altered, or should it be tied to a trademark?

Production

Common unit		
Can this function have the same physical form in	[ ] all [ ] most [ ] some	of the product variants?
Process/Organisation		
Are there	[ ] strong [ ] medium [ ] some	reasons why this part should be a separate module because: - a specific or specialised process is needed? - it has a suitable work content for a group? - a pedagogical assembly can be formed? - the lead time will differ extraordinary?

Quality

Separate testing		
Are there	[ ] strong [ ] medium [ ] some	reasons why this part should be a separate module because its function can be tested separately?

Purchase

Black-box-engineering		
Are there	[ ] strong [ ] medium [ ] some	reasons for which this part should be a separate module because: - there are specialists that can deliver the part as a black box? - the logistics cost can be reduced? - the production and development capacity can be balanced?

After Sales

Service/maintenance		
Is it possible that	[ ] all [ ] most [ ] some	of the service repair will be easier if this part is easy detachable?

Upgrading		
Can	[ ] all [ ] most [ ] some	of the future upgrading be simplyfied if this part is easy to change?
Recycling		
Is it possible to keep	[ ] all [ ] most [ ] some	of the highly polluting material or easy recyclable material in this part (material purity)?

Step 4 concentrates on the evaluation and selection of concepts. Interfaces are considered as a highly important topic in this step. Erixon recognises three types of interfaces: fixed, moving and media transmitting. He has also identified two types of assemblies from an interface viewpoint: base part and "hamburger" assembly. Base part assembly has parts around the base part whereas in "hamburger" assembly, the parts are on top of each other. Erixon has built a matrix to demonstrate this issue. This is shown in Figure 3.66.

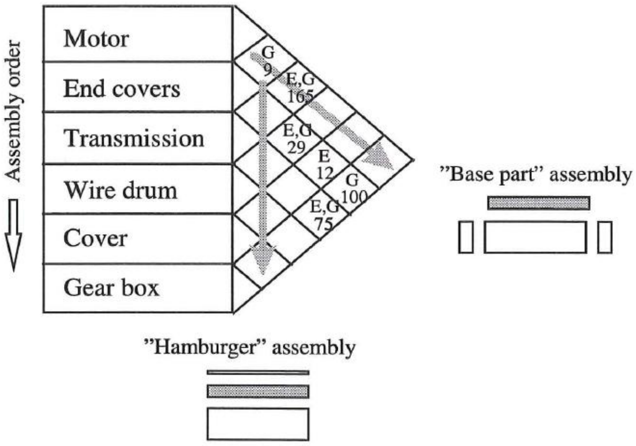


Figure 3.66. *Erixon (1998) suggests evaluation of interfaces from assembly perspective. 'E' defines that there are moving and/or media transmitting interfaces whereas 'G' stands for fixed or geometric interfaces. The objective is that there would only be relations that are aligned with arrows. Markings outside the arrows are not desired and should be avoided. These are considered as a potential for improvement. Numbers in this figure are estimated assembly times, according to Erixon.*

Erixon states that economy is another important aspect in this step. He has identified ten effects – product characteristics and metrics/rules for a life phases of development, assembly and sales and after sales that can be used for evaluating a good modular design, according to him. These are presented in Table 3.13 and discussed briefly in the following.

Table 3.13. *Proposal by Erixon for evaluation of modular design. (Erixon 1998)*

Effects (life phases)	**Product Characteristics**	**Metrics/rules**
Development		
1. Lead time in development	Interface complexity	Metric
2. Development costs	Share of carry over	Rule
3. Development capacity	Share of purchased modules	Rule
Assembly		
4. Product costs	Assortment complexity	Metric
5. System costs	Share of purchased modules	Rule
6. Lead time	Number of modules in product	Metric
7. Quality	Share of separately tested modules	Metric
Sales/After sales		
8. Variant flexibility	Multiple-use	Metric
9. Service/Upgrading	Functional purity in modules	Rule
10. Recyclability	Material purity in modules	Rule

Referring to Table 3.13, Erixon explains that **lead time in development** decreases if there is the possibility to work in parallel. He continues explaining that easily specified and fixed interfaces make it possible to develop modules independently. It is also noted that when the information flow between different design groups is minimal, possibilities for shorter development times are enabled. According to Erixon, interface specification should consider form, fixation principles, contact surfaces and attachments, energy connection points, material flow and signals. Erixon defines how it is possible to reduce the **development costs** if the share of carryover parts is increased. This means more re-use of available assets. He also states that **development capacity** can be affected by the share of purchased modules. Erixon discusses the fact that the minimum number of modules and interfaces that fulfil customer needs is a good objective because **product costs** are strongly dependent on the number of articles, modules and complexity of module assortment, in addition to material, tool and fixturing costs. Erixon states that an increased number of purchased modules decreases **system costs**. Purchasing of modules can, for instance, be a strategic decision because of capacity issues. If the number of vendors, different parts and complexity increases, assembly supporting costs typically increase because of relations to different functions such as purchasing, production planning, quality control, production engineering and logistics. Erixon also focuses on the assembly issues because he states that assembly has a strong relation to overall **lead time**. He notes that the lead time in assembly is dependent on the number of modules. He has made estimates of the ideal number of modules, which is calculated with the help of the number of parts in a complete product and the relation between the average assembly time on the final line for one interface between modules (T_{int}) and the average assembly time for one part (T_{norm}). This is shown in Figure 3.67. (Erixon 1998)

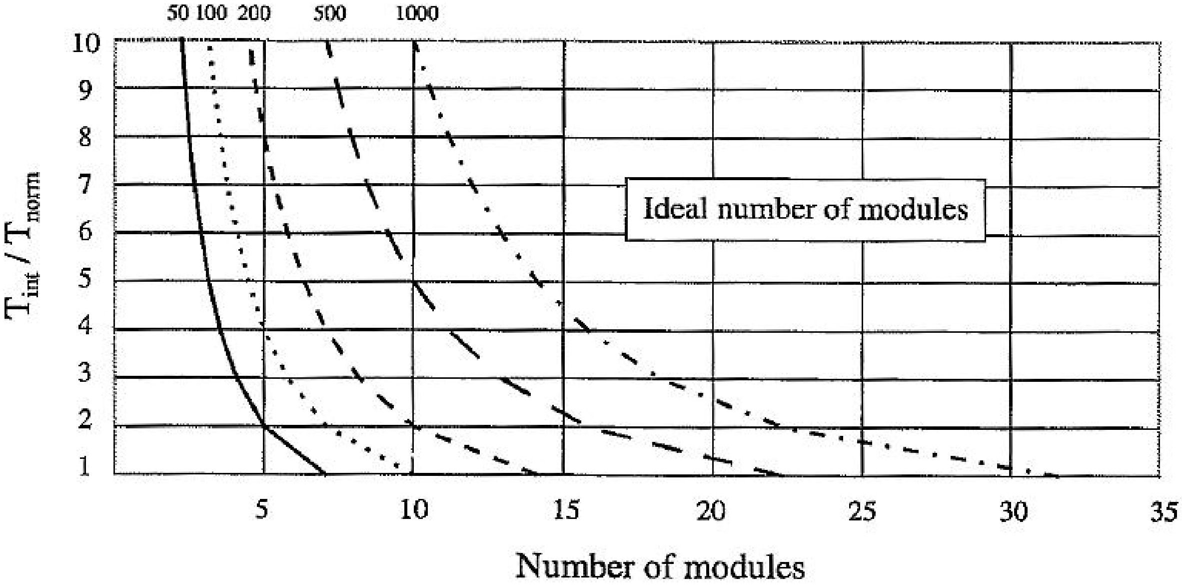


Figure 3.67. *Erixon has given an estimate of the ideal number of modules in the product from an assembly perspective. (Erixon 1998)*

Erixon explains that the best **quality** can be achieved if all modules are separately tested. Separate testing has shorter feedback loops than in the testing of fully assembled products. This increases the overall quality of the assembly system, according to Erixon. He also defines how the **flexibility** of the module assortment can be evaluated by calculating how many variants can be achieved by a certain number of modules. The bigger the relation is, the more similarities can be found from the products. More similarities mean less settings and tools needed in the production of modular products, according to him. Erixon highlights the fact that if modules are functionally independent, they are more easily interchangeable. As a final evaluation aspect, he discusses **recyclability**. This is strongly affected by the number of different materials in the product according to Erixon (1998).

Step 5 of the MFD considers the improvement of each module. Erixon proposes that the MIM could be used in this step because important drivers affecting each module can be checked with its help. As a generic suggestion, the minimising of a part number is discussed by Erixon. In this final step, the documentation of modules is also done. Documentation should at least include the names of the modules, their targets, responsibilities, technical solutions (the MIM), interfaces (interfacing with, type of interface) and other considerations, according to Erixon.

To conclude, several aspects of the design process are considered in the MFD. The method considers the design process of a modular product in which existing products are used. The MFD has strong function-orientation for modularisation. In this method, a product is considered as a functional decomposition consisting of separate sub-functions. Thus, sub-functions and related technical solutions are a premise for modularisation and those can be considered as initial module candidates. The objectives for the modular product are considered by analysing the relevance of different generic module drivers for each technical solution. Consequently, initial modules that are formed based on the functional structure are refined according to these relations. The aim in this approach is to develop a rational module division which does not include conflicts between relevant module drivers. It is stated that there might be a need for the reorganising of technical solutions by, for instance, grouping them differently. Thus it can be said that the MFD is not a strict function-oriented modularisation approach. Based on the issues discussed in Chapter 3.5.6 of Modularisation, this function-oriented approach cannot be considered as an answer to the research question of this thesis in itself, although the MFD includes several interesting and well defined areas. An analysis of interfaces from an assembly viewpoint is suggested as one way of finding improvement sections within the product. This is relevant if benefits could be achieved via assembly by modularisation.

3.8.5 Krause et al.: Integrated PKT-approach

The integrated PKT-approach for the development of modular product families has been discussed in several publications such as Krause & Eilmus (2011), Eilmus et al. (2012) and Krause & Ripperda (2013). It is explained that the overall goal of the approach is to reduce internal variety for the company and enable the offering of optimised external variety to customers. Figure 3.68 presents the approach. According to these authors, the approach includes two methods – Design for Variety and Life Phases Modularization. Krause & Ripperda explain that other method units shown in Figure 3.68 are under development.

Eilmus et al. (2012) presents that the approach includes eight steps, of which steps 1-6 consider Design for Variety and steps 7-8 Life Phases Modularization:

- Step 1: Analysis of external variety using tree of variety
- Step 2: Analysis of variant functions generating a product family function structure
- Step 3: Analysis of variant components drawing the Module Interface Graph
- Step 4: Analysis of variant working principles
- Step 5: Allocation of variant elements (steps 1-4) and derivation of variety-optimised component concepts using the Variety Allocation Model

- Step 6: Evaluation and choice of new product family concept
- Step 7: Identification of life phases-specific module drivers
- Step 8: Modularisation over all life phases using the Module Process Chart

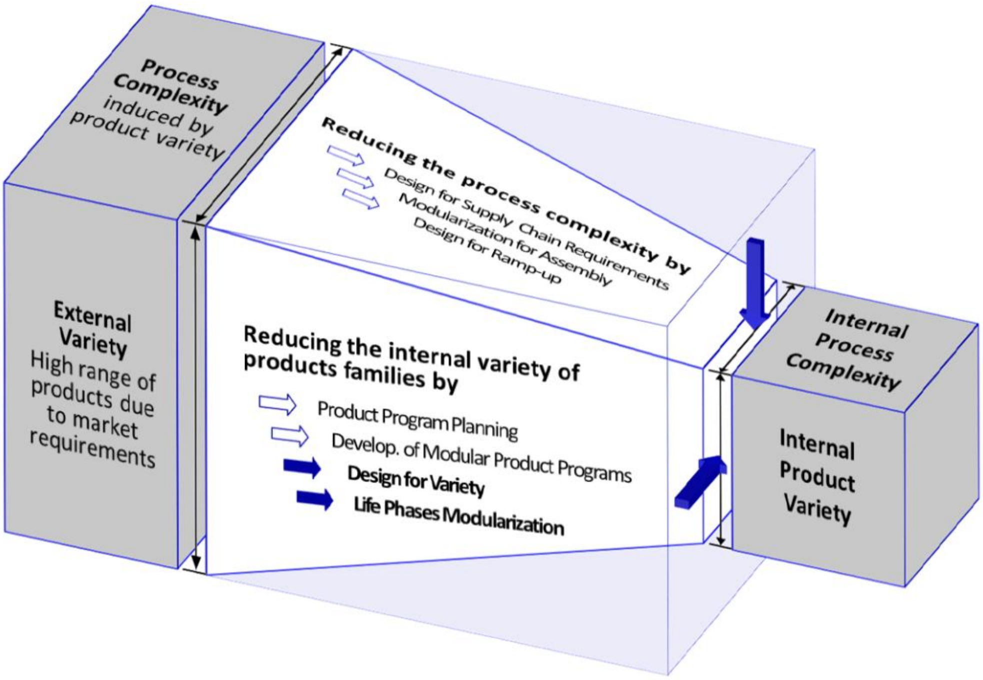


Figure 3.68. *The Integrated PKT-approach for developing modular product families. (Krause & Eilmus 2011)*

As the names of the steps demonstrate, the Integrated PKT-approach includes multiple tools. Eilmus et al. (2012) explain that the tree of variety can be used in visualising the external variety in **Step 1**. They explain that the aim is to show customer-perceived differentiating attributes and all product variants. Figure 3.69 shows an example of the tree of variety.

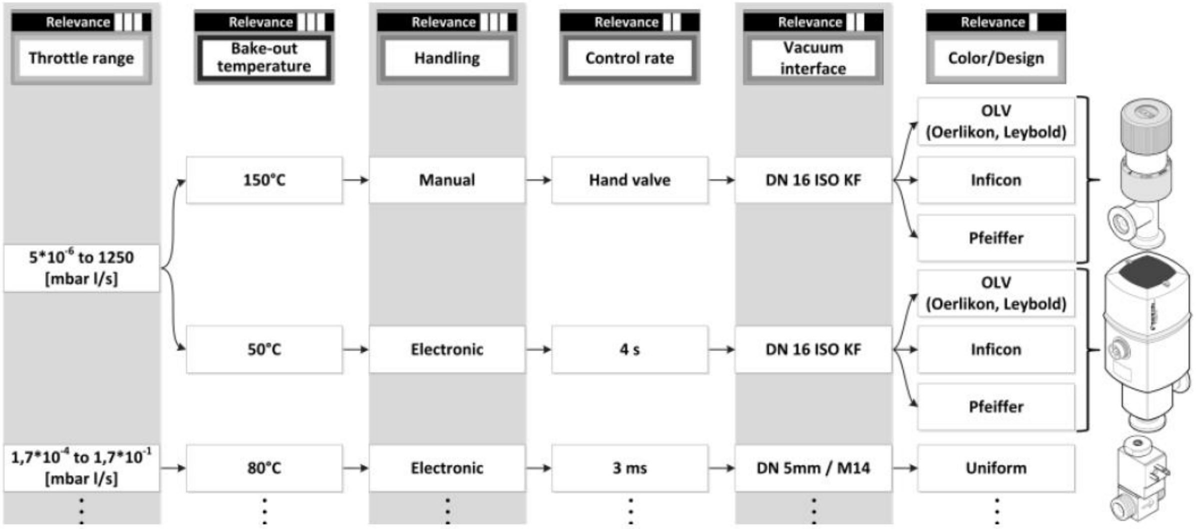


Figure 3.69. *Tree of variety for analysis of external variety in step 1. (Eilmus et al. 2012)*

Eilmus et al. explain that steps 2-4 relate to the analysis of internal variety from three viewpoints: functions (Step 2), components (Step 3) and working principles (step 4). In **Step 2**, it is suggested that the hierarchical function structure of the existing product families is made (Eilmus et al. 2012). This function structure follows the principles discussed in, for example, the book by Pahl & Beitz (1996).

A Module Interface Graph is suggested for visualising the variety of components in **Step 3**. An example of this is presented in Figure 3.70. This graph includes all components, their types and connection types among components in a product family. Eilmus et al. (2012) also explain that working principles are allocated for each function, as **Step 4** suggests.

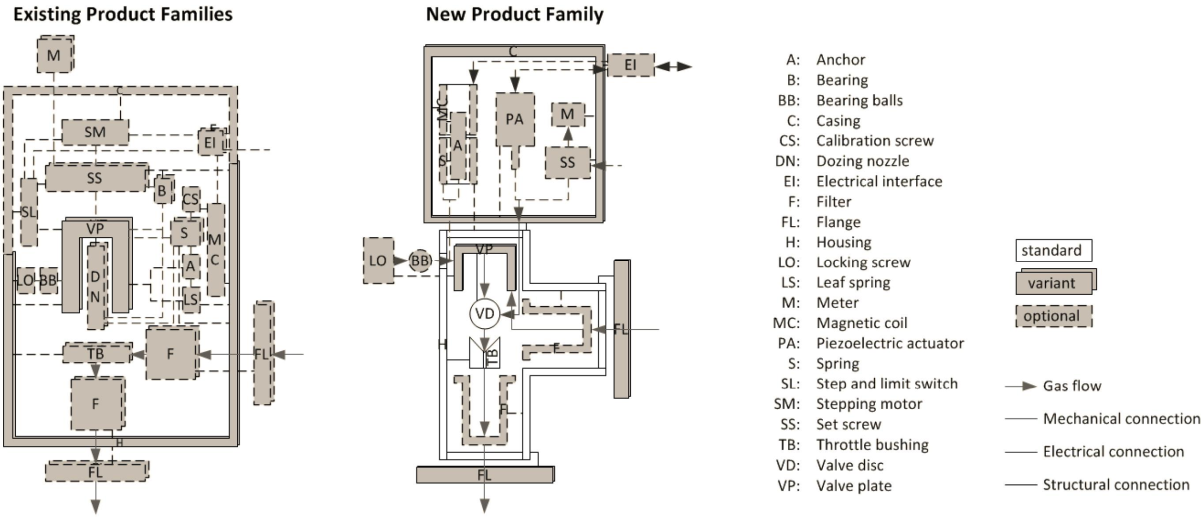


Figure 3.70. Module Interface Graph for showing the variety of components and their connection flows. The new product family is also explained in this figure. (Eilmus et al. 2012)

Eilmus et al. presents Variety Allocation Model (VAM) for **Step 5**. This model includes four levels, including differentiating attributes, variant functions, variant working principles and variant components, according to Eilmus et al. They explain that the aim in this model is to map one level to the next and the result explains the connections between external and internal variety. An example of the VAM is shown in Figure 3.71. According to Eilmus et al. this can be used for analysing variety-oriented product structure. They state that weak points in the existing structure can be improved by redesigning, modifying or by developing a new design for components. The result is a variety-oriented concept of a product family (**Step 6**).

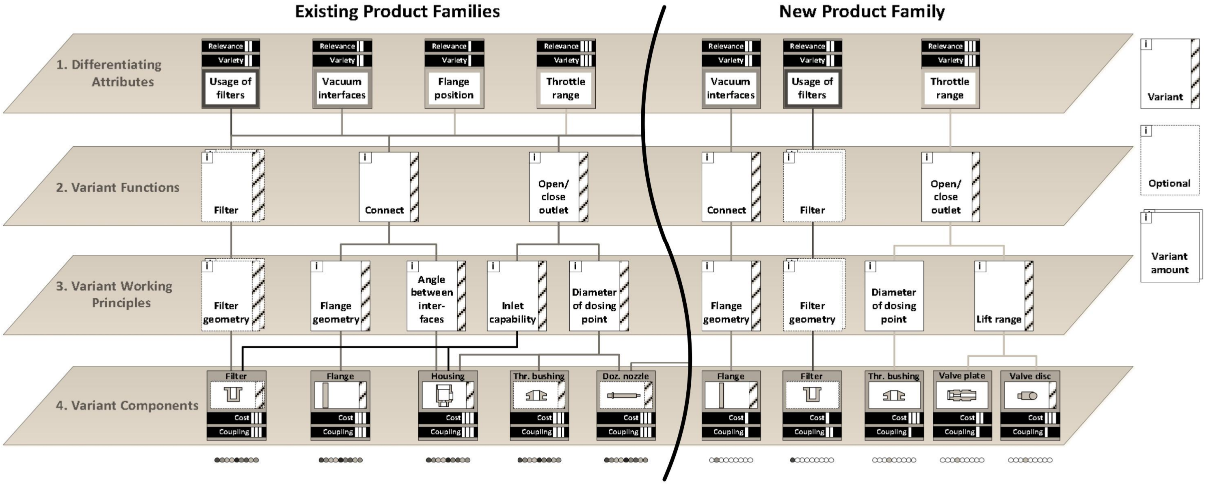


Figure 3.71. Variety Allocation Model of the existing product family and new product family according to Eilmus et al. (2012).

Eilmus et al. (2012) explain that the aim of **steps 7-8** is to set a module strategy for the product family concept defined in the earlier steps. The Integrated PKT-Approach suggests developing independent modularisation concepts for each life phase by considering any life-phase-specific targets of the company. Here network diagrams are used. Authors of the approach explain that these modularisation concepts can be different in order to satisfy different life cycle phases and the exploiting of possible benefits. It is suggested that the concepts be visualised using Module Interface Graph and all modular concepts from each life phase perspective can be combined in the Module Process Chart shown in Figure 3.72.

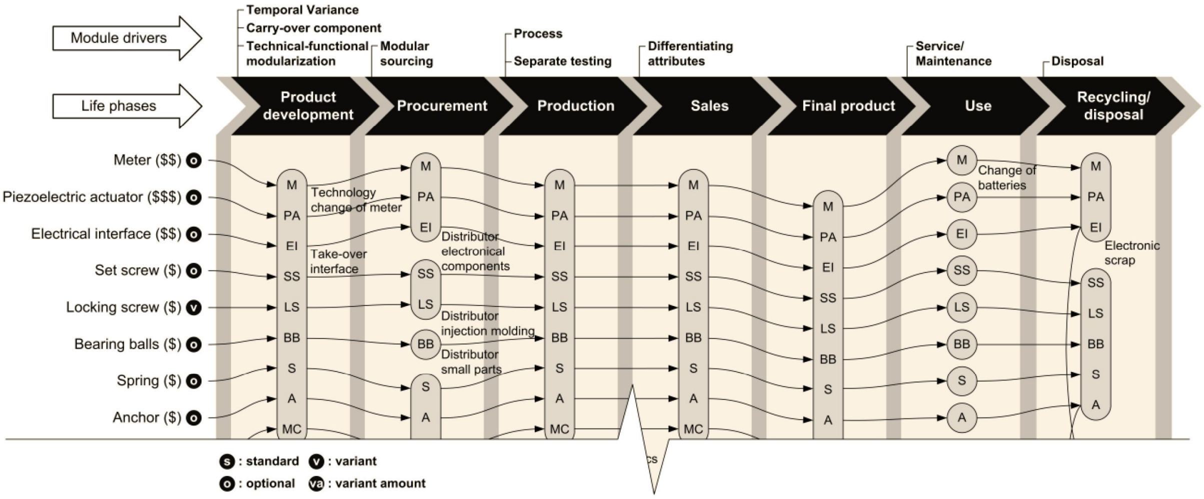


Figure 3.72. Module Process Chart is meant for presenting module concepts from viewpoint of life phases (Eilmus et al. 2012).

Blees et al. (2010) and Eilmus et al. (2012) present the idea that these different views can include conflicts, and thus they argue that this kind of approach, as shown in Figure 3.72, can lend support in the finding of and designing of an adequate modularisation that considers every life phase.

To conclude, The Integrated PKT-approach is a function-oriented product family design method that has been successfully applied, particularly in the reduction of parts, according to studied references. The approach includes architectural considerations such as Module Interface Graphs, which seem to be clearly defined and also uses ideas from other methods, such as the module driver thinking of Erixon (1998). The VAM level model for the designing of the product structure is discussed in the approach but, for example, Eilmus et al. (2012) note that the considering of working principles has been recognised to be challenging. The Domain Theory by Andreasen has similarities to the VAM model. In the example shown in Figure 3.71, working principles seem, however, to be more of design parameters than function carriers or organs, as in the model by Andreasen. Also the papers discussed in this section do not consider the specification of working principles in great detail. Thus these sections of the method could be defined more in order to enable the application of the approach without the need for extensive coaching.

3.8.6 Harlou: Developing product families based on architectures

Harlou (2006) presents an approach for defining a product family based on architectures. He discusses how architecture includes design units, interfaces and application characteristics. According to Harlou, design units can be both reusable (standard designs) and non-reusable. He also notes that existing and future design units should be considered. Harlou lists two types of interfaces: interfaces among design units and interface to surroundings. Application characteristics include responsibilities, coordination and documentation.

As explained above, Harlou defines standard designs as reusable solutions. He further defines that standard designs can be described using three classes of characteristics, including structural elements, functional properties and application characteristics. Harlou suggests that structural elements of standard design can be described using organs, parts and interfaces. Organs and parts classes adhere to the Domain Theory by Andreasen (2011). In describing interfaces of standard design, internal interfaces and interfaces among design units should be considered.

Harlou also makes a distinction regarding assortment architecture, family architecture and product architecture. According to Harlou, assortment architecture is a class of architectures covering a product assortment. It includes existing and future standard designs and design units. He suggests that assortment architecture should look 3-5 years ahead; thus, the road-mapping of future designs is suggested. Assortment architecture covers several product families, unlike family architecture, which covers a single product family. Product architecture is an instance of a family architecture and valid for only one specific product, according to Harlou.

Harlou also discusses platforms. Several definitions of platforms were already discussed in Chapter 3.5.7. According to Harlou, a platform is an instance of an architecture that includes existing re-usable standard designs and their interfaces. As architectures, he also divides platforms into three classes: assortment platform, family platform and product platform. A summary of the different classes of architectures and platforms is given in Figure 3.73 by Harlou.

According to Harlou, interfaces have a central role in architectures and platforms. He has presented interesting approaches to the ownership of interfaces. He explains that there are at least three approaches:

1. *“The owner of the architecture owns the interfaces.”*
2. *“The owner of the standard design owns the interfaces.”*
3. *“Each interface is appointed an owner.”*

According to Harlou, different motivations in companies have effects on the selection of the above approaches, and thus no single recommendation exists. He explains, however, that as an example, the second approach can be beneficial if the ownership of the architecture is not decided upon yet and if responsibilities for standard designs are well defined. The third approach can be a good choice in, for instance, cases in which interfaces are desired to be maintained longer than the standard designs and a lot of work is allocated into the designing of interfaces, according to Harlou.

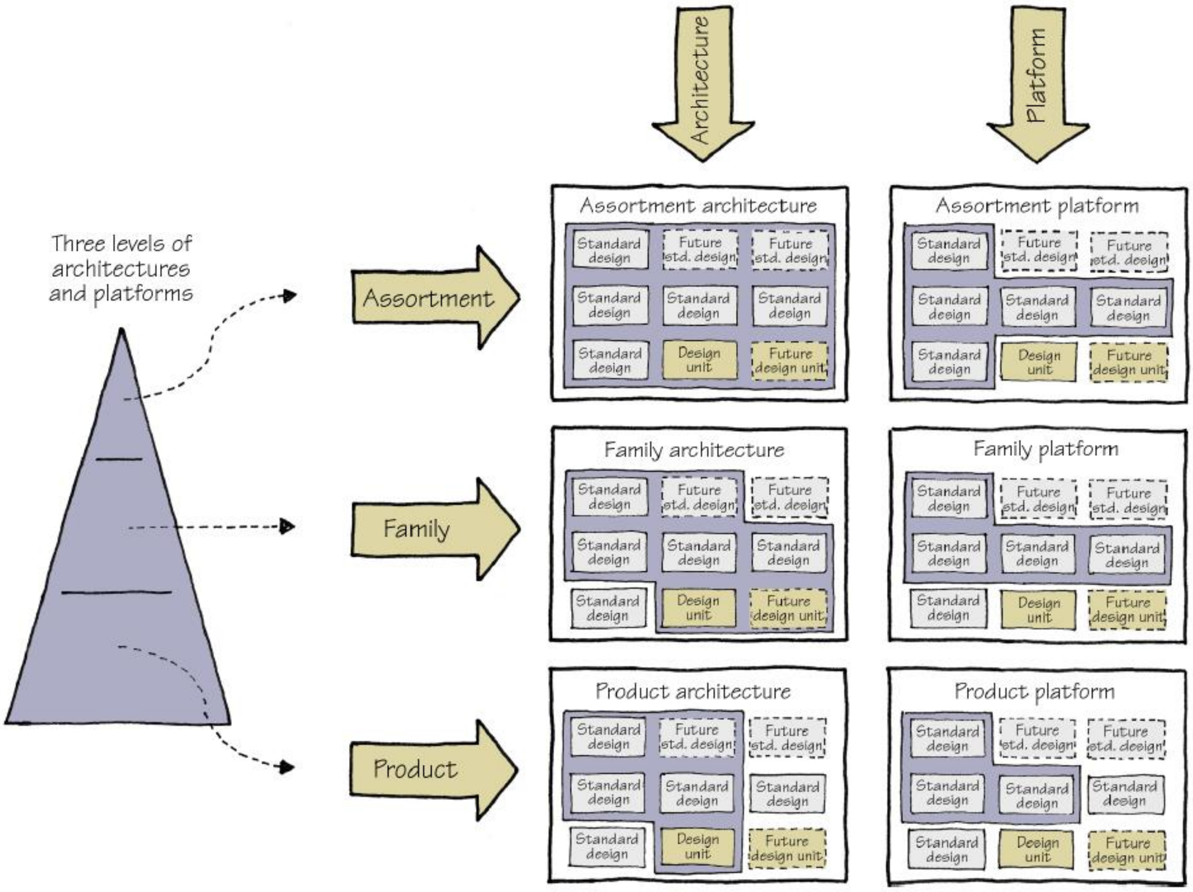


***Figure 3.73.** Three levels of architectures and platforms as defined by Harlou (2006).*

Based on the issues presented in Figure 3.73, Harlou suggests two tools; **generic organ diagram** and **product family master plan (PFMP)**. The aim of the generic organ diagram is to help in modelling the organ structure and the interfaces in the organs. The basic notation of the generic organ diagram is presented in Figure 3.74. PFMP is directed for modelling a variety of features, organs and components in a product family, and it is discussed later on in this section.

As can be seen from Figure 3.74, the generic organ diagram resembles the description of architecture as explained, for example, in publications such as that of Fujimoto (2007). The difference is that generic organ diagram includes only organs and their interfaces, and thus the diagram is not considered as architecture itself, according to Harlou. Nevertheless, Harlou explains that this kind of modelling formalism is intended for the modelling of standard designs and architectures.

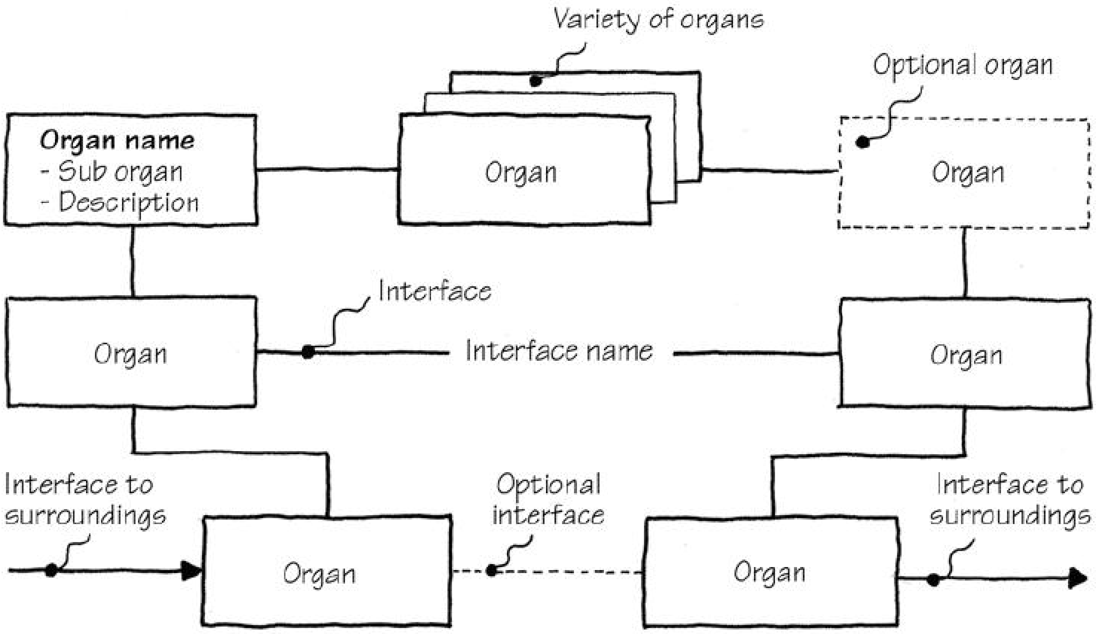


Figure 3.74. *The generic organ diagram has organ structure and organ interfaces in a central focus. This tool can be used for identifying standard designs and architectures, according to Harlou (2006).*

The PFMP that Harlou has presented focuses on giving an overview of the variety within the product family. The main content of the PFMP approach is visualised in Figure 3.75. This tool highlights customer, engineering and part views when modelling a product family.

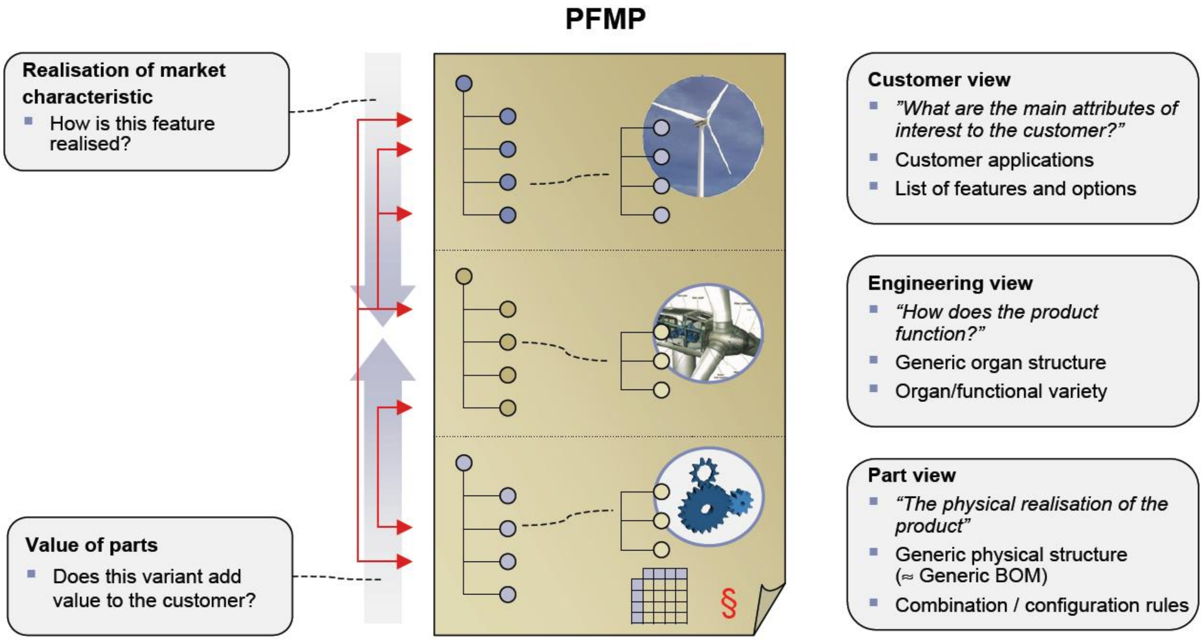


Figure 3.75. *The main content of product family master plan (PFMP). (Harlou 2006)*

An example of the application of the PFMP is shown in Figure 3.76. According to Harlou, the customer view describes the product family from a customer viewpoint. Thus this view focuses on showing the variety from a market perspective. The engineering view describes the organ structure of the product family and the organ variety. The part view includes a description of the physical realisation of the product. (Harlou 2006)

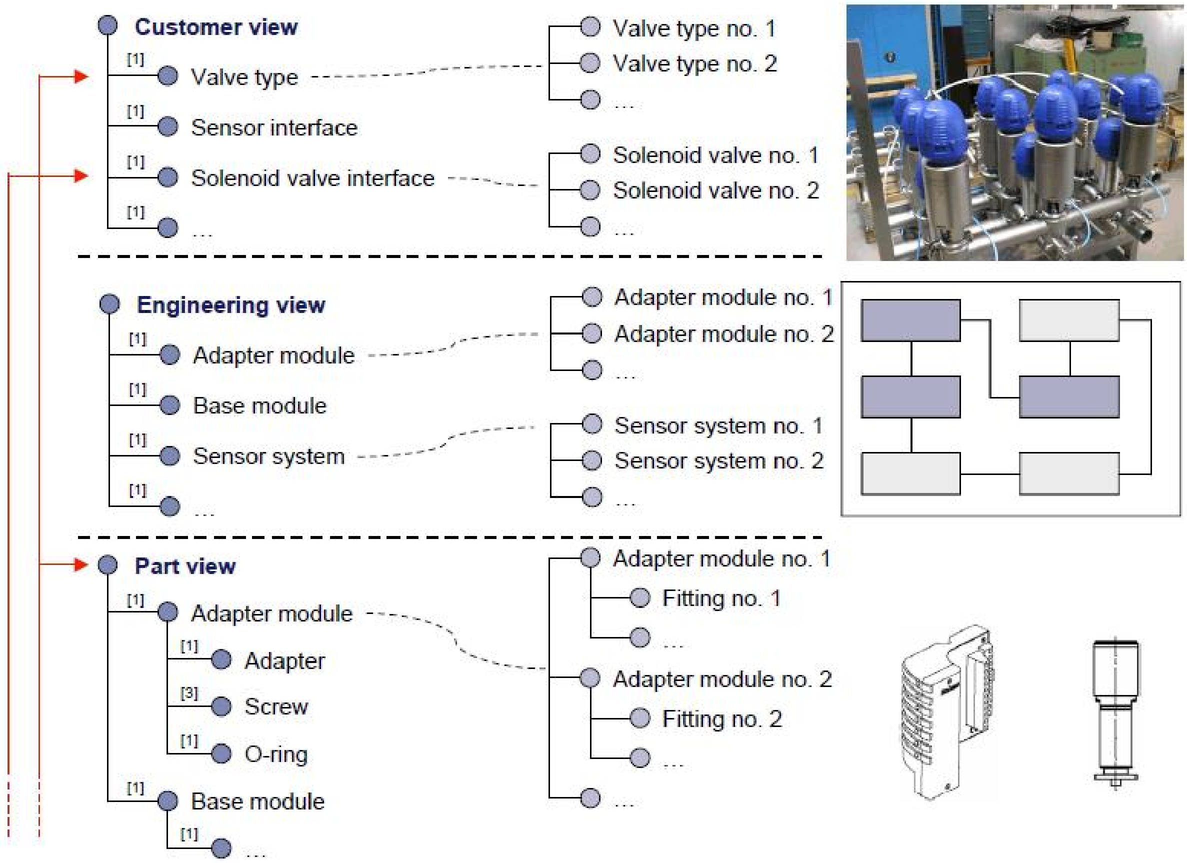


Figure 3.76. *An example of the PFMP describes the product family from three different views. The case product is a mechatronic device for valve controlling. (Harlou 2006)*

To conclude, Harlou (2006) presents interesting approaches that are validated with several industrial cases. The generic organ diagram and the PFMP include multiple viewpoints that are worth considering when developing a product family. The defining of objectives for the product can be seen to be considered, especially in the PFMP when the customer view is analysed. Harlou describes how the PFMP can be used in two situations: 1) when a company is starting to consider the platforms and architectures (utilising of existing products, families and assortment with these tools) and 2) when new standard designs and architectures are developed (drafting of desired situation). Thus, there is not any presumption that the variants must already exist when utilising the tool. Consequently, the content and supporting descriptions of the approaches can be used in highlighting the essential issues such as considering different views in the designing of a product family. Design re-use aspects are explained in the generic organ diagram and background material regarding architectures and platforms. Harlou describes how standard designs and interfaces are essential in enabling design re-use. Re-designing is also taken into consideration. Harlou discusses how PFMP can be used in re-designing situations for analysing the existing products. To conclude, the tools developed by Harlou seem to also be meaningful for the context of this thesis, in which a module system is pursued.

3.8.7 Bongulielmi: The K- & V-Matrix

Bongulielmi et al. (2001; 2002) and Bongulielmi (2003) discuss a description language for variant products known as the K- & V-Matrix method. Bongulielmi argues that this approach is meant for analysing variants in the realisation process of the product and when describing the logic of configuration in sales. Thus this approach is not actually a design method for modular and configurable product families, but is presented here nonetheless since in order to enable effective creation of product instances, configuration knowledge must be presented clearly. Bongulielmi explains that the objective in the development was to provide a description language that would, in particular, consider different product views and mapping between different views, provide an overview on product variants, help in the re-designing of products at a later stage and would be easy to use, as well as generic (Bongulielmi et al. 2000).

The structure of the K- & V-Matrix is shown in Figure 3.77. The method is based on two kinds of matrices according to Bongulielmi (2002):

- The K-Matrix: configuration matrix
- The V-Matrix: compatibility matrix

In the K-Matrix, relations between the technical view and customer view are defined. Bongulielmi et al. (2000) discuss how a typical K-Matrix explains customer relevant properties of the product and a technical (enterprise-internal) view. According to Bongulielmi et al. (2002), an enterprise-internal technical view includes all variant modules in the product structure. Thus the K-Matrix is suggested for choosing the correct technical solutions against certain customer requirements.

Bongulielmi explains that there are two kinds of V-Matrices: the one in which compatibilities between customer views are defined and the one in which compatibilities between technical views are defined. The V-Matrix can be, for instance, used to describe components that can be combined, according to Bongulielmi.

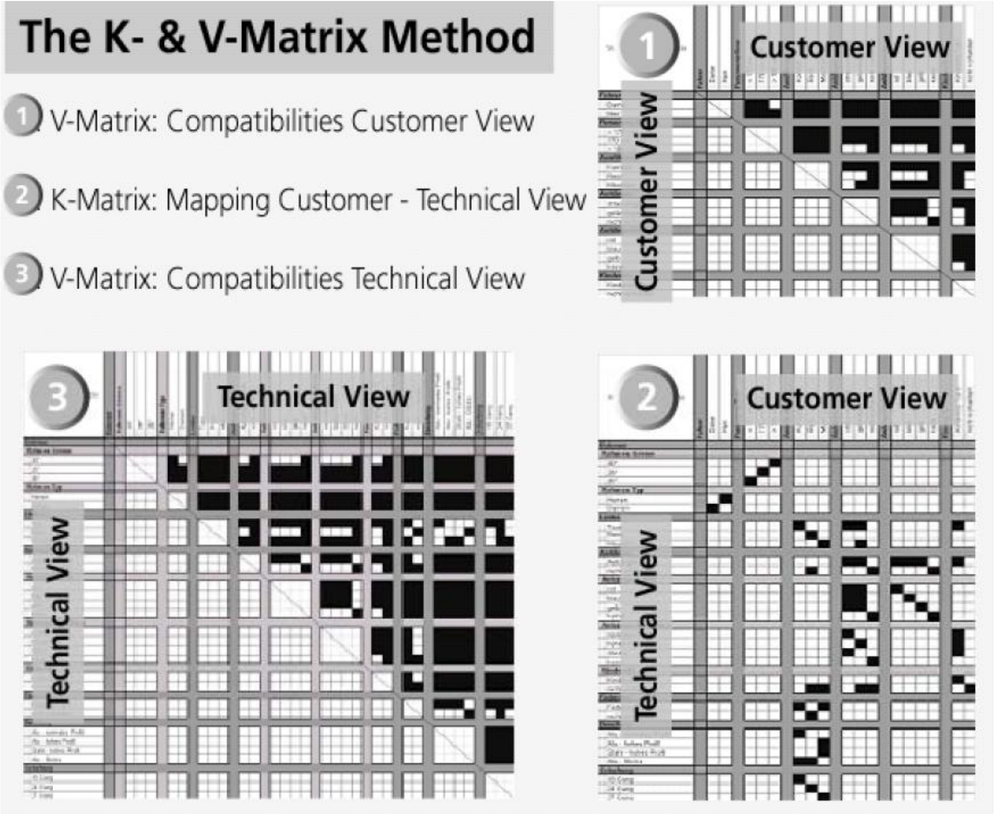


Figure 3.77. K- & V-Matrix method includes three matrices describing compatibilities between different views. (Bongulielmi et al. 2002)

The K- & V-Matrix method does not cover the design process extensively, as already discussed at the beginning of this section. Bongulielmi et al. (2002) confirm this by stating that the method does not support the development of a modular architecture and that this matrix method only represents the product modules. Thus the architecture has to be defined until the K- & V-Matrix method is used. Bongulielmi et al. (2002) suggest that the method can be combined with other methods at the end of the embodiment design phase.

Bongulielmi et al. (2002) explain that the K- & V-Matrix method is typically applied when configuration-relevant issues are considered. They state that this can happen in the late phases of engineering design process or re-engineering.

Bongulielmi et al. (2002) describe that during the configuration process, the customer refers to the properties described in the customer view and related technical properties are chosen according to the selections by the customer.

In conclusion, the approach is a generic tool for representing compatibilities and configuration knowledge systematically between different views. This kind of knowledge is needed when product instances are defined. The method supports the storage of product knowledge regarding, for instance, modular structures and the relating of these to certain customer requirements that create the need for variety. The method could be used as, for instance, a supporting tool in sales. This kind of representation of product knowledge could also be used in re-designing situations because from the matrices the relations between different viewpoints in existing products can be checked. Relations in matrices are of the yes/no type. According to Bongulielmi et al. (2002), this makes the method easier to understand and use. In some cases, however, it might be beneficial to define compatibilities in more detail. In these situations, the presentation as shown in Figure 3.77 could be insufficient and other tools might be needed in order to describe the reasoning.

3.8.8 Nummela: Configuration matrices

There also exist other matrix approaches for representing configuration knowledge besides the approach by Bongulielmi that was discussed in the previous section. Nummela (2006) explains that the main purpose of configuration matrices is to present configuration rules that reveal configuration-related knowledge of modular structures. This can include several issues, such as saleable options at the moment, connections between combinations of the selected options and modules for the production.

It has been presented by Nummela, that the documenting of configuration knowledge and an understanding of modularity increase the capabilities of the company to design product architectures. He argues that documented configuration knowledge can reveal any hidden knowledge needed in order to define configurations and maintain them. If configuration knowledge is not documented clearly, the risk is that modularisation and configuration will not necessarily be understood correctly, according to Nummela. He also states that the implementation of a configurator is difficult unless configuration knowledge cannot be defined clearly. These same kinds of issues were recognised in Chapter 3.5.8 on configuration by Haug (2007) and Haug et al. (2012).

Nummela (2006) presents that well-established modules, including modular architecture and change management, are enablers of an effective configuration process. Nummela therefore also explains how the requirement for the defining of configuration matrices is that the decomposition of product structure and definitions of module interfaces have been defined.

Nummela (2006) has presented a process for the establishment of configuration knowledge for existing products. These steps presume that the modular product structure is defined and saleable options are known.

1. gather the required configuration knowledge by interviewing experts
2. define the generic list of options
3. define the generic product structure
4. define the variable part of the product structure
5. define the base machine part of the product structure
6. define the sequence of the saleable options
7. generate the square matrix by listing the options and modules according to the sequence
8. define the dependencies of the modules about the options
9. finalize the sequence of the matrix

This process requires that an initial plan for configurability be made. Nummela defines this plan according to Aarnio (2003). The plan should consider variety, commonality, differentiation, outsourcing and upgrade plans. An initial plan for configurability is used in defining the generic list of options, according to Nummela. He defines that generic product structure includes all the modules of the modular system that are related to a configurable product and configuration knowledge. It is explained that this structure enables the handling of different situations at an operative level. A variable part of the product is considered by using modules in Nummela’s approach. The base machine (product) means the proportion of the product which is standard in all the configurations that can be derived from the modular system.

The above-mentioned definitions are needed in order to create a configuration matrix. Nummela presents how a configuration matrix includes the collection of options (customer choices), all the modules and also the base product. This kind of configuration matrix is shown in Figure 3.78. According to Nummela, the sequence of saleable options is considered by analysing the relations between each saleable option. If an option doesn’t have any relation to other options, the selection of the option can be made at any point. In other situations, the relations have to be analysed in order to find a reasonable selection sequence for the options.

Nummela also discusses further possible actions available after configuration knowledge have been defined. He notes that the configuration knowledge has to be maintained if customer needs and the modular system change accordingly. It is also noted that continuous changes during the life cycle of the configuration model should be avoided. Otherwise, benefits of the configuration are lost. It is explained that the maintenance of configuration matrices should have a connection to product development, which maintains existing products in order to maintain the matrices’ validity.

In conclusion, the study by Nummela (2006) consolidates the importance of defining configuration knowledge and suggests matrices for this activity. The matrix approach combines customer and technical views and separates variable and standard structure in the same matrix. This is the main difference when compared to the approach by Bongulielmi (2003). Research by Nummela (2006) also highlights the fact that modular structures need to be designed until configuration matrices can be formed.

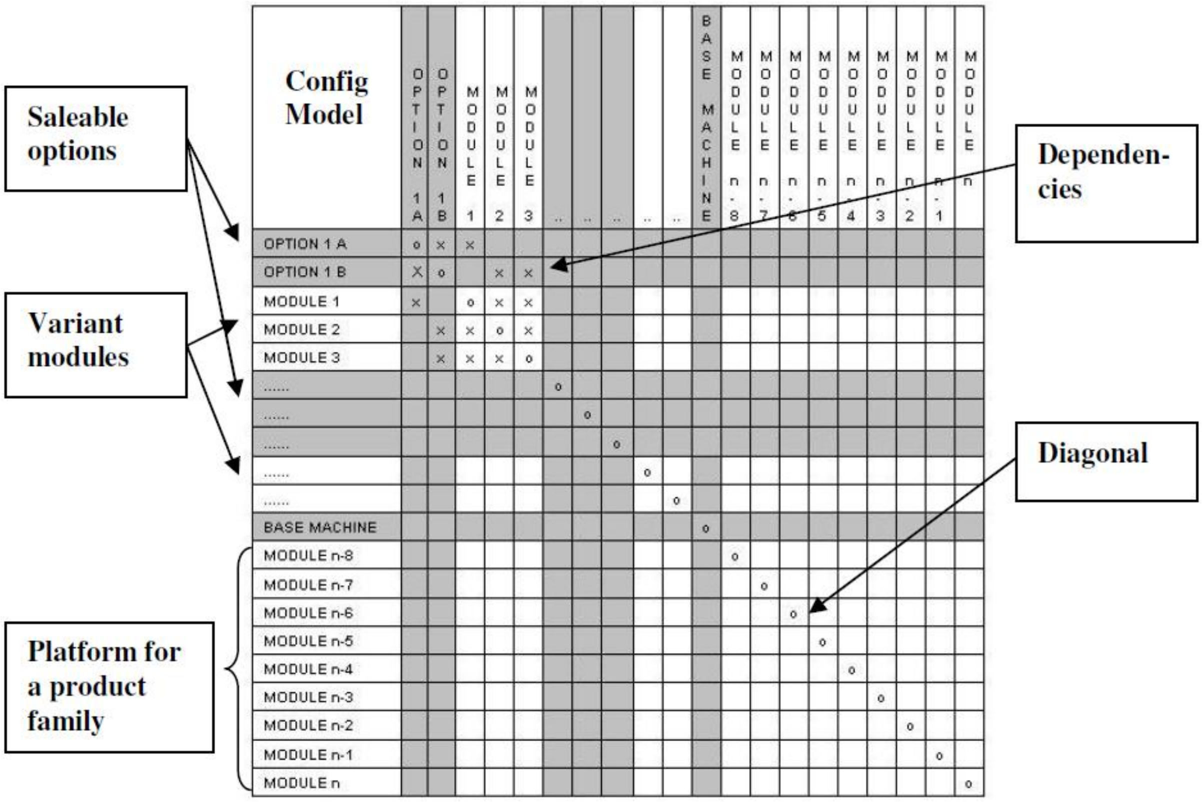


__Figure 3.78.__ An example of the configuration matrix by Nummela (2006).

3.8.9 Fixson: Product architecture costing

Erixon (1998) discussed in MFD how the evaluation of a designed modular structure is important. Lehtonen (2007) also highlights the fact that the results of modularisation should be validated against the business goals in order to gain acceptance. The same kinds of ideas were also suggested on a more generic design level. For example, Olesen (1992) and Andreasen (2011) discussed universal virtues and evaluation life-cycle phase-specific effects of the designed solutions. In this section, another approach by Fixson (2006) is discussed. He considers product architecture as the main potential for providing variety with the benefits of mass production. In order to gain these benefits, he emphasises the role of commonality. Fixson discusses how product development is a multi-dimensional activity in which balance between costs, revenue and performance has to be found when designing product architecture. It is explained that there are reasons to consider costs as a main factor in decision making. He notes that cost is the main decision-making variable, especially in parts which do not have a major effect on the overall quality of the product. Fixson presents that building a relational model of product architecture and costs is a starting point for the designing of more advanced support tools for the designing and optimising of product architecture.

The approach of Fixson models the relations between product architecture characteristics and the costs related to specific life-cycle phases. Time issues are also considered because time can be a relevant measure of performance in some cases, according to him.

Fixson presents that the analysis of cost effects of the architecture includes four steps:

1. Assessment of differences in product architecture candidates

2. Identifying of cost-relevant life-cycle phases and their product architecture-cost relationships
3. Determining of cost allocation rules and their impact on cost analyses
4. Selecting of cost model

Fixson states that the building of understanding regarding relations between product architecture and costs requires a good understanding of how the product architecture is described. He explains that function-component allocation (FCA) and interfaces are two important dimensions of product architecture. FCA considers how well the functions are separated from physical parts. Fixson states that the most modular FCA is when one function is realised by one component. Thus Fixson also emphasises function-oriented modularisation. He also explains how interfaces should be considered. Interfaces are discussed from three viewpoints according to him:

- Interface intensity describes the role of an interface to the functioning of the product. The interface can be spatial and the flow of material, energy and signal may be considered in the interface.
- Interface reversibility considers how well two modules that are connected using an interface can be disconnected from each other and how the interface is located in the product architecture.
- Interface standardisation depends on product features and the quantity of alternatives. The level of standardisation can be different for each component that is connected using a specific interface.

Fixson explains that up until the analysis is performed, the costs to be studied need to be decided upon. Relevant life-cycle steps related to costs and relevant product architecture-cost relations have to be decided upon, according to him, as Step 2 suggests. Fixson presents product architecture-cost (and time) relational models of four different life-cycle phases. These phases are product development, production, use and retirement. The models are shown in Figures 3.79-3.82. References shown in these figures can be found in the original publication by Fixson (2006). As was presented earlier, Fixson considers FCA and interface characteristics as main dimensions of product architecture. Between the dimensions and resulting effects, mechanisms that have an effect on the results have been presented.

Figure 3.79 describes the relations from a product development perspective. Process complexity, work parallelisation and economies of scale are considered as mechanisms in this phase. Characteristics of the product architecture have a direct relation to the process complexity, according to findings by Fixson. He presents that the more complex the product architecture is, the more complex the processes related to the designing of the architecture probably are. Interface characteristics have an effect on work parallelisation. He states that a simpler interface makes it easier to carry out simultaneous designing because this kind of interface means that there are less important relations between two or more product elements. Economies of scale are also considered to be an important aspect when considering the architecture.

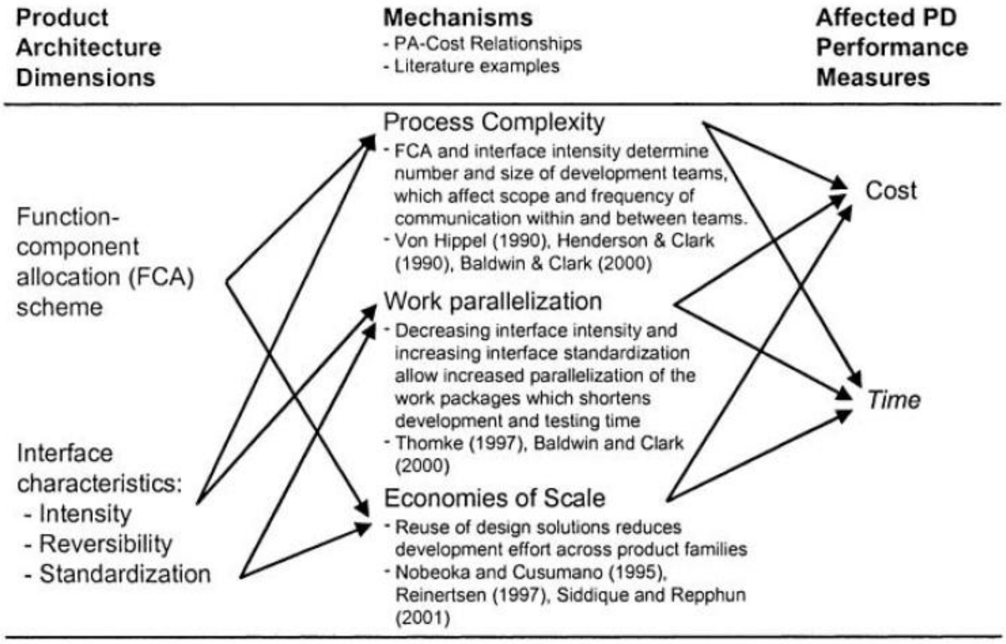


***Figure 3.79.** Effects of product architecture dimensions on product development costs and time. (Fixson 2006)*

Figure 3.80 describes the effects from a production viewpoint. In this product life-cycle phase, Fixson discusses the fact that the product architecture has an effect on the resulting production process complexity and economies of scale because of a level of commonality that exists in the products and risk pooling. He explains that in the designing of product architecture, necessary inventory and possibilities for re-sequencing of processes are defined. Huang et al. (2005) define how “risk pooling” is important in supply chain management. They argue that risk pooling is one of the most noticeable effects of the commonality of a product family. Huang et al. explain that risk pooling involves reduction of the inventory levels of the common modules.

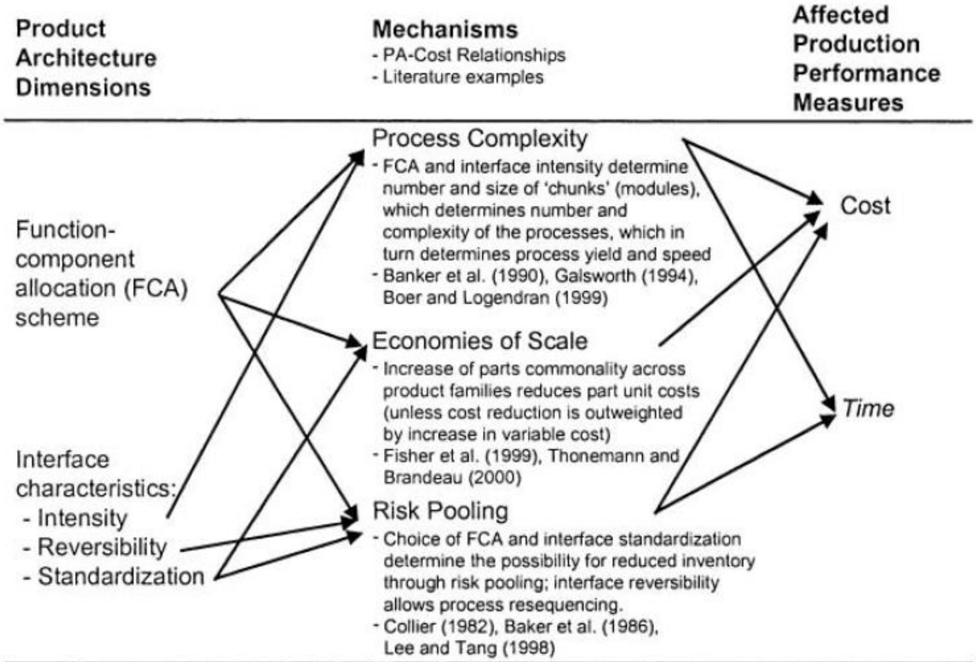


***Figure 3.80.** Effects of product architecture dimensions on production costs and time. (Fixson 2006)*

Figure 3.81 explains the relational model from a use phase perspective. Regarding use, Fixson highlights the fact that product architecture dimensions can, for example, affect the role of maintenance, training and variability of the necessary spare part assortment.

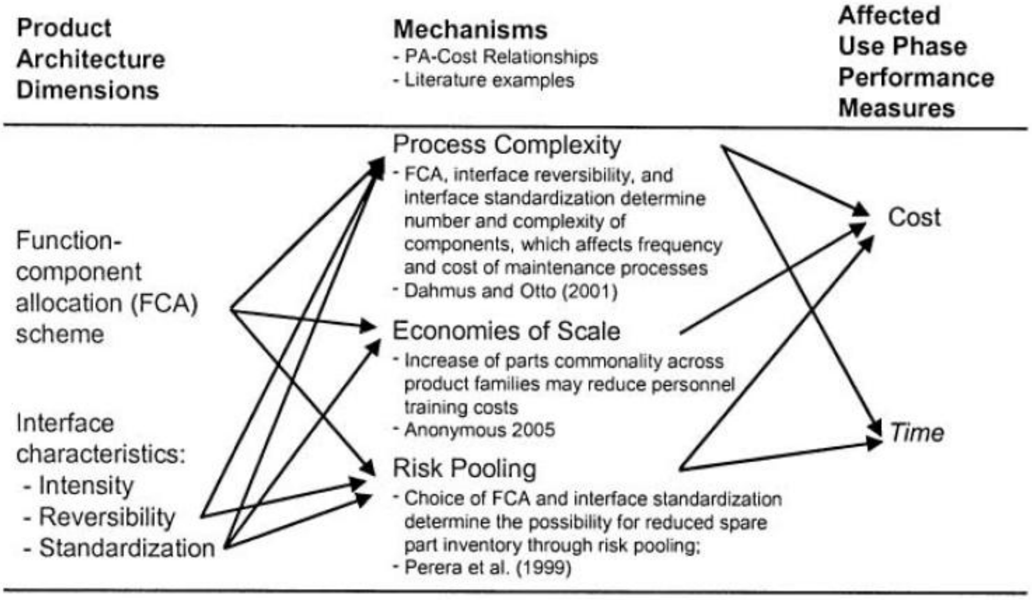


***Figure 3.81.** Effects of product architecture dimensions on use costs and time. (Fixson 2006)*

Figure 3.82 includes issues related to the retirement phase of the product. In this phase, Fixson states that quantitative cost estimation for these issues can be especially difficult because, for example, the cheapest disassembly sequence is often unclear, and a reverse assembly sequence is not necessarily the best option.

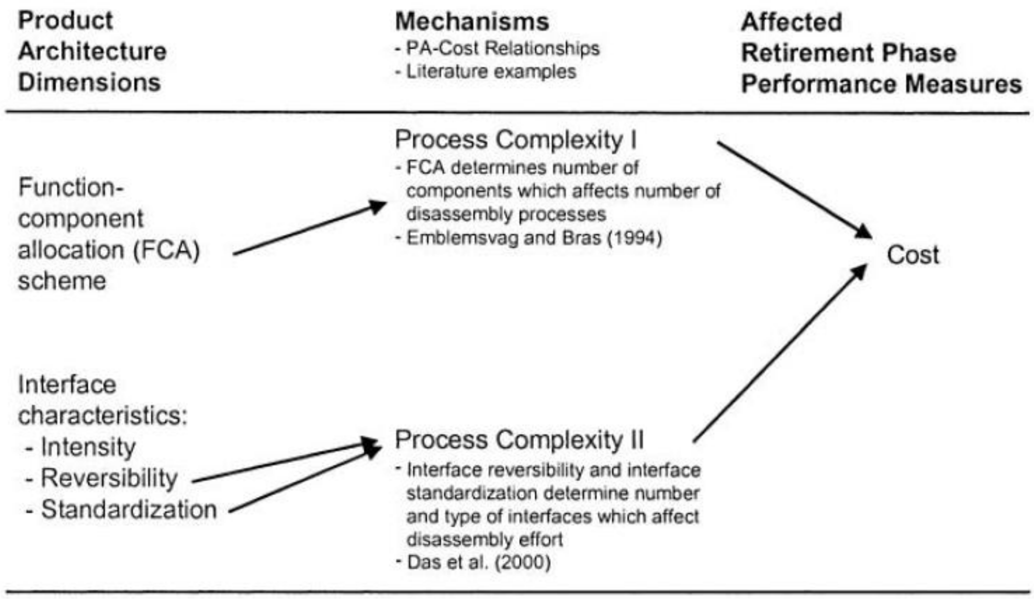


***Figure 3.82.** Effects of product architecture dimensions on retirement costs. (Fixson 2006)*

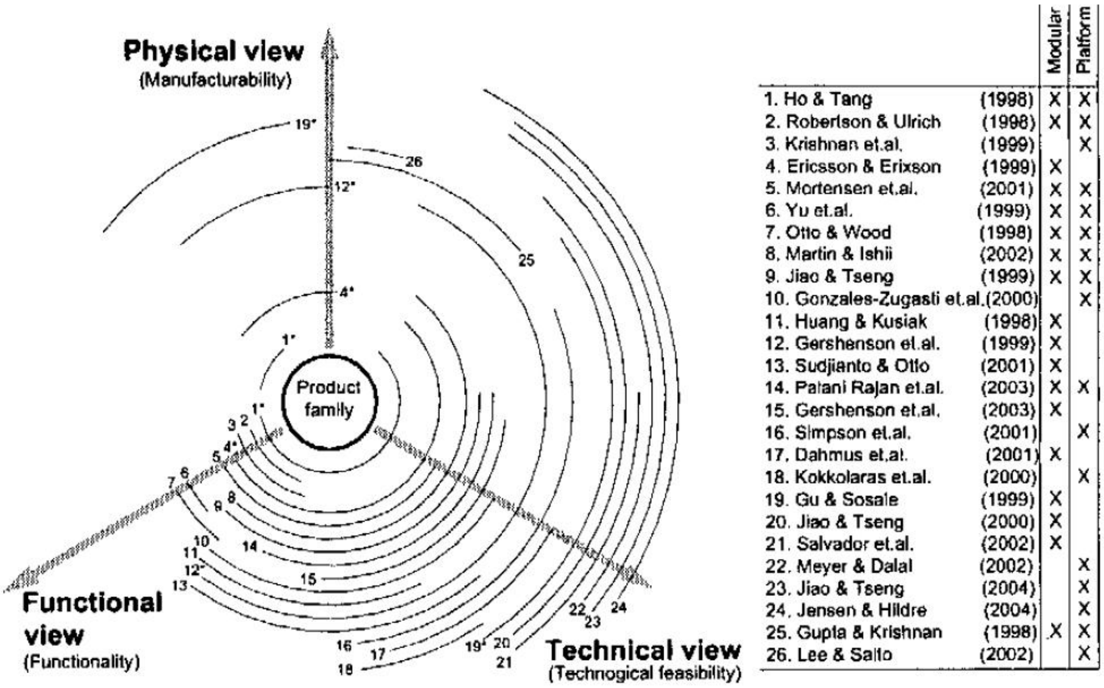
In the above figures, Fixson presents the main dimensions in defining architecture – FCA and interface characteristics. Process complexity (all discussed life-cycle phases), work parallelisation (product development), economies of scale (product development, production, use) and risk pooling (production and use) are considered as mechanisms which have either cost or/and time effects, depending on the dimensions of product architecture. As for analysis, Fixson emphasises that designers have to understand the trade-offs between and within product life-cycle phases. He also explains that in deciding relevant trade-offs, the business model of the company, warranty policies and competition and the legal environment must be understood.

To conclude, Fixson brings up issues that relate to analysis of the effects of product architecture dimensions and underline the importance of a cost-evaluation framework for product development decision making and the designing of support tools for product architecture. Nevertheless, these models cannot be used directly in a way where they are presented without expertise, but the models do offer an example of a structure for defining more concrete approaches for analysing the effects of product architecture for different life-cycle phases and thus they can also be considered important for this thesis.

3.8.10 Review and conclusions on other approaches and methods of designing of modular product families

Multiple other publications exist which are related to modularisation, product family development and product platform development. Several publications in which different methods and approaches have been reviewed also exist. For example, Jensen & Hildre (2004), Jiao et al. (2007), Salvador (2007), Gershenson et al. (2007), Borjesson (2010), Daniilidis et al. (2011), Nomaguchi et al. (2012), Okundan Kremer & Gupta (2013) and Krause & Ripperda (2013) have published summaries, comparisons and analysis of these issues. The basics of these works are presented before a review by the author is presented and discussed.

Jensen & Hildre (2004) have done a review of product family architecture design methods. Their review focused on categorising approaches based on functional, technical and physical viewpoints. A summary of their review is shown in Figure 3.83.



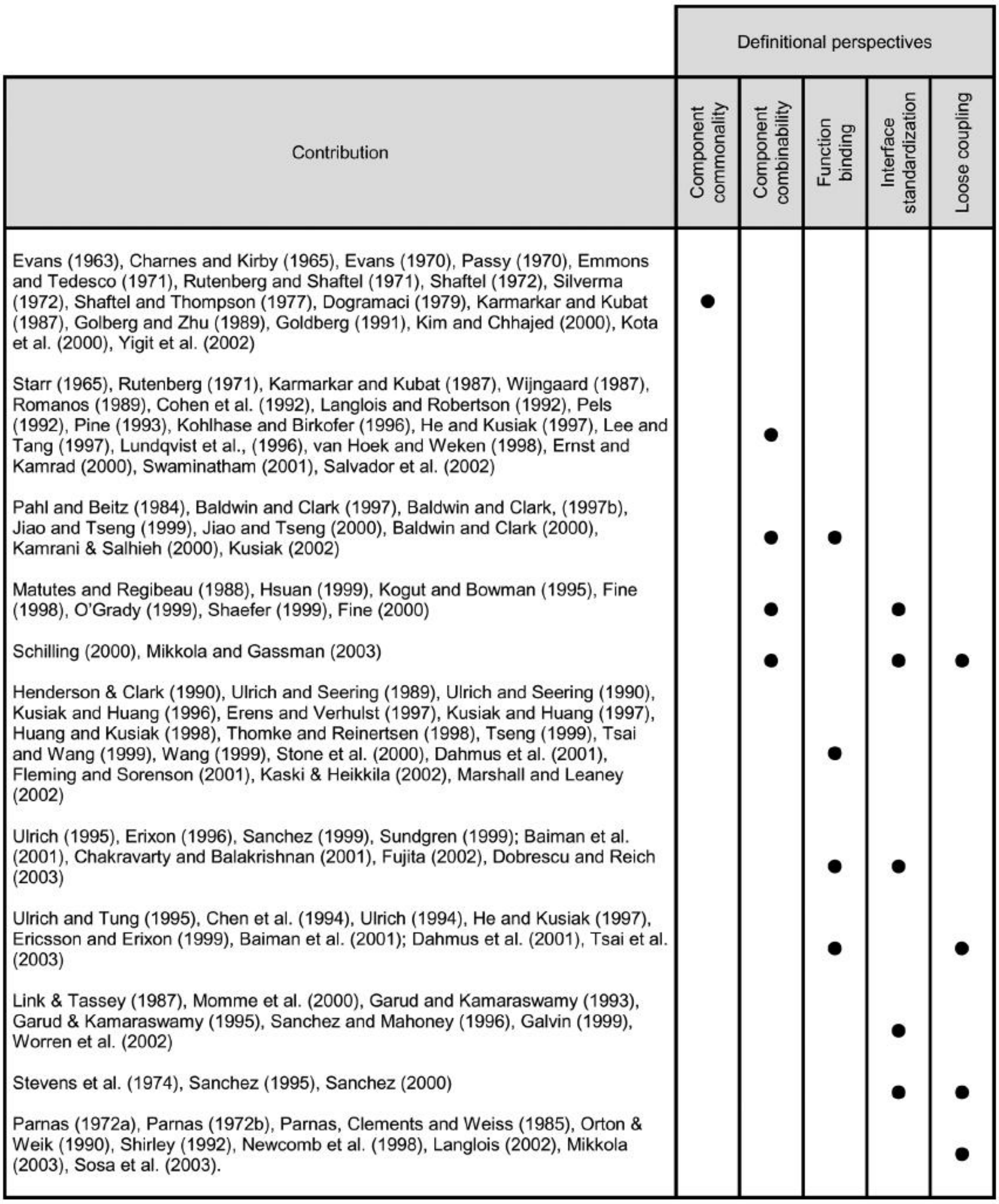
		Modular	Platform
1. Ho & Tang	(1998)	X	X
2. Robertson & Ulrich	(1998)	X	X
3. Krishnan et.al.	(1999)		X
4. Ericsson & Erixson	(1999)	X	
5. Mortensen et.al.	(2001)	X	X
6. Yu et.al.	(1999)	X	X
7. Otto & Wood	(1998)	X	X
8. Martin & Ishii	(2002)	X	X
9. Jiao & Tseng	(1999)	X	X
10. Gonzales-Zugasti et.al.	(2000)		X
11. Huang & Kusiak	(1998)	X	
12. Gershenson et.al.	(1999)	X	
13. Sudjianto & Otto	(2001)	X	
14. Palani Rajan et.al.	(2003)	X	X
15. Gershenson et.al.	(2003)	X	
16. Simpson et.al.	(2001)		X
17. Dahmus et.al.	(2001)	X	
18. Kokkolaras et.al.	(2000)		X
19. Gu & Sosale	(1999)	X	
20. Jiao & Tseng	(2000)	X	
21. Salvador et.al.	(2002)	X	
22. Meyer & Dalal	(2002)		X
23. Jiao & Tseng	(2004)		X
24. Jensen & Hildre	(2004)		X
25. Gupta & Krishnan	(1998)	X	X
26. Lee & Saito	(2002)		X

Figure 3.83. *A review made by Jensen & Hildre (2004) reveals that several methods focus on functional and technical viewpoints in modularisation and platform development.*

Jiao et al. (2007) have studied publications related to product platforms, product architecture, product variety, modularisation and commonality. They consider most of the product family development methods to be platform based in their often-cited publication. They also divide product family development methods into scale-based and configurative (module-based) methods. In their review, Jiao et al. also highlight the relationship of manufacturing and production to product family development. It is discussed that process variety, process platform, process configuration and supply chain issues are important aspects in the main context. The weakness of the review by Jiao et al. is that it gives poor consideration to Scandinavian research. For instance, approaches developed by the Danish researchers are completely missing from this review. In those approaches, product family development is considered using visual and structural methods more than using mathematic models, as has also been discussed earlier in this thesis. Function-oriented approaches, which are especially common in German research groups, are also almost completely unrecognised in the review by Jiao et al. Many approaches studied by Jiao et al. focus on algorithms and mathematical models. As a conclusion, Jiao et al. note that there exists extensive research related both to front-end and back-end issues in product family development. Jiao et al. recommend that customer viewpoints in product family development, modelling of product architecture and platforms, configuration models of product families, design support, linking of production and supply-chain issues to product family development and analysing of economic effects should be considered as important high-level research areas for the future.

Salvador (2007) has written a review article on modularisation that focuses on definitions of modularity and on a timeline analysis of the modularisation aspects. The results of his analysis are shown in Table 3.14 and in Figure 3.84. Categorisation by Salvador includes five areas – component commonality, component combinability, function binding, interface standardisation and loose coupling. Salvador explains that *component commonality* means that the same components are used across a given product assortment. He explains that these kinds of definitions are common in management science and that these definitions had already begun to appear in the 1960's. *Component combinability* means that different product configurations can be created by mixing and matching components taken from a given set, according to Salvador (2007). Thus this relates to the definition of variability discussed earlier in this thesis (see, for instance, Figure 3.20 by Juuti). Salvador explains that product platforms and different kinds of modularity, such as component-swapping modularity, are close to this area. Thus he also highlights that some of the modules might remain unaltered and there might be a need to only change a specific module in order to satisfy different market needs. The third class presented by Salvador is *function binding*. Salvador states that product modularity in function view enables the fulfilment of various overall functions by combining modules. He has recognised that most of the studies that include function view and modularity are based on the definition of a function module explained by Pahl & Beitz (1996). Salvador describes how *interface standardisation* essentially originated in the computer industry, going back to the 1930's. He explains that interface standardisation has been discussed more widely in economics literature ever since the concept of connection standard was presented by Rosenberg (1982). Besides business issues, Salvador discusses the effects of standardised interfaces to vertical integration. One finding of his review study is that standardised interfaces can facilitate the breaking of the integration because standard interfaces makes it easier to find alternatives for components and suppliers because of, for instance, technology and cost factors. Salvador concludes that interface is a set of design parameters describing how two objects interact. *Loose coupling* is the fifth area of the summary made by Salvador. He explains that this issue can be explained by considering system view. Salvador states that a loosely coupled system can be broken down into smaller units or modules to a degree. It is explained that this kind of module partitioning makes it easier to understand, conceive and build a system instead of considering the system as a whole. According to Salvador, this issue has brought up typical questions found in modularisation literature, such as what is the correct complexity or size of modules. Table 3.14 summarises the review by Salvador. The table shows that there are multiple publications related to function-oriented modularity. Salvador explains that there also exists production-oriented modularity, but he considers these cases special ones. He also discusses the submarine example about production-oriented modularisation, which Lehtonen (2007) also discusses in his dissertation. Figure 3.84 of his review explains that the thinking on modularity issues is not a new topic, although terms and their definitions have developed further. Compared to the review done by Jiao et al., one could state that Salvador follows more function-oriented approaches than mathematical optimisation methods in his review.

Table 3.14. *The summary by Salvador (2007) of modularity definitions shows, for example, that multiple contributions consider function view in modularisation although the function structure-oriented view has been considered a non-optimal starting point for all case in studies such as that of Lehtonen (2007).*



	Definitional perspectives				
Contribution	Component commonality	Component combinability	Function binding	Interface standardization	Loose coupling
Evans (1963), Charnes and Kirby (1965), Evans (1970), Passy (1970), Emmons and Tedesco (1971), Rutenberg and Shaftel (1971), Shaftel (1972), Silverma (1972), Shaftel and Thompson (1977), Dogramaci (1979), Karmarkar and Kubat (1987), Golberg and Zhu (1989), Goldberg (1991), Kim and Chhajed (2000), Kota et al. (2000), Yigit et al. (2002)	●				
Starr (1965), Rutenberg (1971), Karmarkar and Kubat (1987), Wijngaard (1987), Romanos (1989), Cohen et al. (1992), Langlois and Robertson (1992), Pels (1992), Pine (1993), Kohlhase and Birkofer (1996), He and Kusiak (1997), Lee and Tang (1997), Lundqvist et al., (1996), van Hoek and Weken (1998), Ernst and Kamrad (2000), Swaminatham (2001), Salvador et al. (2002)		●			
Pahl and Beitz (1984), Baldwin and Clark (1997), Baldwin and Clark, (1997b), Jiao and Tseng (1999), Jiao and Tseng (2000), Baldwin and Clark (2000), Kamrani & Salhieh (2000), Kusiak (2002)		●	●		
Matutes and Regibeau (1988), Hsuan (1999), Kogut and Bowman (1995), Fine (1998), O'Grady (1999), Shaefer (1999), Fine (2000)		●		●	
Schilling (2000), Mikkola and Gassman (2003)		●		●	●
Henderson & Clark (1990), Ulrich and Seering (1989), Ulrich and Seering (1990), Kusiak and Huang (1996), Erens and Verhulst (1997), Kusiak and Huang (1997), Huang and Kusiak (1998), Thomke and Reinertsen (1998), Tseng (1999), Tsai and Wang (1999), Wang (1999), Stone et al. (2000), Dahmus et al. (2001), Fleming and Sorenson (2001), Kaski & Heikkila (2002), Marshall and Leaney (2002)			●		
Ulrich (1995), Erixon (1996), Sanchez (1999), Sundgren (1999); Baiman et al. (2001), Chakravarty and Balakrishnan (2001), Fujita (2002), Dobrescu and Reich (2003)			●	●	
Ulrich and Tung (1995), Chen et al. (1994), Ulrich (1994), He and Kusiak (1997), Ericsson and Erixon (1999), Baiman et al. (2001); Dahmus et al. (2001), Tsai et al. (2003)			●		●
Link & Tassey (1987), Momme et al. (2000), Garud and Kamaraswamy (1993), Garud & Kamaraswamy (1995), Sanchez and Mahoney (1996), Galvin (1999), Worren et al. (2002)				●	
Stevens et al. (1974), Sanchez (1995), Sanchez (2000)				●	●
Parnas (1972a), Parnas (1972b), Parnas, Clements and Weiss (1985), Orton & Weik (1990), Shirley (1992), Newcomb et al. (1998), Langlois (2002), Mikkola (2003), Sosa et al. (2003).					●

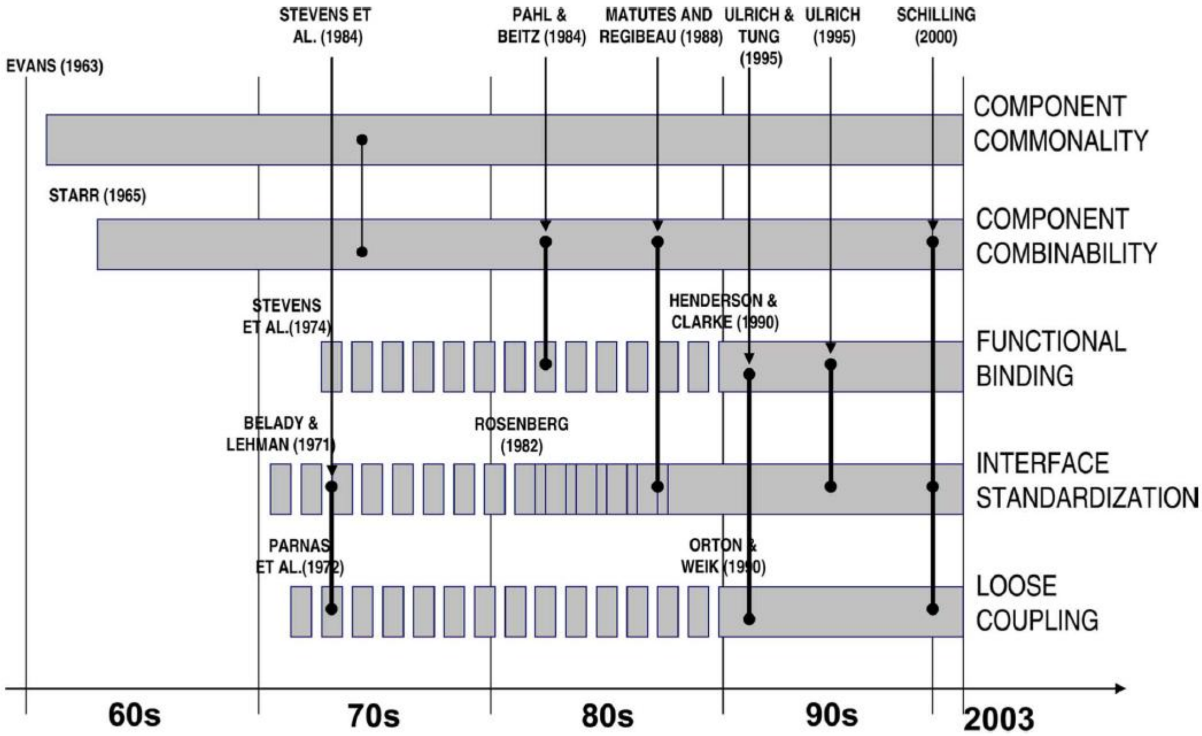


Figure 3.84. *Perspectives on product modularity and their historical evolution (Salvador 2007).*

Gershenson et al. (2007) have analysed existing literature on modularisation, product family development and platform development. The main contribution of this publication is a research roadmap for product family design, which is shown in Figure 3.85. The roadmap includes three elements: single product modular product design, in-time product family design and over-time product family design. Gershenson et al. describe how in-time factors present design factors that are static and over-time factors present dynamic nature that might change over time. They explain that over-time factors include technological, market and life-cycle changes. Gershenson et al. state that the issues presented in Figure 3.85 should be considered in robust product family design.

Gershenson et al. highlight several questions related to product family development. From a single product perspective they explain that the main question is: "*How can one systematically achieve modular product design*?" Gershenson et al. present five more specific questions that should be considered in order to answer the key question:

- *"How does one define, represent and assess modules?"*
- *"At what level should the modules be defined?"*
- *"How does one define, represent and assess the interfaces between modules?"*
- *"What is the effect of taking a life-cycle perspective on modular design?"*
- *"How does the drive (market or technology) for modularity affect the modular design process?"*

They also emphasise how modular product architectures in the design process should be presented, and discuss matrix and function-structure approaches as widely accepted methods as an example. Gershenson et al. criticise the lack of interface design methods in modular research. They also discuss life-cycle perspective and note that there are different drivers (organisationally internal and external) for the modularisation, and thus modularisation can facilitate a specific life-cycle process as well.

From a product family viewpoint the main question, according to Gershenson et al., is: "*How does one systematically achieve product family design?*" They discuss the inputs and outputs of product family design methods. It is stated that inputs are either a set of separate products or customer requirements and market segment information, as well as also being a method to affect product modularity. As an output they expect a classification of platform (common) elements or modules and variant (differentiating) elements or modules. These together form products of the product family, according to Gershenson et al. More detailed questions are also presented for product families:

- *"How does one define and assess product families?"*
- *"How does one define and assess platforms within these families and when should platforms be used?"*
- *"At what level should product families be defined and in what situations are each of these and product families themselves beneficial?"*
- *"What is the effect of taking a life-cycle perspective on product family design and process design?"*

Gershenson et al. (2007) have noticed that both top-down and bottom-up approaches exist for defining product families, and several measures exist for assessing product families. They still criticise the fact that the connection to single product factors, as shown in Figure 3.85 for product family design methods, is missing. Gershenson et al. highlight how product families can be designed based on commonality and variety at several levels, such as in functions, components, sub-systems, market segments, brand positioning, manufacturing, supply and distribution chains, design processes or technology. They state that the larger scope of product family design can be better understood when product family design is first seen individually at each level, including the understanding of differences that existing methods include on that specific level. Gershenson et al. conclude that after this it is then easier to discuss at which level the product family design should take place. They add that an understanding of the impacts of product family design decisions on life-cycle cost facilitates this objective. Thus they conclude that different design methods, measures or combinations of them suit different scopes.

The bottom of Figure 3.85 includes dynamic factors related to product family development. Gershenson et al. suggest that product family design methods should consider planned changes over the life of the product family. They also note that there are risks for unplanned innovation due to external push of technology or the external pull of the market place. These are also important aspects in product family development and Gershenson et al. highlight the importance of recognising factors that particularly affect technological change. To this issue they suggest cross-functional consideration.

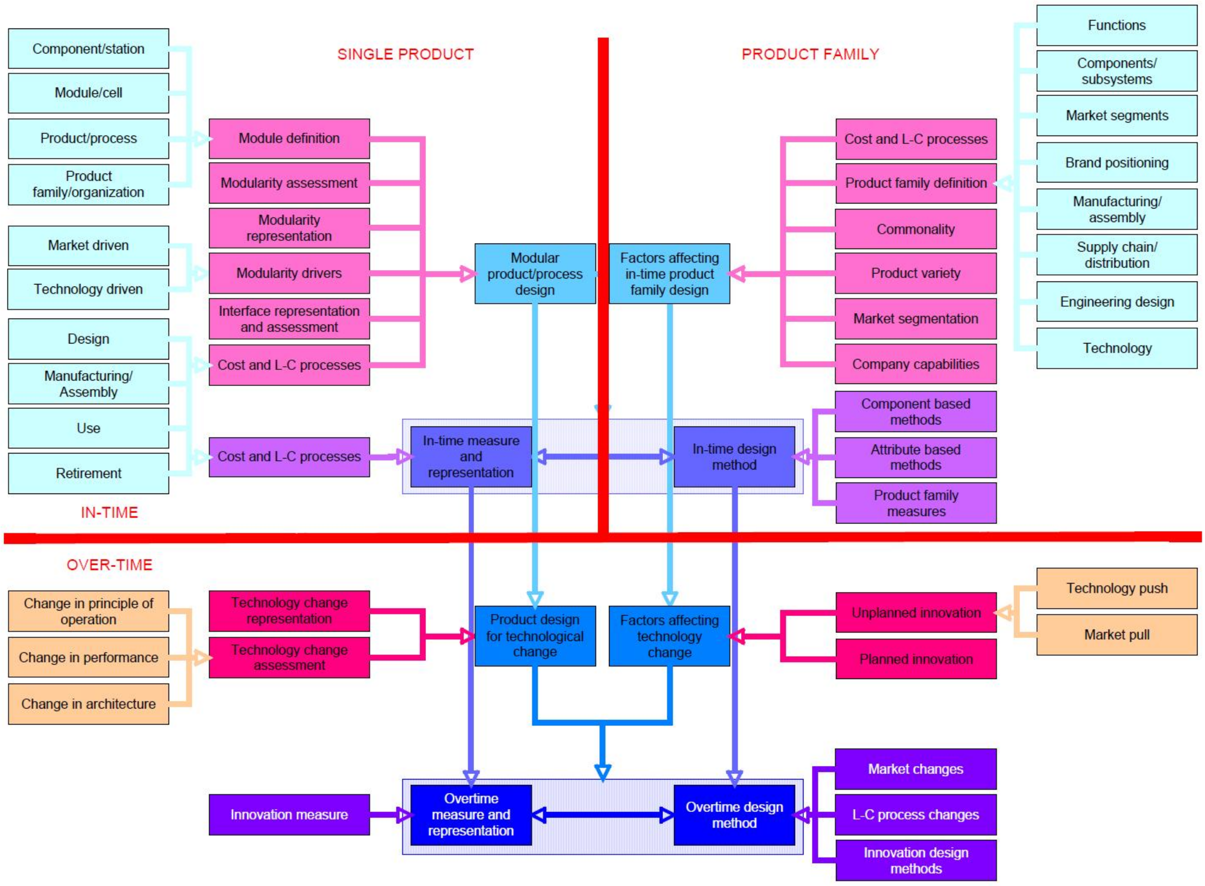


Figure 3.85. *Product family design research roadmap according to Gershenson et al. (2007).*

Borjesson (2010) has aimed at finding an approach for comparing modularity approaches and for studying whether or not derived approaches are better than originals. He has compared five modularity approaches using the criteria shown in Table 3.15. Four of those methods are mainly matrix based: Design Structure Matrix (DSM) (Hölttä-Otto 2005), Extended Implementation Structure Matrix (eISM) focusing on human, environment and technical systems and their relations (Sellgren & Anderson 2005), Modular Function Deployment (MFD) (Erixon 1998) and Functional-Strategic DSM (FS-DSM) (Blackenfelt 2001). One approach is heuristics (Stone et al. 2000). Results of the review are shown in Table 3.16.

Table 3.15. *Borjesson (2010) used 12 criteria for comparing modularity approaches.*

Criteria	Explanation
Flexibility	Method is flexible, allows adjustments
Concurrent execution	Promotes concurrent execution in groups
Easy to learn & use	Easy to learn, well-known concepts
Software support	Conducive to software support, including large projects
Design handover	Simplify handover from concept phase to detailed design
Repeatable	Method is repeatable and allows iterations
Competitive	Method represents an improvement over existing methods
Scientific	Based on science, valid, verifiable, accurate
Support interfaces	Supports generation of interfaces in modular architecture
Common sense	Allow common sense (physics & product geometry)
Specific to modularity	Specific to generation of modular architecture
Describe data	All data, including customer requirements and strategic intent

***Table 3.16.** Results of how different approaches support certain criterion (Borjesson 2010).*

	Heur.	DSM	eISM	MFD	FS-DSM
Concurrent execution	○	◑	●	●	●
Software support	◑	●	●	●	●
Describe data	○	○	◑	●	◑
Support interfaces	○	○	◑	●	●
Specific to modularity	●	◑	●	●	●
Easy to learn & use	○	●	◑	◑	○
Design handover	○	◑	◑	●	◑
Scientific	○	◑	◑	◑	◑
Repeatable	◑	●	◑	◑	◑
Competitive	●	◑	●	●	◑
Flexibility	●	○	◑	●	◑
Common sense	●	●	◑	○	●

●	Strong support
◑	Medium support
○	Weak support
	No support

Two of the criteria are directly related to modularisation: “support interfaces” and “specific to modularity”. Other criteria are more generic. The results by Borjesson explain that of these selected approaches the MFD is the most comprehensive, using the selected criteria. Borjesson’s background is in the management consultant company Modular Management, which applies MFD in their operations.

Daniilidis et al. (2011) consider DSM (Pimmler & Eppinger 1994), Function Heuristics (Stone et al. 2000), MFD (Erixon 1998) and Design for Variety (Martin & Ishii 2002) as the key modularisation methods. Daniilidis et al. have presented a classification framework focusing on the application area and the capabilities of each modularisation methodology. They discuss how the important issues that describe the application area are product variety (capability of method in identifying modules in one or more product architectures), product generation (future product generations and new product development and redesign considerations) and product life-cycle (considerations of life-cycle issues in modularisation). Figure 3.86 present examples of the previously mentioned four modularisation methods applied to their framework, based on the literature review by Daniilidis et al. This figure illustrates that none of the selected methods alone is enough if all perspectives are hoped to be considered. This categorising suggests that all of these approaches are based on reengineering rather than on pure new product development. In the paper by Daniilidis et al., it is argued that functional-based modularisation methods can be applied in more different cases than component-based methods when product variety dimensions are considered. They state that component-based methods are better in the optimisation of single products. It must be remembered though that standardisation of components, assemblies or solutions is necessary in order to achieve true benefits of product families and not just single products.

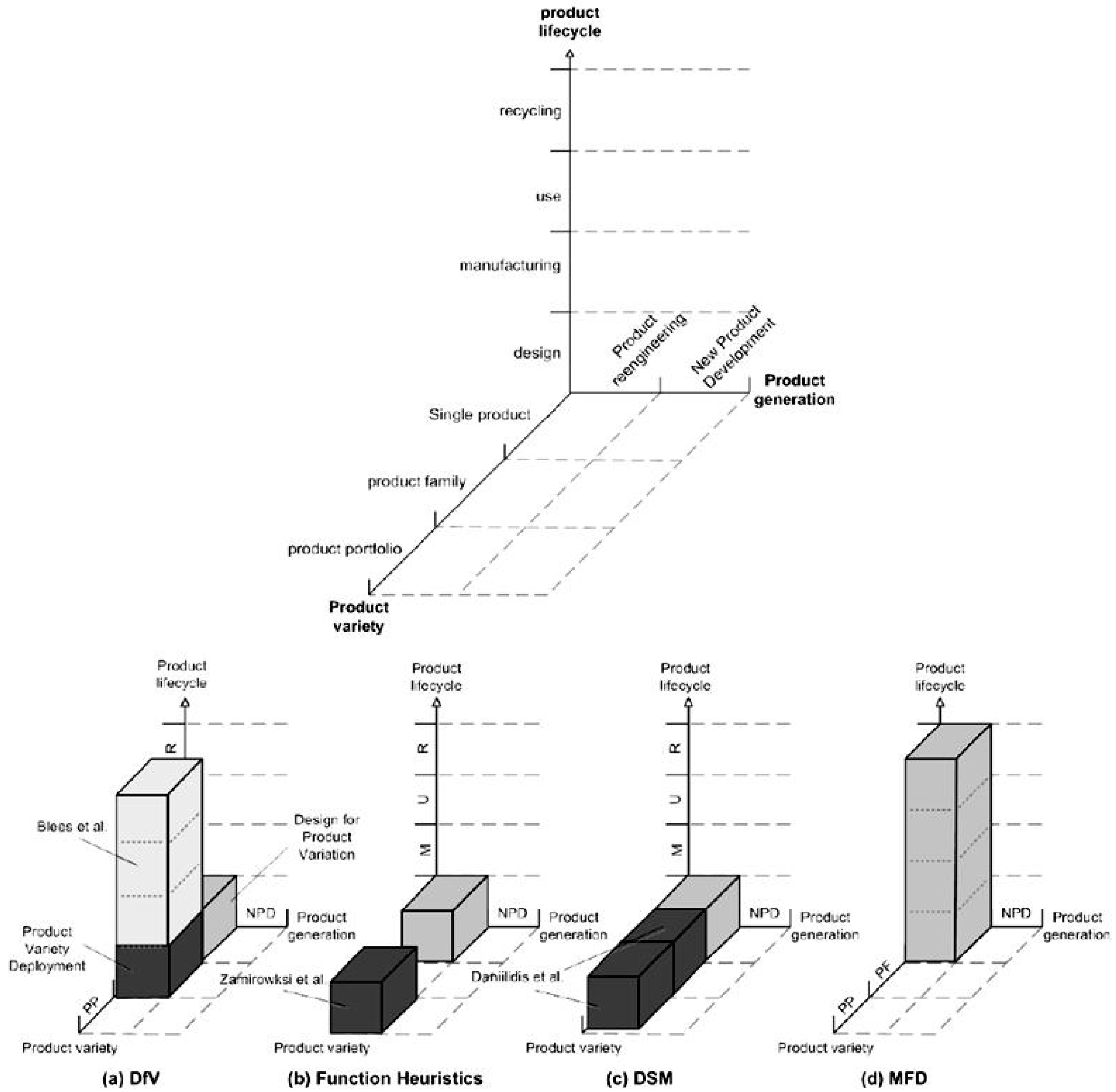
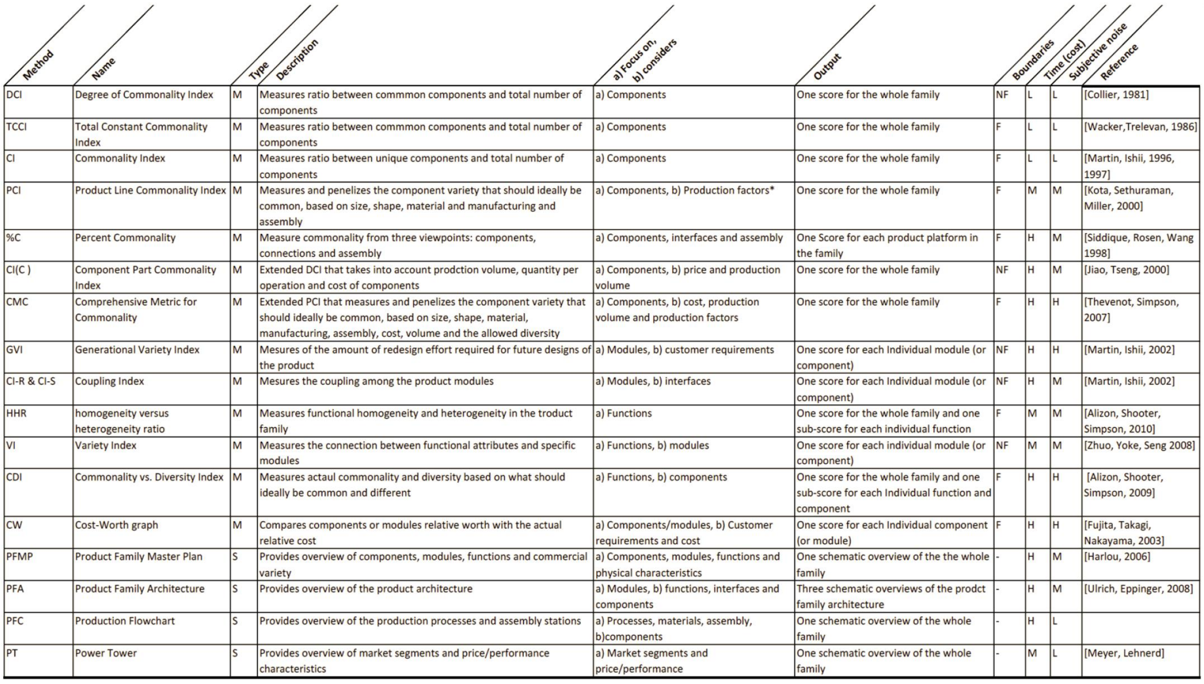


Figure 3.86. *Classification framework for modularisation methods and four methods applied to this framework (Daniilidis et al. 2011).*

Nomaguchi et al. (2012) discuss that the selection of a method to be applied to product platform and product family designing is complicated because there are many different methods that vary in type, focus and complexity. They have presented a Design Method Selection Matrix (DMSM) for this issue. Nomaguchi et al. explain that research within product platforms has led to various evaluating methods for existing product platforms. Thus their review mainly considers different indices, but some other approaches are also included such as PFMP by Harlou. Table 3.17 summarises characteristics of methods according to Nomaguchi et al. They consider that there are two types of methods, mathematical (M in Table 3.17), and schematic (S in Table 3.17). Boundaries of numerical scores in evaluation are discussed in Table 3.17. Nomaguchi et al. explain that these are relevant only for mathematical approaches. They explain that these can be either fixed (F) or non-fixed (NF). In Table 3.17, time relates to how much information is required and how demanding the analyses are. Here a scale of low (L), medium (M) or high (H) is used. Subjective noise is an estimation of how much the output of the method differs if different persons conduct the method separately and compare the results afterwards, according to Nomaguchi et al. This estimation uses the same scale as the estimation of time impacts.

Table 3.17. *Nomaguchi et al. (2011) have studied several methods mainly focusing on indices.*



Method	Name	Type	Description	a) Focus on, b) considers	Output	Boundaries	Time (cost)	Subjective noise	Reference
DCI	Degree of Commonality Index	M	Measures ratio between commmon components and total number of components	a) Components	One score for the whole family	NF	L	L	[Collier, 1981]
TCCI	Total Constant Commonality Index	M	Measures ratio between commmon components and total number of components	a) Components	One score for the whole family	F	L	L	[Wacker,Trelevan, 1986]
CI	Commonality Index	M	Measures ratio between unique components and total number of components	a) Components	One score for the whole family	F	L	L	[Martin, Ishii, 1996, 1997]
PCI	Product Line Commonality Index	M	Measures and penelizes the component variety that should ideally be common, based on size, shape, material and manufacturing and assembly	a) Components, b) Production factors*	One score for the whole family	F	M	M	[Kota, Sethuraman, Miller, 2000]
%C	Percent Commonality	M	Measure commonality from three viewpoints: components, connections and assembly	a) Components, interfaces and assembly	One Score for each product platform in the family	F	H	M	[Siddique, Rosen, Wang 1998]
CI(C)	Component Part Commonality Index	M	Extended DCI that takes into account prodction volume, quantity per operation and cost of components	a) Components, b) price and production volume	One score for the whole family	NF	H	M	[Jiao, Tseng, 2000]
CMC	Comprehensive Metric for Commonality	M	Extended PCI that measures and penelizes the component variety that should ideally be common, based on size, shape, material, manufacturing, assembly, cost, volume and the allowed diversity	a) Components, b) cost, production volume and production factors	One score for the whole family	F	H	H	[Thevenot, Simpson, 2007]
GVI	Generational Variety Index	M	Mesures of the amount of redesign effort required for future designs of the product	a) Modules, b) customer requirements	One score for each Individual module (or component)	NF	H	H	[Martin, Ishii, 2002]
CI-R & CI-S	Coupling Index	M	Mesures the coupling among the product modules	a) Modules, b) interfaces	One score for each Individual module (or component)	NF	H	M	[Martin, Ishii, 2002]
HHR	homogeneity versus heterogeneity ratio	M	Measures functional homogeneity and heterogeneity in the troduct family	a) Functions	One score for the whole family and one sub-score for each individual function	F	M	M	[Alizon, Shooter, Simpson, 2010]
VI	Variety Index	M	Measures the connection between functional attributes and specific modules	a) Functions, b) modules	One score for each individual module (or component)	NF	M	M	[Zhuo, Yoke, Seng 2008]
CDI	Commonality vs. Diversity Index	M	Measures actaul commonality and diversity based on what should ideally be common and different	a) Functions, b) components	One score for the whole family and one sub-score for each Individual function and component	F	H	H	[Alizon, Shooter, Simpson, 2009]
CW	Cost-Worth graph	M	Compares components or modules relative worth with the actual relative cost	a) Components/modules, b) Customer requirements and cost	One score for each Individual component (or module)	F	H	H	[Fujita, Takagi, Nakayama, 2003]
PFMP	Product Family Master Plan	S	Provides overview of components, modules, functions and commercial variety	a) Components, modules, functions and physical characteristics	One schematic overview of the the whole family	-	H	M	[Harlou, 2006]
PFA	Product Family Architecture	S	Provides overview of the product architecture	a) Modules, b) functions, interfaces and components	Three schematic overviews of the prodct family architecture	-	H	M	[Ulrich, Eppinger, 2008]
PFC	Production Flowchart	S	Provides overview of the production processes and assembly stations	a) Processes, materials, assembly, b)components	One schematic overview of the whole family	-	H	L	
PT	Power Tower	S	Provides overview of market segments and price/performance characteristics	a) Market segments and price/performance	One schematic overview of the whole family	-	M	L	[Meyer, Lehnerd]

Based on the review done by Nomaguchi et al., it can be stated that indices focus on different aspects such as the number or ratio of common/unique components, component/unit cost, production volume, size, shape, material, manufacturing process, assembly and fastening types and modules likely to change. Indices can be helpful in evaluating existing solutions from a different perspective, but from a modularisation perspective they do not facilitate the designing of modular structures alone.

Okundan Kremer & Gupta (2013) have studied different modular design methods from an assembly and variety perspective using two different cases. The methods were the function heuristic method by Stone et al. (2000), the behavioural-driven function-environment-structure (B-FES), the modelling framework by Zhang et al. (2006) and the decomposition approach by Huang & Kusiak (1998). A study by Okundan Kremer & Gupta shows that the use of different approaches for modularisation also resulted in a different number of modules. This demands that the results of the modularisation are analysed from an objective viewpoint after designing.

Krause & Ripperda (2013) have analysed different methods for the development of modular product families. A summary of their analysis is shown in Table 3.18. Krause & Ripperda explain that they chose the criteria based on the literature review, focusing on the issues each approach should consider in order to result in an optimal product family for projects they have done. Selected approaches by Krause & Ripperda are discussed briefly in the following. According to Krause & Ripperda, the approach by Caesar (publication in German, see original paper by Krause & Ripperda for the reference) is a cost- and market-oriented approach for designing product variants. They explain that it highlights the role of the variant tree for analysis but that the method does not offer extensive support for variant design at all stages of product development. Of these selected approaches, the methodologies by Pimmler

& Eppinger 1994, Kusiak & Huang (1996), Erixon 1998 (see Chapter 3.8.4 of MFD) and Lindemann et al. 2009 emphasise matrix-based approaches. Viewpoints by Ulrich & Eppinger were already discussed in Chapters 3.5.6 and 3.8.3. Ulrich & Eppinger discuss the linking of functionalities to physical components and they also discuss the formation of architectures. According to Krause & Ripperda, the modularisation method set forth by Göpfert (publication in German; see original paper by Krause & Ripperda for the reference) considers function structure in the defining of modules. This approach also links organisational structures to modularisation as defined by Krause & Ripperda. Heuristics by Stone was also considered in this comparison. This approach considers functions and different heuristics as main elements in modularisation. The method by Jiao & Tseng (1999) focuses on the defining of a product family architecture considering functional, technical and physical views. Martin & Ishii (2002) have presented design for variety method, including indices for measuring redesign effort for future product designs and coupling among product components. Krause & Ripperda explain that the approach by Schuh (publication in German, see original paper by Krause & Ripperda for the reference) focuses on complexity management and cost- and assembly-oriented strategic modularisation. The integrated approach to product family design by Simpson et al. (2012) is a compilation of several separately presented approaches. It includes the defining of the product, differentiation and commonality plans. Hölttä-Otto (2006) discuss evaluation metrics for product platform concepts from the viewpoints of customer satisfaction, variety, after sale, organisation, flexibility to change and complexity. Approaches by Harlou (2006) were discussed in Chapter 3.8.6. He highlights the role of architectures in modular product family development. The research group of Krause & Ripperda have presented the Integrated PKT-Approach for developing modular product families. This was discussed in Chapter 3.8.5 in greater detail. By using the criteria shown in Table 3.18, Krause & Ripperda state that their approach is strong regarding many criteria. They also explain that their approach has been influenced by several other methodologies and thus it is not completely different, but this can also be considered as a natural path in the development of methods.

Table 3.18. *Krause & Ripperda (2013) have analysed different methodologies for development of modular product families and how these methods fulfil the chosen criteria.*

○ not/weakly considered
◑ partially considered
● mainly considered

		methodologies															
		Caesar	Pimmler/Eppinger	Ulrich/Eppinger	Kusiak/Huang	Stone	Göpfert	Erixon	Jiao	Martin/Ishii	Schuh	Simpson	Hölttä-Otto	Harlou/Mortensen	Pahl/Beitz	Lindemann	Krause
	year	1991	1994	1995	1996	1997	1998	1998	1999	2002	2005	2005	2005	2006	2007	2009	2011
criteria	product variety	●	○	◑	◑	●	○	◑	●	●	●	●	○	●	◑	○	●
	technical-functional modularization	○	●	●	●	●	●	○	●	●	○	●	●	●	●	●	●
	product strategic modularization	◑	◑	◑	○	○	◑	●	●	◑	◑	○	○	●	○	◑	●
	product-related visualization	○	○	○	●	◑	●	◑	◑	○	○	○	◑	◑	●	◑	●
	redesign for modularization	●	○	○	○	◑	○	◑	○	●	●	◑	○	●	◑	◑	●
	integration of interdisciplinary expertise	●	◑	●	○	◑	●	●	◑	○	●	◑	○	●	◑	◑	●
	guideline	●	●	◑	◑	●	●	●	○	●	◑	●	●	◑	◑	●	●
	tailored to corporate situation	●	●	◑	○	●	●	●	○	◑	●	●	○	●	●	●	◑
	usability in corporate context	●	●	●	●	●	●	●	○	◑	●	◑	◑	◑	●	●	●
	product program view	○	○	◑	○	○	◑	◑	●	○	◑	○	◑	◑	○	○	○
	process and company structures	◑	●	●	○	○	●	●	●	○	◑	○	○	●	○	●	○
	costs	●	○	●	◑	◑	○	●	●	○	●	○	○	●	◑	○	○
	concept evaluation	●	○	●	○	●	●	●	●	○	●	●	●	●	●	○	◑

Information retrieval as seen by the author of the thesis provides another view of the generic picture of the history and current state in the modularisation, product platform and product family methodologies and approaches. This review was made by using mainly Scopus (www.scopus.com) and the Design Society (www.designsociety.org) databases. The search focused on articles, book chapters and conference papers related to engineering and physical products. Search terms were limited to the title. Search terms included the following terms and their combinations alphabetically:

- configurable AND product
- configuration AND product
- design AND reuse
- design AND re-use
- interface AND defining
- interface AND definition
- interface AND description
- interface AND design
- interface AND designing
- interface AND documentation
- modular
- modularisation
- modularization
- modularity
- module
- platform
- product AND architecture
- product AND families
- product AND family
- product AND interface
- product AND platform
- product AND structure
- product AND structuring
- redesign
- standard AND interface
- standardised AND interface
- variety AND management

The aim of the review was to focus on a search of publications later than 2006. This is because the content of the review articles done in 2007 (for example, an often-cited article by Jiao et al. (2007)) is often considered to include state-of-the-art methodologies, although several approaches have also been presented since then and Jiao’s article is not comprehensive from our perspective. In the research group of the author of this thesis, doctoral dissertations related to the main topics of the thesis have been written during the years 2007 and 2008 (Lehtonen 2007, Pulkkinen 2007 and Juuti 2008). This was also one motivation for mainly focusing the literature research on the various approaches to the years 2007 and later. This focusing does not, however, mean that earlier research should be forgotten completely and should not be acknowledged. Therefore, the summary presented in Table 3.19 made by the author also includes approaches presented prior to the year 2007 which have not been discussed earlier in this thesis in detail. As can be seen, the quantity of the approaches is high. For this reason, the approaches are not described in detail in this review, but the idea has been to map the main content such as method steps, if available, alongside the "big picture" of the other publications in this research field in order to better understand the current state of the research context.

Table 3.19. *Summary of the other approaches (in addition to approaches discussed earlier in this thesis) related to modularisation, product platform and product family development.*

Reference	**Name of the methodology**	**Summary of the approach / type of the approach / focus area**	**Validation**
Pimmler & Eppinger (1994)	Integration analysis methodology for defining of architectural chunks	Method includes three steps: 1. Decompose the system into elements. Elements can be functional (novel design situation) or physical elements (incremental design situation) which fulfil the product functions. 2. Document the interactions between elements. Interactions can relate to spatial, energy, information and materials and they can be positive or negative. Matrix tool is suggested (DSM). 3. Cluster the elements into chunks based on product design strategy. Resulting chunks describe the product architecture. There exists clustering algorithms which aim to reorder the matrix in a way that elements would be closer to the diagonal.	Automotive climate control system
Kusiak & Huang (1996)	Methodology for determining modular products	Interaction graphs are used for describing products. Heuristic algorithm with fuzzy rules (defined by product experts) is used for clustering and defining of module components.	Multichip modules
Martin & Ishii (1997), Martin & Ishii (2002)	Design for Variety (DfV)	Indices (for guiding of designers from design parameter perspective)	Instrument cluster (Martin & Ishii 1997), water cooler (Martin & Ishii 2002)
Meyer & Lehnerd (1997)	Power tower and a process for defining platform strategy	Power tower is a generic model of product and process innovation in platform environment highlighting market segmentation grid (segments vs. cost/performance classes), product platforms and common building blocks. Platform strategy defining process includes five steps: 1. Segment markets 2. Identify growth areas 3. Define current platforms 4. Analyse competing products 5. Consider future platform initiatives.	Several examples
Huang & Kusiak (1998)	Matrix representation of the modularity problem	Matrix-based approach for analysing modularity and focusing on interactions and suitability.	Electric motor
Siddique et al. (1998),	Product Family	Identifying of common platform with	Automotive parts

Siddique & Rosen (2000)	Reasoning System (PFRS)	the help of mathematical modelling aspects, measures	(Siddique et al. 1998), coffee maker (Siddique & Rosen 2000)
Jiao & Tseng (1999)	Product family architecture (PFA) methodology	Focusing on functional, technical and physical views and utilising of mathematical functions	Power supply
Gonzalez-Zugasti et al. (2000)	Platform-based product family design process	Relatively abstract and expertise-oriented process including main steps of: 1. requirements and model gathering, 2. platform design, 3. variants design and 4. platform evaluation and re-negotiation.	Spacecraft and telecommunications
Jiao & Tseng (2000)	Commonality measurement for product family	Indices	Power supply
Stone et al. (2000)	Product architecture design methodology and heuristic methods for identifying modules from functional models	Method includes five steps: 1. Gather customer needs 2. Derive functional model 3. Identify product architecture 4. Generate modular concepts 5. Embody design Paper presents an approach for identifying modules for product architectures from function structures using three strategies named as heuristics. These heuristics are discussed in step 3 of the method: 1. Dominant flow: A flow (material, energy, signal) that passes through a product unchanged defines a module. - Branching flow: A flow branches forming independent function chains, these limbs constitute modules. - Conversion: A flow converts to another type. These sub-functions are modules themselves in many cases according to authors.	Power screwdriver and other consumer applications
Umeda et al. (2000)	Post mass production paradigm	Life cycle based simulation for defining of modular structures	Refrigerator
Dahmus et al. (2001)	Portfolio architecting process	Functional modelling -based method for partitioning a set of products into shared and individual modules. 1. Define technologies to be used and define limits of the product family. 2. Develop independent concepts for each product. 3. Develop function structures for each concept. 4. Define family function structure. 5. List functions in the family versus the products in the family using modularity matrix. 6. Use modularity matrix in constructing different product and portfolio architectures.	Power tools with rechargeable battery pack

		7. Select feasible architectures using a selection method.	
Simpson et al. (2001), Farrell & Simpson (2003)	Product Platform Concept Exploration Method (PPCEM)	Process for designing of scale-based product families including mathematical models. Main steps include: 1. Create market segmentation grid. 2. Classify factors and ranges. 3. Build and validate metamodels. 4. Aggregate product platform specifications. 5. Develop product platform and family.	Universal electric motor (AC/DC) (Simpson et al. 2001), valve yoke (Farrell & Simpson 2003)
Fellini et al. (2002)	Platform selection under performance loss constraints with optimal design of product families	Methodology for making commonality decisions based on mathematical algorithm.	Automotive side frames
Forza & Salvador (2002)	Configuration system	The role and effects of configuration systems in the product variety management in the order process.	Case company with power electric transformers
Fujita (2002)	Module attribute optimisation and module selection optimisation across product variety	Mathematical formulations and optimisation procedures.	Aircraft, television receiver circuits
Andersson & Sellgren (2003)	Non method paper	This paper highlights that consideration of interfaces has been low in earlier publications although they are often mentioned as important issues in modularisation. Authors deal mostly with mechanical interfaces explaining that they represent many types of mechanical contacts from static contacts to lubricated and moving contacts.	A test gearbox
Gershenson et al. (2003)	Non method paper	Definitions and benefits of modularity (business impacts) based on the literature review.	none
Halman & al. (2003)	Non method paper	Discusses mainly about the risks and benefits in platform-driven development of product families (business impacts).	Three companies
Hölttä & Salonen (2003)	Comparing of three modularity methods (function structure heuristics, MFD and DSM)	Different methods produce different results. The choice of method depends on the case. Repeatability of the methods is different.	Camera, electronic pipette, injectors
Sharman & Yassine (2004)	DSM, Molecular Diagrams and Visibility-Dependency signature diagrams	Discusses mainly about the DSM in describing product architectures.	Gas turbine
Sosa & al. (2004)	Comparing and analysing the	Paper discusses about product architectures and interfaces from	Aircraft engine

	product architecture with its development organisation	organisation (design teams) perspective and presents a process for studying the issue including following main phases: 1. Identify design interfaces 2. Identify team interactions 3. Map design interfaces and team interactions 4. Analyse the alignment matrix	
Mortensen et al (2005)	Non method paper	Differences and experiences between single and multi product development. Transition levels from projecting single product development to multi product development. Level 0. Autonomous projects Level 1. Informal architecture Level 2. Management driven reuse of standard designs Level 3. Explicit architectures – not reuse (first generations of products) Level 4. Continuous development based on architecture Level 5. Architecture based product development with a performance measurement system.	Experiences in companies
Zhang et al. (2005)	Non method paper	Configuration modelling process. Product configuration modelling includes capturing and representing of product knowledge.	Personal computer
Avak (2006)	Module sheets	Author presents module sheet that considers module characterisation (version, validity, relevant documents, variants and options, usage list, envisaged changes), module interfaces (geometry, energy, signal or material, interface document) and module configuration (restrictions). The aim of the module sheet is to ensure that the key properties of a modular product family are maintained through different adaptations. It is also explained that if a module has different variants, only one module sheet should exist because interfaces should be similar with different module variants.	Power supply, rail manufacturer, medical technology manufacturer, semiconductor equipment manufacturer
Ong et al. (2006), Xu et al. (2007)	Product family design reuse (PFDR) method	Main steps of this key characteristic (engineering metrics) and function-oriented method are: 1. Product case modelling 2. Knowledge extraction 3. Design synthesis and evaluation	Cellular phone
Thevenot et al. (2006)	Framework for product family redesign	Ontology, commonality index and genetic algorithm based redesign framework.	Stapler
Zhang et al. (2006)	Modular functional design methodology for	Method includes following steps: - customer needs analysis - grouping of the needs into different	Terminal insertion device

	conceptual design	functional modules - searching of matching behavioural modules from the behavioural module library (behaviour describes how the design does what it does and it is higher level of abstraction than structure) - transforming behavioural modules into structural modules - using of structural modules to develop detailed modular product architectures	
Alizon et al. (2007a)	Method for improving an existing product family	Value analysis (selecting of technical solutions for functions), DSM and commonality vs. diversity index based approach.	Refrigerator
Alizon et al. (2007b)	Framework of product family design processes	Generic framework of product family design process alternatives focusing on market, functional and component aspects including: - top-down platform driven, - top-down product-driven, - bottom-up platform-driven and - bottom-up product-driven. Bottom-up approaches are based on existing information.	Product examples from the literature: ice scrapers, cassette players, power tools, lighting control systems
Alizon et al. (2007c)	Product Family Design Process	Process includes following steps: - product leveraging, - product identification, - process driver management - platform integration - technical solutions specification and selection - modules and interfaces specification - scalable components management - architecture management Authors argue that several of the steps, e.g. modules and interface specification, have only partly supporting tools available.	none
Dai & Scott (2007)	Process for designing a multiple-platform product family (scale-based)	Mathematical approach to optimise and select design parameters.	Universal motors
Jacobs et al. (2007)	Non method paper	This study shows that modularity has positive effects on cost, quality, flexibility and time dimensions (business impacts) based on 57 responded to the questionnaire.	Automotive original equipment manufacturers
Jiao et al. (2007b)	A generic genetic algorithm for product family design	Algorithm-based method for designing of product family.	Electronic motor
Meehan et al. (2007)	Multi-viewpoint modular design methodology	Method includes four main steps: 1. The knowledge formalism 2. The interdependency matrix application (DSM) 3. The clustering mechanism	Alternator

		4. The mapping mechanism (cross-viewpoint)	
Pavlic et al. (2007)	Identification of common components in product family	Commonality index and function-component relation based approach.	none
Salhieh (2007)	A methodology to redesign heterogeneous product portfolios as homogeneous product families	Function, function carrier and commonality index based method.	Office furniture
Sosa et al. (2007)	Approach for measuring modularity of product	Authors present three measures for component modularity focusing on: a) the number of components which are directly linked to a specific component (degree modularity) b) distance of a component (in graph theory terms)from all other components (distance modularity) c) components that lie in the dependency path of two components (bridge modularity) Authors suggest that this kind of analysis can be used in supporting decision making related for example to outsourcing and redesign in management and engineer level. Authors have also noted during the dependency analysis of components that design organisation might have been formed in a different way than the component relations would suggest. They argue that this is probably because of all of the relations have not been explicitly mapped. Design dependencies are considered as spatial, structural, material, energy and information related (interfaces).	Commercial aircraft engine
Suh et al. (2007)	Flexible platform design process (FPDP)	The process highlights that "carryover-modified" components should be treated as a flexible elements in designing of new products based on product platform. The iterative process emphasises mathematical descriptions of product family design aspects and consists of seven main steps: 1. Identify market, variants and uncertainties 2. Determine uncertainty related key attributes and design variables. 3. Optimise product family and platform bandwidth 4. Identify critical platform elements 5. Create flexible platform design alternatives 6. Determine costs of design alternatives	Automotive body-in-white

		7. Analyse uncertainties	
Williams et al. (2007)	Augmented Product platform constructal theory method (PPCTM)	Product platform design method with mathematical optimisation functions relying on that the demand for each variant is same in the market. The method includes six steps: 1. Define the geometric space and the demand scenario 2. Define the objective functions 3. Identify the modes for managing customisation 4. Identify the number of stages and define a multi-attribute utility function for each stage 5. Formulate a multi-stage utility-based compromise decision support problem 6. Solve the utility-based compromise decision support problem	none
Ye et al. (2007)	Commonality / variety trade-off angle	Overview on impact factors, their states and how the factors affect commonality and variety (business impacts).	Cordless power tools
Farrell & Simpson (2008)	Product platform portfolio optimisation method	Mathematical optimisation and redesign method including four steps: 1. Determine an optimal component solution for each member in the market segment grid. 2. Test the feasibility of each component of using it as a platform on each market segment grid member. 3. Formulate an optimisation problem to identify the component platform portfolio. 4. Solve the optimisation problem using an algorithm.	Gate valve
Forza & Salvador (2008)	Non method paper	Authors highlight the role of sales and technical configuration models as important for companies offering product variants because the models enable facilitating functions of operations that are supported by IT systems such as PDM.	none
Seliger & Zettl (2008)	Methodology for product modularisation	Method highlights the role of functional carriers in creating of modular architecture. Main steps are: 1. Identifying future potentials 2. Identifying current customer needs 3. Deriving future-robust requirements 4. Developing a conceptual product model for generating modules. 5. Pre-grouping functional carriers and collecting properties 6. Generating and selecting module configurations 7. Definition of the product architecture	Mobile phone
Umeda et al. (2008)	Modular design	Modular structure is defined based on	Printer

	method	the life cycle options of components thus this approach highlights that based on life cycle scenario, modular structure differs. Main steps are: 1. Calculation of similarity of attributes of components by using self-organising maps in order to classify components into different groups with same life cycle. 2. Derivation of physically plausible modular structure by dividing the component groups into modules based on geometric information and connectivity of components.	
Zacharias & Yassine (2008)	Model for platform-based product families	Function-structure is the base for modularisation. No clearly defined steps of the approach. The approach includes mathematical functions from market coverage perspective.	Ice scrapers
Alizon et al. (2009)	Commonality versus diversity index	Index for assessing a product family based on component categories of common, variant and unique.	Single-use cameras, power tools
Cai et al. (2009)	Interface analysis matrix (IAM)	Interface analysis matrix is presented for analysing couplings of product parts. This matrix resembles calculation of coupling index discussed by Martin & Ishii. Matrix studies offering and receiving perspectives of coupling. Design variables are entered in the matrix and their sensitiveness is rated using scores. Authors also suggest rating system for component swapping difficulty, this includes four levels: - Component can be swapped into any variant with no changes (0 points). - Component requires extra mounting hardware to interchange (1) - Component requires redesign of existing interface or extra uniform interface (5) - Component requires extra unique interfaces for each variant (9) Authors explain that architecture is fully modular if it includes only full-zero couplings using above levels.	Cordless drills
Kazemzadeh et al. (2009)	Product family design method composed of conjoint analysis and two-stage clustering method	Market research oriented modified version of QFD’s house of quality (HOQ) including five main steps: 1. Conjoint analysis for all customers 2. Market segmentation by customers’ benefits 3. Conjoint analysis for each segment 4. The HOQ mechanism 5. The analysis of the results	Office chair
Kong et al. (2009)	Framework for modular product development	V-model based approach including functional modularisation (left-hand side of the V-model) and physical	none

	(MPD)	modularisation (right-hand side) viewpoints. Framework includes 15 steps: 1. Product family planning 2. Customer options determining 3. Objectives of modularisation 4. Functions decomposition 5. Identification and definition of modules 6. Identification and definition of interfaces 7. Establishment of architecture 8. Assessment of architecture 9. Physical alternatives 10. Realisation of interfaces 11. Realisation of modules 12. Base-line product physical structure 13. Detailed specifications 14. Building of variants 15. Configuration management of variants	
Kumar et al. (2009)	Market-driven product family design method	Main steps of the method are: 1. Create market segmentation grid 2. Estimate demand model 3. Build models for product performance 4. Profit maximisation model	Universal motors
Rahmani & Thomson (2009)	Interface decomposition method	This paper states that interface control documents (ICD) are only documents without automatic managing possibilities from PLM perspective causing for example difficulties in change management. Authors suggest that interface recognition needs that the product is decomposed into subsystems and boundaries are defined. Authors have functional view on decomposition of the product. DSM, block diagrams and function tree are explained as possible tools for analysing connectivities. The main contribution of the paper is framework for implementing and integrating interface specification into PLM software. Spatial, energy, information and material interfaces and their decomposition into more detailed definitions is discussed using class diagrams and documenting these in XML (extensible mark-up language) format is suggested.	Piston and cylinder
Helmer et al. (2010)	DSM	Paper presents component DSM clustering method with schematic representation of products for definition and identification of modular product architectures (assembly module perspective). Interactions are mapped from	Generic jet engine

		structural, energy, signal, material and spatial perspective.	
Schuh et al. (2010)	Integrated development of modular product platforms	Platform development includes: - definition of common features on function, technology and geometry level. - planning of platform products - definition of platform structure - development of modules. In defining of the geometry level, authors highlight standardising installation space and interfaces. The paper also considers organisational issues.	none
Simpson et al. (2012)	Integrated approach to product family design	Approach includes defining of product plan, differentiation plan and commonality plan based on several separate approaches such as market segmentation grid, indices, DSM (architecture), and optimisation approaches.	Unmanned ground vehicles
Bruun et al. (2013)	Process for bringing modularisation into a PLM system	PLM perspective of modularisation including suggestions for the needed information and how it can be visualised. This paper suggests for example creating and maintaining of interface diagrams.	Loader
Cabigiosu et al. (2013)	Non method paper	This paper discusses about defining of the component-vehicle interfaces in component co-development projects. Authors have noticed that definition of interfaces is not completely guided by the product architecture and technological aspects. They state that also capabilities of OEMs and suppliers, degree of vertical integration (ownerships in the supply chain), knowledge scope and strategic focus are also considerable in the definition of interfaces. Authors for example explain that in a design project of air condition system for a car, the aim of the interface standardisation was not aimed at improving the modularity level but to enable better control of the overall system performance. Authors discuss about three types of interfaces: - open standard interfaces, - closed standard interfaces and - non-standard interfaces. They also discuss that stability of these types of interfaces should be considered (frozen-unstable). For example standard interfaces can be unstable if there is possibility to substitute it with another standard interface.	Vehicle air conditioning systems

The above reviews and comparisons revealed several aspects of modularisation, product family and product platform development approaches. There are multiple different approaches and the subject topic is not completely new, as review articles discussed earlier in this chapter and in Table 3.19 also reveal. Based on the reviews, methods can be categorised as, for example, function-oriented, index-based, mathematical and algorithm-based optimisation methods and matrix-based approaches. Several of the methods fit into these categories. In addition to this, there exist methods in which some special aspect, such as supply chain or assembly perspective, is emphasised when the product is modularised or the product platform or product family is defined.

Well-known (often-cited) approaches and methods can be also be recognised from the review articles. For example, the heuristic method by Stone represents an often-referred-to approach regarding function-oriented methods. Generic algorithm-based publications are common among the approaches using mathematical models and optimisation. Many works have also been published around DSM matrices. As for indices, commonality indices have been discussed in several publications. These are typical approaches discussed in publications within the research context.

Differences exist in the coverage of the methods. Some of the methods focus only on defining a common section of the product family known as a product platform, whereas some methods focus on defining modular architecture more comprehensively. There exist different approaches for these issues, such as the above-mentioned matrix clustering methods, algorithms, mathematical and also more heuristic and generic expert-based methods. Indices and measures are mostly used for analysing an existing product assortment to facilitate the finding of a development focus in this way.

There also exist a lot of publications in which modularisation, product platforms and product families are discussed, but in which actual design method is not presented. These publications often concentrate on discussing benefits and disadvantages in the use of these design strategies. For example, Gershenson et al. (2003), Halman et al. (2003) and Jacobs et al. (2007) include these kinds of considerations. These publications are included in the above table. Not all of the business effects approaches are included in Table 3.19 because the scope of this review was more aligned with actual design methods. If one is interested in reading more about research related to modularisation, product platform and product family business effects, then the following publications may be of interest, in addition to the above-mentioned papers: Hansen & Suh (2010), Kwak & Kim (2010), Jacobs et al. (2011), Harland & Uddin (2012), Danese & Filippini (2013) and Kamrad et al. (2013). Many of the design methods do not include evaluations of the business effects of the designed modular, platform or product family solution, although the importance of this is emphasised in several publications in order to validate the design for a more detailed further development or implementation.

Division to scale-based and modular product families can be recognised from the perspective of designing product variants. In the scale-based variants, the type of design parameters remains the same in different variants but the values of these parameters change. In modular products, products can be varied to customer needs by adding, removing or substituting modules. This division is also visible when the nature of design methods is analysed. Methods using mathematical functions are common with the scale-based approaches (e.g. Simpson et al. (2001)). Mathematical approaches aim to help in the finding of quantitative values for the design parameters. When discussing modular products, the situation is different because all of the variants do not necessarily include the same design parameters, since modules can be different or they are even not included in all of the product variants of the same family.

At the beginning of this chapter, review articles about the methods were discussed. These reviews included different criteria for analysis and comparison of the approaches. Criteria discussed in publications in which methods are compared revealed that approaches can be analysed and classified very differently. Typically, authors who have made these review articles have also presented their own approaches. In these situations, it seems that criteria have naturally been formed from their own approach perspective, highlighting the issues they see as important and what their own method suggests and can fulfil.

Earlier, in the modularisation chapter of this thesis, the important design information elements in modularisation were discussed. Partitioning logic, modules, interfaces, architecture and configuration knowledge were suggested as the main elements which facilitate understanding the central issues in the designing of modular and configurable product in a redesign situation in which commonality and standardisation is pursued. The literature review carried out in this chapter supports the existence of these elements, although configuration aspects are not seen very often in the studied approaches in this chapter. Technology could be another separate element, but in the redesign situation it is considered as a part of modules and interfaces.

When considering partitioning logic, several of the methods highlight the need for customer requirements in application of the method. Ignoring of business requirements cannot be confirmed, although in many of the methods the role of customer requirements is more often highlighted.

Architecture is often also considered in the design methods of modularisation, product platforms and product families. Function structure is often suggested as a starting point for the defining of the modular or product family architecture, but there exist also approaches such as the matrix method by Pimmler & Eppinger (1994), in which it is stated that physical-(component) based consideration is suitable for situations in which the design is based on existing designs. This means that in these situations the structure of the products is better understood and thus the examination is not needed on a function level which can be considered as a more abstract level. Otherwise, defining of the modules is basically considered as a task in the conceptual stage if the traditional division of designing to clarifying of task, conceptual design, embodiment design and detail design (Pahl & Beitz 1996, see Chapter 3.6.1) is used.

The number of relevant publications considering only interfaces in design method level is low, although standardised interfaces are considered an essential part of modularisation. The following terms are often introduced when interfaces are discussed: spatial, geometry, structural, material, energy, information and signal. Of these alternatives, spatial, geometry, structural and material can be considered as a mechanical view (terms include overlapping). Information and signal interfaces can be related to control systems and monitoring of the state of the product. This is a traditional division of interfaces according to the literature review. The viewpoints of Fujimoto (2007) were discussed in the standardisation chapter of this thesis. He categorised interfaces (and also components) to model-specific, company-specific and industry-standard categories. To this topic, the publication by Cabigiosu et al. (2013) (see Table 3.19 also) is a welcome addition. They discussed open standard interfaces, closed standard interfaces and non-standard interfaces and how the standardisation of interfaces affects innovativeness in co-creation development projects. Those authors concluded that the defining of interfaces is not only an architectural question but that the decision making process also includes several issues related to strategy, such as considerations of supply chain questions. Defining the stability of the interface was also suggested. This is because even if the interface is open standard but unstable and not fixed, there can be multiple open standard solutions for the interface, which increases the complexity of product development by changing dispositions.

Integrated configuration aspects for modularisation, product platform and product family design methods are represented in a very limited way in the studied methods. Design methods create design information. For this reason it would be beneficial if the configuration knowledge aspects were considered at this stage of design, because configuration knowledge is at least needed in the sales processes of the company if configurable products are offered to the customers. There exist, however, separate approaches for this task, as the literature review of this thesis has already shown, but integrated methods that include both modularisation and configuration design information aspects are rare.

Thus it seems that the numbers of methods that include an analysis of business and customer requirements explicitly in a modularisation, product-platform and product-family design context are limited. It also seems that management level approaches other than function structure-oriented methods are rare in redesign situations for product assortment. There is also a lack of integration of configuration aspects in a modularisation, product-platform and product-family design method context. In other words, this means a lack of approaches suitable for synthesis that highlight the design information aspects in modularisation and from a configuration environment perspective. Business impact analysis frameworks integrated with design methods are also uncommon among the design methodologies used to validate the partitioning logic and resulting modular product family, although several publications discuss the possible effects of modularisation and the importance of analysing them.

Table 3.19 also included validation aspects. Validations of the methods have usually been done with relatively small products such as handheld power tools. In addition to this, there exist publications which do not include real-life industry cases, but the validations of the approaches have been done with relatively simple products which are familiar to many people, such as office equipment. There also exist publications in which a validation case has been adapted from another publication in which it was originally presented by another author, and the case was then used for comparing the results of the selected methods. In these situations, it has been recognised that the results differ, depending on the method used.

The fit of the studied methods and approaches to the research problem of this thesis is discussed below, using a set of questions describing the main classes of design methods that could be identified based on the literature review done in this section. The aim has been to clarify why specific approaches are not valid answers to the research questions, at least not as separate solutions as they have been presented in the studied publications.

- Why do scale-based methods not solve the research problem?

In fulfilling the variation need, configuration possibilities (such as addition, exclusion and substitution of modules which have different design parameters) for the products have to be considered. This means that scalability analysis (size-ranges with the same design parameters) is not sufficient. This thesis focuses mainly on product variation done with alternative modules.

- Why do mathematical models and optimisation methods and algorithms such as genetic algorithms not solve the research problem?

It is emphasised in several publications that the defining of module structure is concept level designing. Optimisation methods go deeply into details. One challenge is how much input information is available from the module concepts and how many variables can be used in these approaches, because modularisation is a design task that needs to consider several perspectives and a task in which trade-offs necessarily need to be done. Some of the trade-offs are conscious decisions and some are unconscious decisions, which may not reveal themselves until the products are in use or in some other life cycle phase. Another relevant question is how much of the needed information to these methods exists in the early phases of redesigning and what kinds of resources exist for only focusing on the definition of optimisation problem and the modelling of it. In the paradigm of the research and method applying environment for this thesis, mathematical optimisation methods are not tackled but rather these methods are left outside the scope of this work.

- Why do DSM and other matrix based methods not solve the research problem?

Matrices are easy to use and understand for the mapping of relations, even though in the cases in which the number of elements is high, matrices become heavy to read and modify. Matrix- based tools often include clustering algorithms used for reorganising the relation matrices in order to make architectural decisions. The problem is that neither of these approaches removes the need for context expertise in design decision making. Additionally, matrix-based methods are not comprehensive for holistic modularisation, platform development or product family development projects in which other tasks such as objective setting from different perspectives is needed.

- Why do function structure-based methods not solve the research problem?

The weaknesses of these approaches were already discussed in the modularisation chapter of this thesis. In that chapter it was stated that function structure is not an obvious solution for module division in order to enable business benefits based on earlier research.

- Why do index-based methods not solve the research problem?

Indices can be useful in analysing existing products in situations in which it is not known upon which areas the redesign should be focused and in which areas standardisation and modularisation could be beneficial. Indices alone do not help in the designing of modular product families, but the designing of a method that also guides performance of other relevant tasks in creating the needed design information is necessary, such as when considering the configuration aspects and validation of the design.

Consequently it can be stated that, based on the literature review done in this thesis, that the existing research cannot provide a direct solution to the research problem, even though several interesting and also valuable separate contributions have been presented. Thus the purpose of the following section is to define design support that could solve the research problem of this thesis.

4 PROPOSED DESIGN SUPPORT

This chapter presents support for the research problem. Support focuses on defining the important aspects in modularisation, and aims to facilitate the designing of modular product families. In this chapter, the type of product-structuring knowledge that needs to be considered in the designing of variable products in the manufacturing industry is considered. The support also suggests steps for defining the structure of the modular product family. These steps are also discussed in this chapter.

4.1 The Brownfield Process: overview

Several approaches and methods for modular product structuring were dealt with in Chapter 3. It was discovered that there exist design supports, which are also partially suited to the research problem of this thesis, but that a comprehensive approach is missing. Thus in this chapter a process model known as the Brownfield Process (BfP) is proposed for tackling the research problem. The first version of the BfP was presented in Lehtonen et al. (2011b). The author of this thesis was co-author of that paper. In that paper, the process model included five main steps:

1. Defining business targets.
2. Drafting the proposed module architecture using mainly old solutions and components.
3. Updating and rationalising the market and customer requirements.
4. Creating a modular architecture with minimum amount of variation. Defining the amount of new design required.
5. Documenting the reasoning behind the selected architecture.

Although the basic concept is the same, the BfP as discussed in the earlier-mentioned paper is modified in this thesis so that it appears in more manageable sections, and so the content of the process is defined in more detail. The process model presented in this study also consists of new steps that have not been discussed in earlier publications. The BfP as discussed in this thesis is presented in Figure 4.1. The term *Brownfield* originates from the building industry and from modernisation projects of process facilities (Alker et al. 2000). In this context, Brownfield stands for the reusing of available assets, and use of this term includes the notions that there are limitations in designing and solutions because of existing structures. The DRM term *design support* refers to the BfP in this thesis when not specified in other ways.

The BfP includes ten steps, as shown in Figure 4.1. The process starts and ends by considering the business issues, since results of the design have to fit the business environment of the company in order to support competitiveness and profitability. From a design viewpoint, the process focuses on the designing of modular architecture for a product family. Configuration knowledge has also been considered in the process in order to facilitate re-use in the sales-delivery process and because this kind of knowledge also supports documentation of design reasoning and can be helpful in the later possible updating of the product family.

In each step of the BfP, the aim is to define design information related to the specific elements of the Module System. In this thesis it is suggested that the main elements of the Module System are partitioning logic, set of modules, interfaces, architecture and configuration knowledge. The elements are shown in the top row in Figure 4.1. The specific content of these elements was already discussed in Table 3.5. The results of the literature review in Chapter 3.8 regarding design methods in modularisation, product platform, product family and product configuration context support the fact that these elements are important, although a design method that would highlight all of these elements has not been presented. Figure 4.1 also shows which steps of the BfP relate to which elements of the Module System, and are described using blue rectangles. For example, the first step relates to partitioning logic (blue rectangle behind the step's name bar). These relations between process steps and elements of the Module System are explained below. The process steps are explained in more detail in the following Chapters 4.2.1. - 4.2.10.

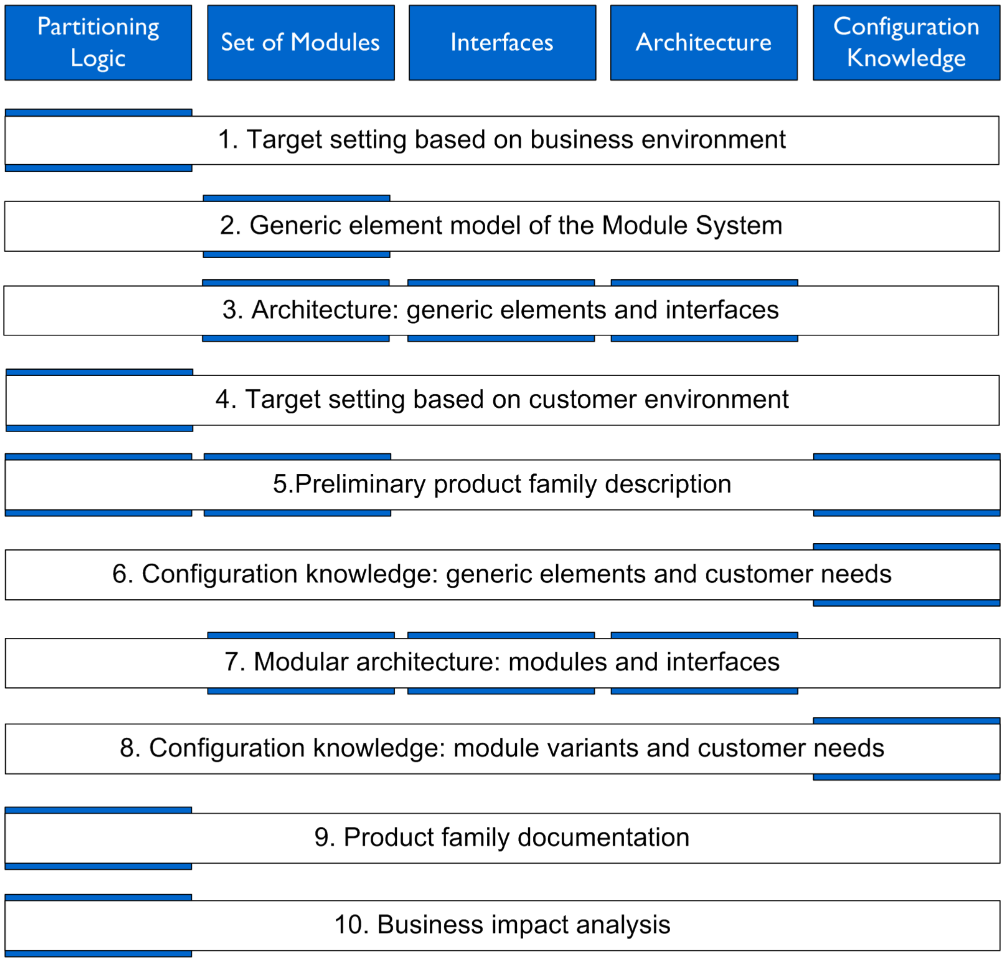


Figure 4.1. *Brownfield Process (BfP). Although the content of the BfP has been presented here as a linear process, the process may involve iteration and customisation. Customisation of the BfP is discussed in Chapter 4.3.*

Partitioning logic is considered in:

- Step 1: Target setting based on business environment: When defining the module division, business objectives should be considered. This step aims to define the business objectives and thus contributes to partitioning logic.
- Step 4: Target setting based on customer environment: Variation needs within a customer context have essential roles affecting partitioning logic of the modular product family.
- Step 5: Preliminary product family description: In this step, preliminary product element division and its reasoning are discussed. Thus this step contributes also to partitioning logic.

- Step 9: Product family documentation: This step illustrates partitioning logic of the designed product family. In documenting the product family, other elements of the Module System are also naturally considered, but the final result of the step represents partitioning logic in particular.
- Step 10: Business impact analysis: In this step, the designed product family is analysed from a business perspective. The result of the business impact analysis reflects how good the partitioning logic of the designed product family is for the company.

Set of modules is considered in:

- Step 2: Generic element model of the Module System: Generic elements are preliminary modules, which are defined in more detail in the subsequent steps of the Brownfield Process.
- Step 3: Architecture: generic elements and interfaces: Architecture, as defined in this step, can be considered as a preliminary modular architecture. Thus preliminary modules are discussed also in this step.
- Step 5: Preliminary product family description: In this step, possibilities for standardising the part sets related to preliminary modules (generic elements) are discussed.
- Step 7: Modular architecture: modules and interfaces: Modules are defined in this step in more detail, taking into consideration different product structuring strategies such as standardisation, configuration using interchangeable modules and delivery specificity. Thus results of this step explain what kind of modules the product consists of.

Interfaces are considered in:

- Step 3: Architecture: generic elements and interfaces: In this step, relevant interfaces between generic elements are recognised. Thus this is the first step that contributes to the defining of interfaces.
- Step 7: Modular architecture: modules and interfaces: Definitions of interfaces in more detail are considered in this step. The aim is to define standardised interfaces because those kinds of interfaces enable effective interchangeability of product elements.

Architecture is considered in:

- Step 3: Architecture: generic elements and interfaces: The basic architecture for a starting point of defining a modular architecture is discussed in this step.
- Step 7: Modular architecture: modules and interfaces: Modular architecture is defined in this step by considering the context of business and variation needs. The architecture description done in this step should consider variation possibilities in addition to standardised sections of the architecture.

Configuration knowledge is considered in:

- Step 5: Preliminary product family description: Relations between customer variation requirements, generic elements and parts/assemblies are considered in this step. Thus this step contributes to the defining of configuration knowledge.
- Step 6: Configuration knowledge: generic elements and customer needs: As the name of the step suggests, relations between generic elements and customer needs are defined systematically in this step. The aim is that this kind of preliminary

configuration knowledge facilitates the defining of modules because it shows the relevant customer needs for each generic element.

- Step 8: Configuration knowledge: module variants and customer needs: In this step, configuration knowledge is defined using more detailed product elements, and using the same principles as in Step 6.

4.1.1 Reasoning for the elements of the Module System

Figures 3.44 – 3.49, which were presented in Chapter 3.5.9 (Conclusions of product structuring), included models that described impacts of different product structuring factors related to product variety, design re-use, standardisation, modularisation, product platforms, product family and configuration based on the literature review. These figures can be understood as Reference Models, but these figures also include possible impacts. Consequently these figures also include characteristics of the Impact Model. The Reference Model and the Impact Model are DRM-suggested (Blessing & Chakrabarti 2009) tools for describing existing and desired situations. Figures 4.2 - 4.7, which are presented below, are based on Figures 3.44 – 3.49. In this chapter, the aim has been to describe how factors and impacts presented in these figures support the classification of the five elements of the Module System, including partitioning logic, set of modules, architecture, interfaces and configuration knowledge.

Figure 4.2 includes factors and impacts related to **product variety,** explaining how these factors relate to the five elements of the Module System. Group technology principles relate mainly to modules and their interfaces because these elements can include similarities affecting production decisions. Modularisation is discussed mainly in Figure 4.5. Thus the figure below does not include the relation of that factor to the five elements. Parametrisation and modularisation are discussed as separate definitions in, for example, Andreasen et al. (1996). In our context, parametrisation is an option for the enabling of variety by enabling the modification of product elements (modules) based on certain predefined design parameters. Configurable product structure presents different element types of which the product can consist, as discussed in Figure 3.37 by Juuti (2008). This relates mainly to types of modules. An analysis of value chains and processes was suggested in the CSL (see Chapter 3.5.3) for the analysing of requirements for product structuring; thus these aspects are related to partitioning logic of the modular product family. Design re-use factors are discussed mainly in Figure 4.2, but from a modularisation and product family perspective these issues relate especially to the re-use of modules, their interfaces and architecture. Other aspects in Figure 4.2 describe possible impacts related to product variety. In the figure below, the main impact relates to costs based on definitions by the selected authors.

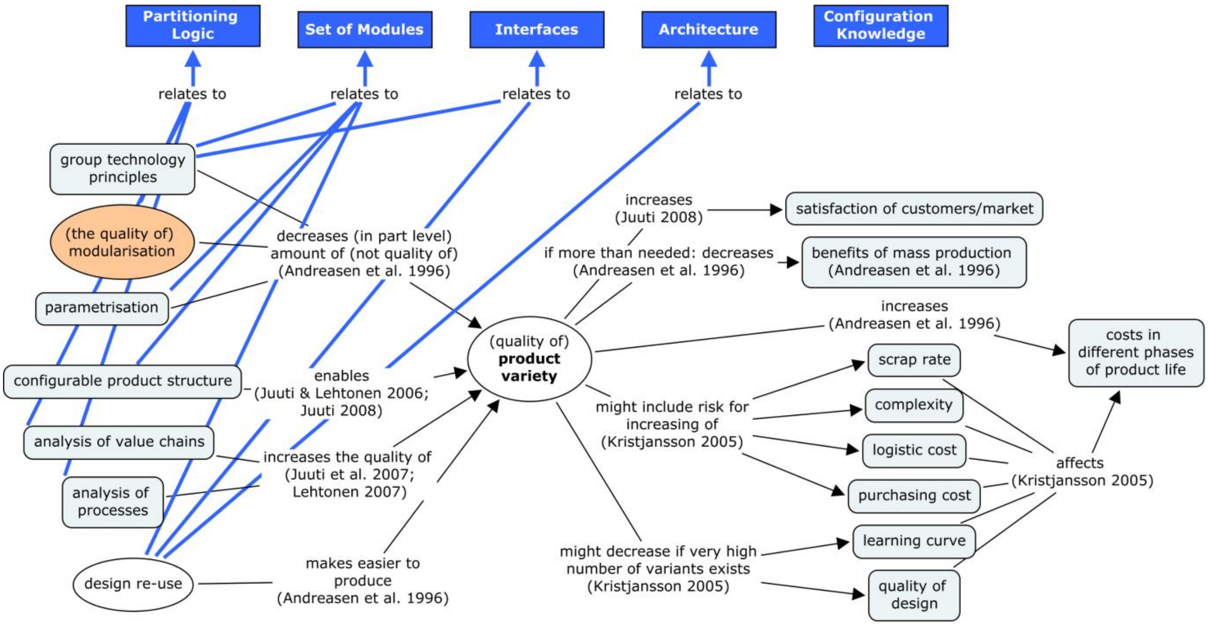


Figure 4.2. *Relations between elements of the Module System and factors and impacts related to product variety (modified from Figure 3.44; see also Chapter 3.5.9).*

Figure 4.3 includes factors and impacts related to **design re-use**. Design re-use aspects are also discussed in Figure 3.20 (Designing of variety with commonality to Technical System) by Juuti (2008). The figure by Juuti suggests impacts from commonality and variability perspectives. That figure is also valid in this thesis, and can be considered as the Impact Model as suggested in DRM by Blessing & Chakrabarti (2009). In the figure below, factors relate mainly to modules and interfaces. The commonality viewpoint is typically related to analysis and the defining of similarities of product elements. Thus it is suggested that it relates to modules and their interfaces. From a product-structuring viewpoint, standardisation aspects also relate to modules and their interfaces. This is especially supported in definitions by Fujimoto (2007), who discusses different standardisation levels. Documentation of interfaces is related to design re-use, as seen in Stevens et al. (1998). This naturally relates to interfaces from a Module System viewpoint. Standardisation viewpoints are also discussed in Figure 4.4. As mentioned, impacts of design re-use are also discussed in Figure 3.20 by Juuti. The figure below suggests similar kinds of impacts.

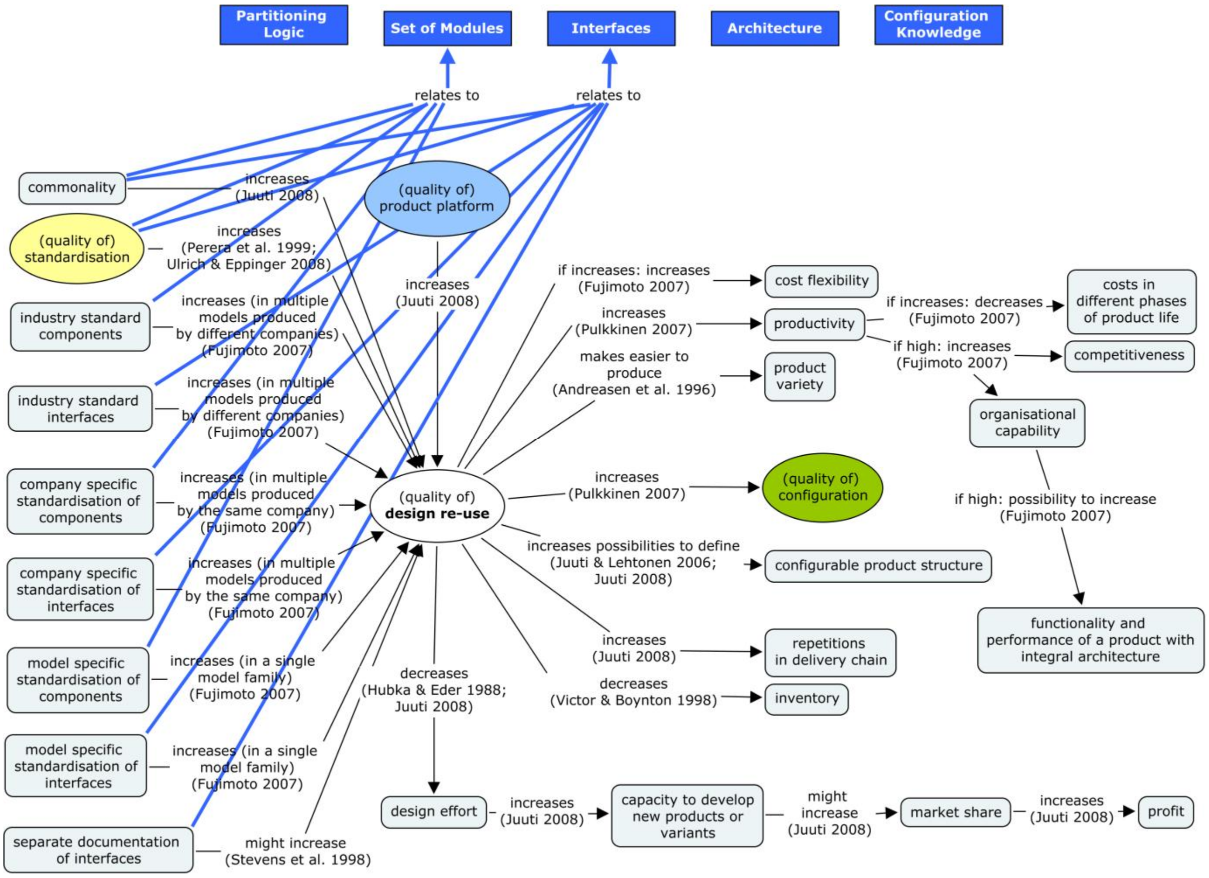


Figure 4.3. *Relations between elements of the Module System and factors and impacts related to design re-use (modified from Figure 3.45; see also Chapter 3.5.9).*

Figure 4.4 includes factors and impacts related to **standardisation**. Standardisation of components and interfaces is also highlighted in this figure. In addition, this reference model includes factors that relate to partitioning logic of the modular product family. Hubka & Eder (1988) explain that, when considering standardisation aspects, international, national and company-in-house agreements and also market trends should be considered in order to improve the quality of standardisation. These factors have similarities to the suggestion by Fujimoto (2007); thus these aspects could also be pictured as being related to modules and interfaces, but considerations by Hubka & Eder (1988) have a higher abstraction level and thus are considered to be related to partitioning logic and also to interfaces. Partitioning logic would describe what kind of issues should be considered as product requirements in decision making and why the product family is what it is. The figure below also highlights analysis aspects related to standardisation. This relates to modules and their interfaces because those can be considered as the main subject of this kind of analysis as, for example, different index-based methods suggest. Figure 4.4 also includes the link between product platform (this is discussed in Figure 4.6 in greater detail) and standardisation. Product platform issues relate especially to modules, interfaces and architecture because typically the aim is to re-use these issues. Impacts of standardisation highlight design re-use aspects.

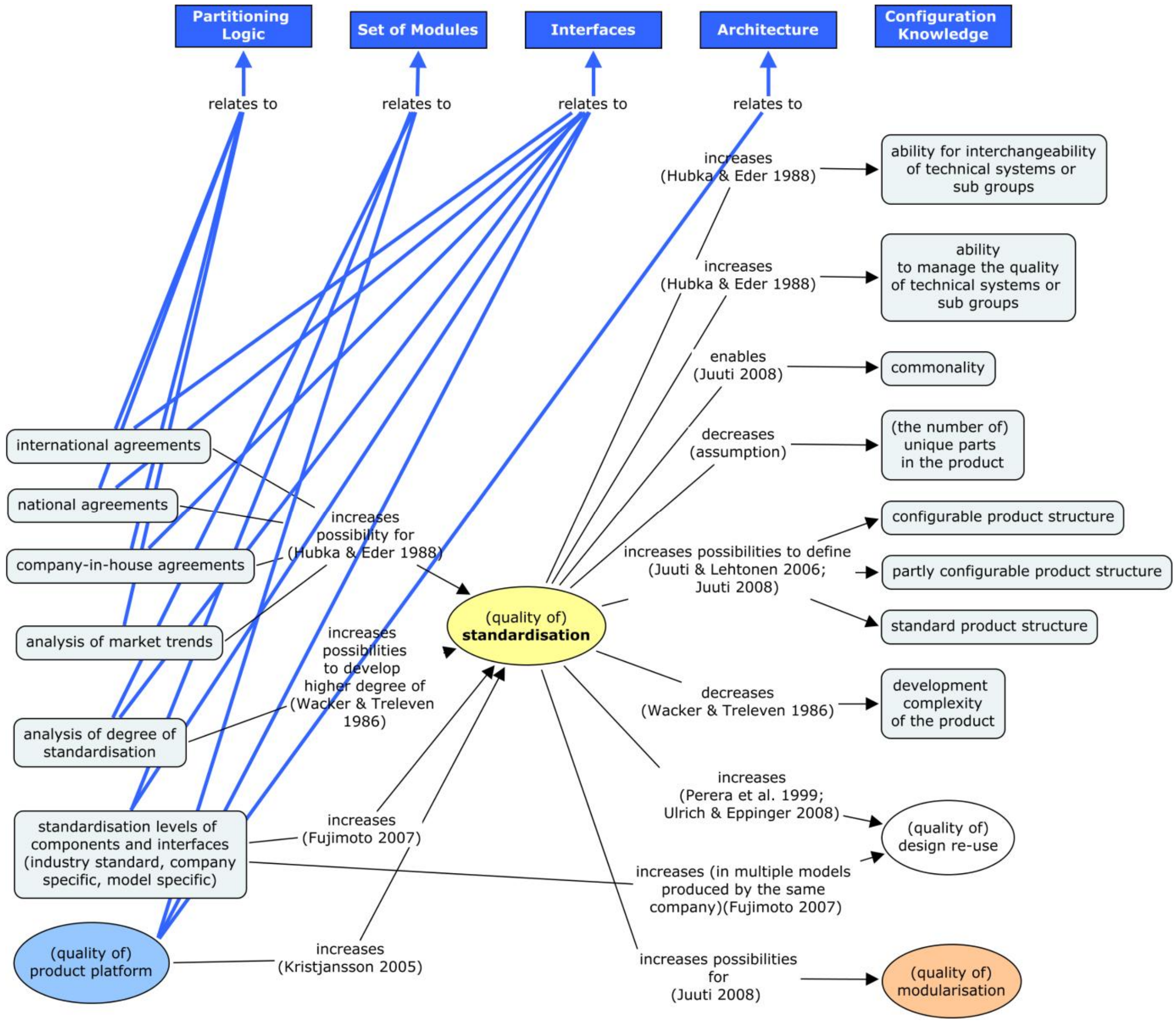


Figure 4.4. *Relations between elements of the Module System and factors and impacts related to standardisation (modified from Figure 3.46; see also Chapter 3.5.9).*

Figure 4.5 includes factors and impacts related to **modularisation**. The figure includes factors related to every element of the Module System. Factors related to partitioning logic consider analysis of reasoning for modularisation, based on recognition of benefits related to different processes and value chains in the company. The possibility of combining process units also relates to partitioning logic because this can be an important driver in modularisation from an organisational viewpoint. Variety perspectives relate mainly to modules. Variety issues highlight definition and the managing of variety in each chunk (in the Brownfield Process, we use the term ‘generic element’), the number of modules for creating the needed variety and the possibility of using a module in different variants. The number of modules can also be connected to configuration knowledge because it should consider available modules for a certain need. Different product- structure types such as partly and fully configurable product structures are also related to modules. Product structure types relate to modules because it is important to recognise what kind of product elements the products consist of as discussed in, for example, Juuti (2008). Interface viewpoints were already discussed in the earlier Figures 4.3 and 4.4. Figure 4.5 also suggests documentation and defining of interfaces. Importance of interfaces is also presented in order to enable independence and interchangeability of modules. Interchangeability can also be connected to configuration knowledge because it deals with compatibility rules of product elements. The literature also suggests consideration of layout and variety-related sections in management of variety and commonality. Of the suggested five elements of the Module System, these aspects can be related to architecture. According to the figure below, interfaces enable the use of modules in several product variants. This is more akin to the impact of modularisation and relates to the need of configuration knowledge. Impacts in Figure 4.5 relate to benefits of design and component re-use and commonality, decreasing of complexity and in-depth knowledge and enabling of product configuration against customer and market needs.

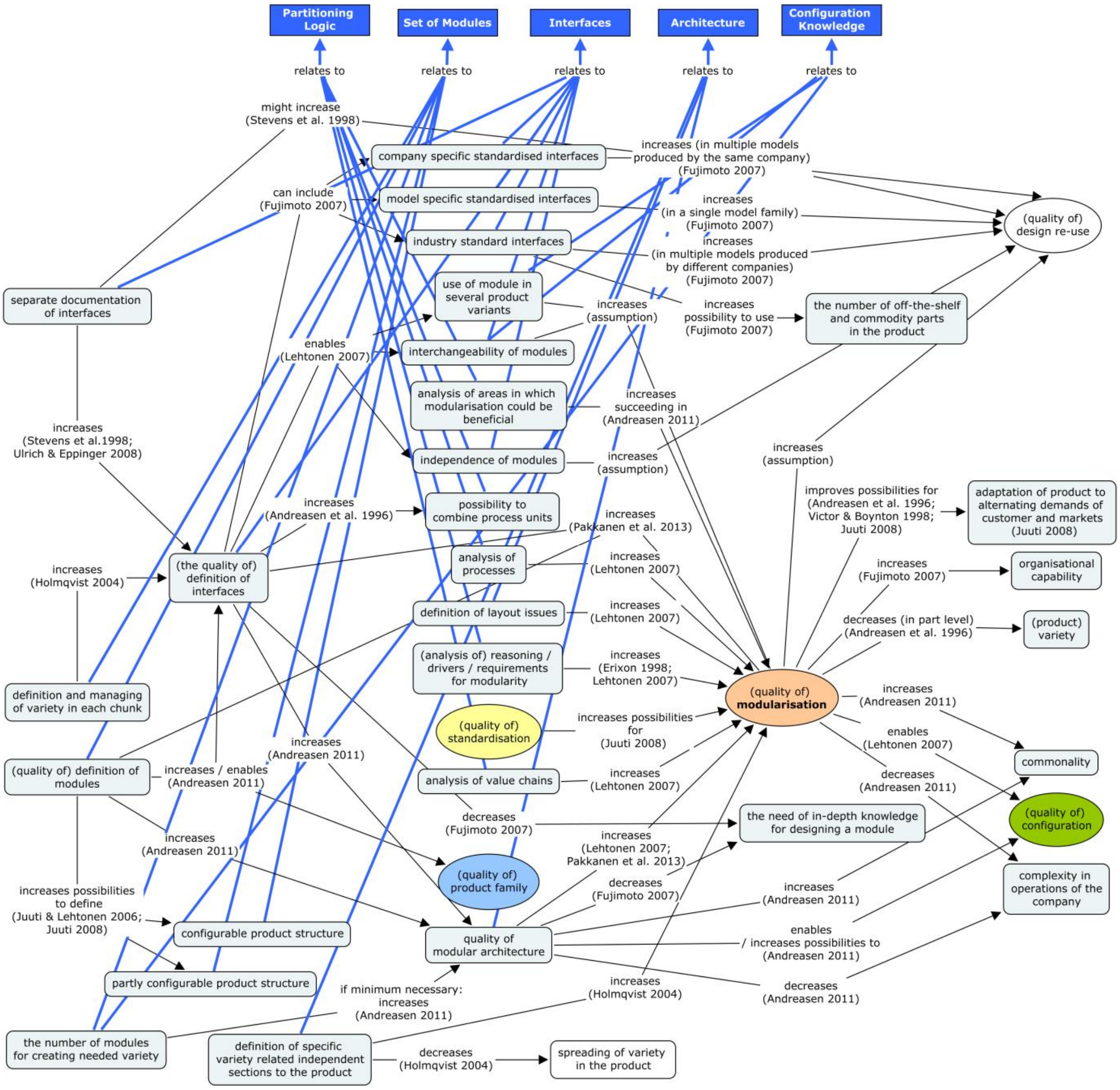


Figure 4.5. *Relations between elements of the Module System and factors and impacts related to modularisation (modified from Figure 3.47; see also Chapter 3.5.9).*

Figure 4.6 includes factors and impacts related to **product platforms** and **product families**. In this research context of product development, road-mapping considers future needs and describes what kinds of product elements are included in the product family and for how long. Thus it relates to several elements of the Module System. Definitions of modules and interfaces are also considered in a product family context, as presented in Figure 4.6. From a product platform perspective, the defining of reusable assets is essential. In our context, reusable assets can include modules, their interfaces and whole architectures. The defining of re-usable assets is also linked to partitioning logic, because in the early phases of modularisation and product family development focus, there can be business reasons for emphasising re-use of certain assets. The impacts of product platforms and product families include cost, time and quality impacts because of reduced numbers of unique product elements. There are also recognised risks involved with the introduction of a product platform. As shown in the figure below, Kristjansson (2005) discusses the risk of products being too similar.

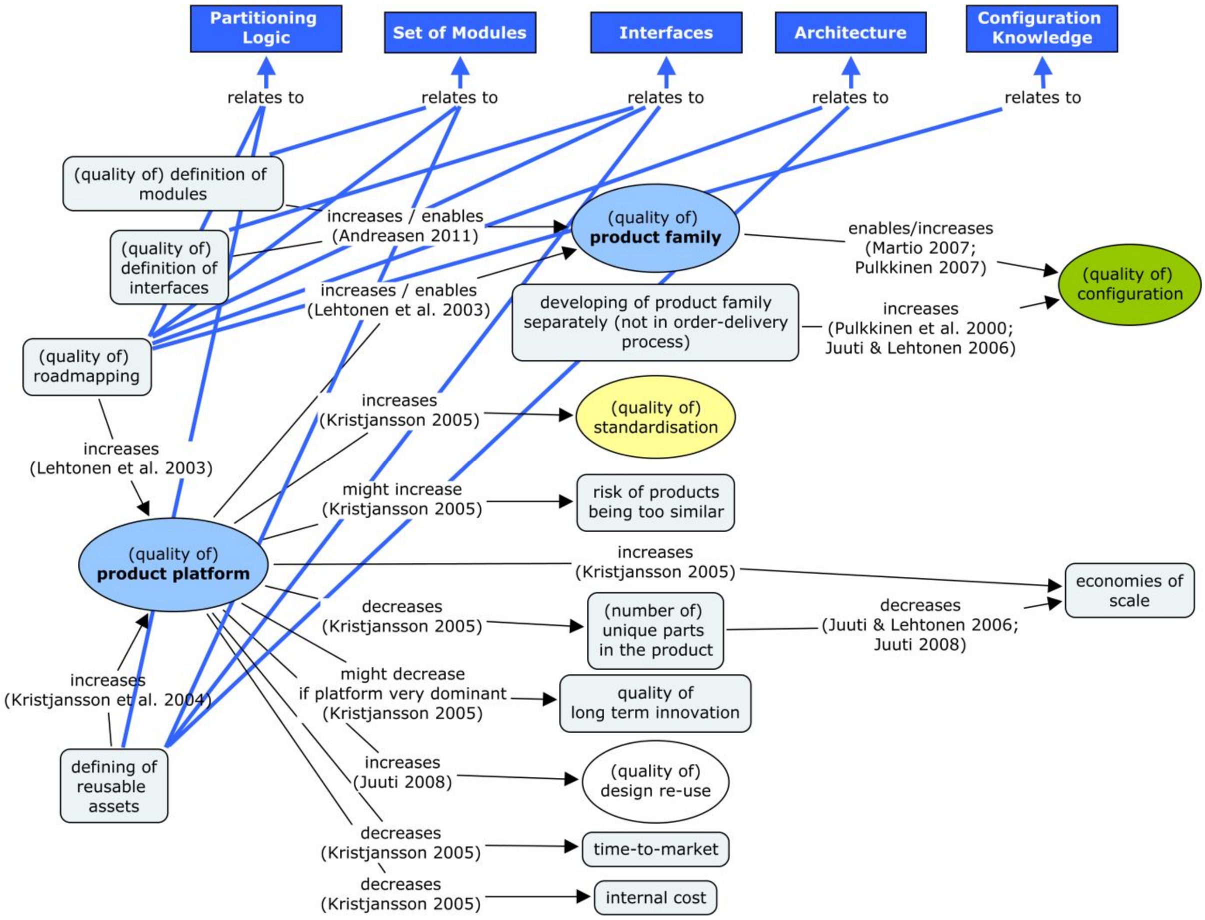


Figure 4.6. *Relations between elements of the Module System and factors and impacts related to product platforms and product families (modified from Figure 3.48; see also Chapter 3.5.9).*

Figure 4.7 includes factors and impacts related to **product configuration**. This figure emphasises the importance of defining all possible module combinations and constraints within the product family. The figure also highlights the importance of IT-support for configuring, which relates also to a factor of product configurator. Thus these aspects are especially related to configuration knowledge. The figure also includes a factor that highlights the role of customer requirements when defining a configurator. Consequently, factors related to partitioning logic can also be recognised from the figure. Development of a product family separately (not in the order-delivery process) can be linked with partitioning logic. This is because organisational aspects should be considered in setting requirements for product development. This was discussed in, for example, the CSL (Lehtonen 2007). Figure 4.7 also includes more generic factors related to modularisation and definition of a product family, which were discussed in earlier figures. It is suggested that consideration of the five elements of the Module System is important for both topics in general. Impacts in Figure 4.7 relate mainly to impacts of product configuration in general and impacts when using a configurator. General impacts explain the ability to fit the product to customer and market needs by facilitating defining of product variants. Impacts of configurator relate to cost, time, quality and resource use aspects.

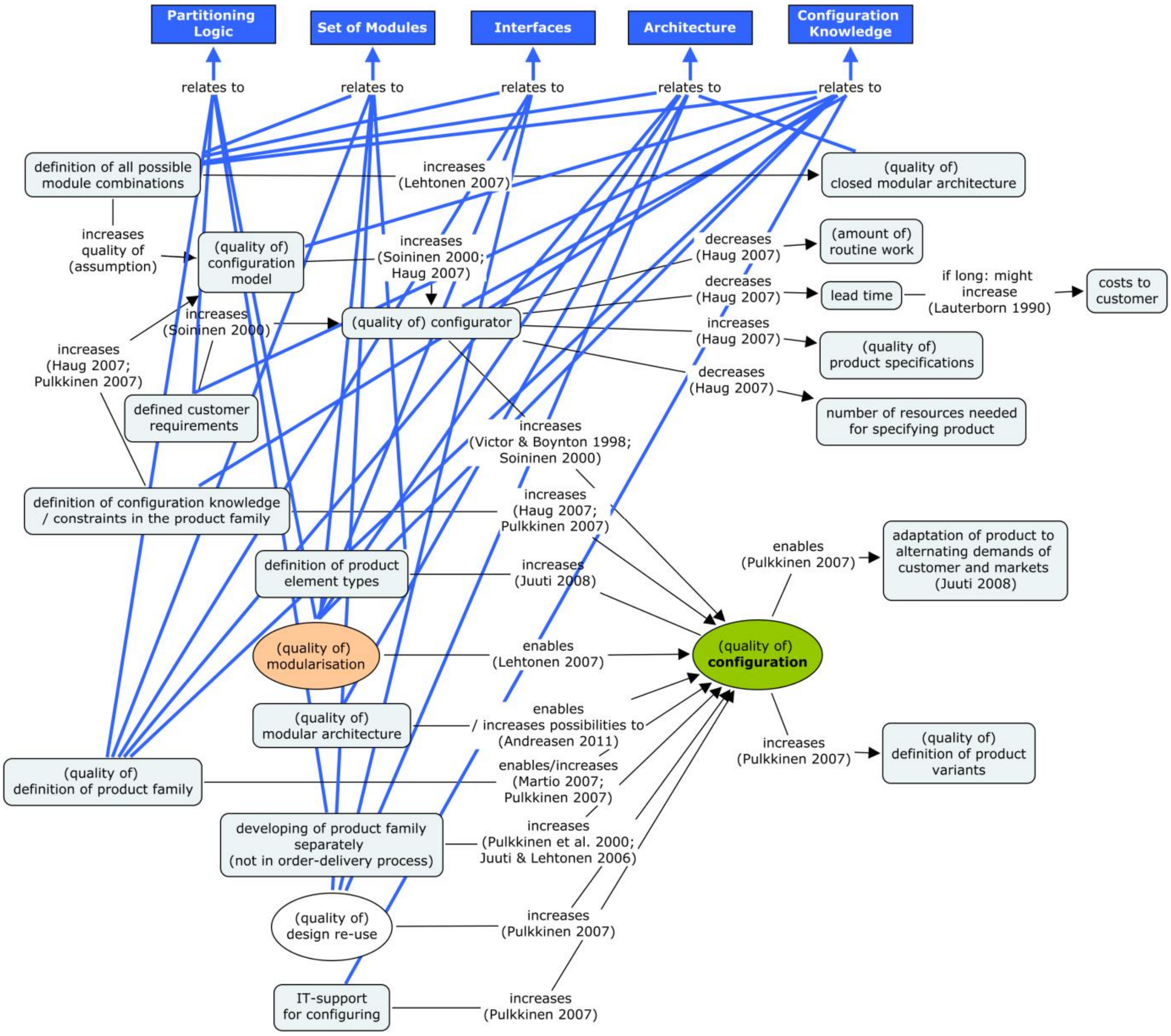


Figure 4.7. *Relations between elements of the Module System and factors and impacts related to product configuration (modified from Figure 3.48; see also Chapter 3.5.9).*

Several factors which relate to different product-structuring viewpoints and strategies can be recognised, as Figures 4.2 – 4.7 also show. By considering these factors successfully it is possible to enable impacts especially related to cost, quality, time and resource use according to studied publications. In addition to this, these separate factors can be linked with the suggested five elements of the Module System. These links ("relates to") in Figures 4.2 – 4.7 are an interpretation done by the author of this thesis.

4.1.2 Applying of the Brownfield Process

As can be seen from Figure 4.1, the BfP includes built-in iteration. Architecture, for example, is defined first using generic elements (Step 3), and later on when the design has advanced these generic elements and their interfaces are defined in more detail, considering whether, for example, the product consists of standardised, modular variants or delivery specific elements (Step 7). The BfP does not consider extremely detailed design tasks of different types of product elements. This is left outside the scope of this support because this would easily lead to case-specific considerations and the scope of this thesis would therefore become too large and the results of the design method description might not be generalisable to other situations.

At what kinds of needs is the BfP aimed? The main driver for applying the BfP is an unwanted situation, from a business perspective, related to the existing product assortment. This unwanted situation means that the product assortment, including part and assembly assortment, has increased during the course of time. Existing products do not then necessarily fit business and customer requirements anymore in an optimum way, and this widespread variety also causes confusion in the sales-delivery process and in later life-cycle phases. In spite of this, when using the BfP there is a premise that the products have design potential from the viewpoint of increasing commonality without forgetting variability needs, and enabling this potential would increase the possibilities of design by re-use. The primary goal of the design support is not in the designing of a completely new product assortment; the process is rather more related to re-designing, in which old or existing design solutions are used. Thus the support aims at rationalising the existing product assortment towards a modular product family, as already discussed in the objectives of this thesis. This rationalising includes, for example, analysis of the existing products and reduction of overlapping design elements (e.g. parts made for similar purposes) and the forming of a common architecture for studied products. As already discussed, the process aims to discuss what kind of design information needs to be defined in modular product family development and to describe the steps that could facilitate the defining of this information. Consequently, it can also be stated that the aim of the support is to reduce the design complexity of the modular product family by dividing the design activities into separate steps and by highlighting the specific information elements that these steps contribute to.

Based on the previously discussed reasoning for the design support, the pursued output of the BfP in general is an improved situation from a business perspective related to the studied product assortment. In the last step of the BfP, the purpose is to analyse the business impacts that the designed product family would cause in a situation in which the design project succeeds as a whole. Consequently, it has to be understood that the company needs also to invest in redesigning, if change is really desired. The last step of the process may reveal if the designed product family would improve the situation and how much improvement would occur in a positive case, or if iterations are needed in the structure of the product family in order to fit the product family better to the existing business environment.

In each step, there are suggested approaches and tools that could facilitate the defining of the expected results of the step. Because of this, outputs of the BfP steps have been described using these suggested approaches and tools. The aim of the steps is to facilitate production of design information which is represented by, for example, the use of diagrams, figures, tables and matrices, depending on the step in question. For the output of each step, the input required in the same step is exploited. Hereby the refining of design information elements, as well as considerations of new issues, can be seen between steps. Correctness or optimality of outputs of the steps is probably difficult to analyse, but generic suggestions related to what the results should look like are provided in the descriptions of the BfP steps. Thus these suggestions aim to describe, for example, what the result should look like and what issues should be considered when applying a specific step of the process. The BfP does not include mathematical model-based optimisation in any step and thus it can be considered more as a heuristic approach.

How does the BfP affect the work situation? The assumption is that the BfP facilitates defining of the content of a product family. In the process, the aim is to define the product family so that the result would enable more effective defining of product individuals in the sales-delivery process because of re-use and commonality issues and resulting benefits with repetitions. If the product family needs to be re-designed or modified in the future, investments are needed again, especially in product development. This also applies to using the BfP. Designing of a product family in parallel to phases of the sales-delivery process using the same resources can be difficult if extra time and resources are not allocated for the designing. These and other potential side effects are discussed in the last step of the BfP, in which business impacts are estimated.

The nature of this design support includes method-like properties, as defined by Newell (1983) (see Chapter 3.4.2). The design support in itself cannot define the best solution in a design situation but it provides suggestions and guidance about what should be developed or defined in each step:

1. The BfP aims to present a specific way to proceed in the designing of a modular product family, including different steps. The goal of these steps is to define needed design information from a Module System viewpoint.
2. The aim of the BfP is that by following the steps, possibilities for defining a rationalised product assortment (a modular product family) increase.
3. The BfP includes generic sub-goals and sub-plans. The name of each step tries to describe the result of the step. In addition to this, steps contribute to suggested elements of the Module System. The BfP does not define exactly how these sub-goals can be achieved in every different case, but the process aims at offering generic suggestions that may help in the realisation of these sub-goals.
4. Use of the BfP (whether the method is used or not) can be estimated by comparing the existing results of design information related to product family development and the suggested main results of each step in the BfP. The aim in the BfP description has been to define the results of each step, including what these results look like and to which other steps the results of a specific step relate.

The direct user of the BfP is the organisation or team whose task it is to rationalise the product assortment. Because of the nature of the task (impacts on the whole product life cycle exist) to which the design support has been made, it is beneficial that different functions of the company participate in the defining of issues in product family development, such as partitioning logic for the product family (e.g. target setting from different viewpoints). Thus the users of the process should have, for example, a vision regarding the possible benefits that the rationalisation could enable, along with knowledge of currently existing problems. Participants should have a good overall picture regarding what kinds of requirements different functions of the company and life cycle set on the product family. In addition to this, the ability to estimate possible effects of design decisions from a life-cycle phase perspective is also a highly appreciated skill in the process. The basics of how and why each step should be accomplished have been represented in the descriptions of process steps. This is also because all of the users of the process might not have earlier experience with issues related to the designing of a modular product family. Thus consultancy related to the process steps is also possible. Altogether, a holistic consideration of product family development may improve the overall quality of the main result because elements of the Module System have effects on the whole life cycle, as discussed in the business impact analysis (Step 10). Those quarters which relate to a specific result of a certain step should at least know what kind of decisions have been made in a certain step. The situation is better if they also have possibilities of contributing to the steps.

The author of this thesis has not completely designed the content of the BfP. Different approaches and tools are suggested in the steps of the process. Some of these suggestions have been tested separately in several cases and the functioning of these has also been discussed in multiple publications written by other researchers (see descriptions of individual steps). Thus the process aims to use existing design methods, approaches or tools where applicable. In some steps, existing design support has been modified or new support has been designed. As said, these have been explained in the introduction of each step.

When using the tools, documentation is created by the users. Thus the role of the users of the BfP is primarily in defining and creating the necessary design information. Tools and steps of the process aim to guide what kind of information is needed and how it can be presented. The BfP suggests workshop-like structure in many steps. All of the things related to the designing of product family might not be feasible to define in these workshops but it is suggested that at least in the beginning of each step the participants of the steps should have common understanding about what should be done in the step, why the step is done and how it is done basically. After this, the division of labour can be organised in a case specific way if necessary. The BfP in itself does not consider the division of labour in detail.

The maintenance need related to the BfP relates mainly to documentation of design information defined in each step. Documenting of the design reasoning pattern of a modular product family may be beneficial in possible further developments, when modifications to an existing product family are made or when a completely new product family is designed. In these cases, documentation can help to reveal, for example, against what kind of requirements the old or existing product family has been designed. The organisation that does the design work should take care of the documentation of the results and the path that has led to the results.

4.2 The Brownfield Process: steps

In the following sections, the ten steps of the BfP are presented.

4.2.1 Step 1: Target setting based on business environment

In this step, the BfP aims to provide a framework for target setting in a design situation in which selected products are partially re-designed towards a modular product family. The aim of the target setting is to define objectives for the designing of a modular product family which is based on the existing product assortment. The main questions and resulting information elements of this step are shown in Figure 4.8 and are discussed in this section in more detail.

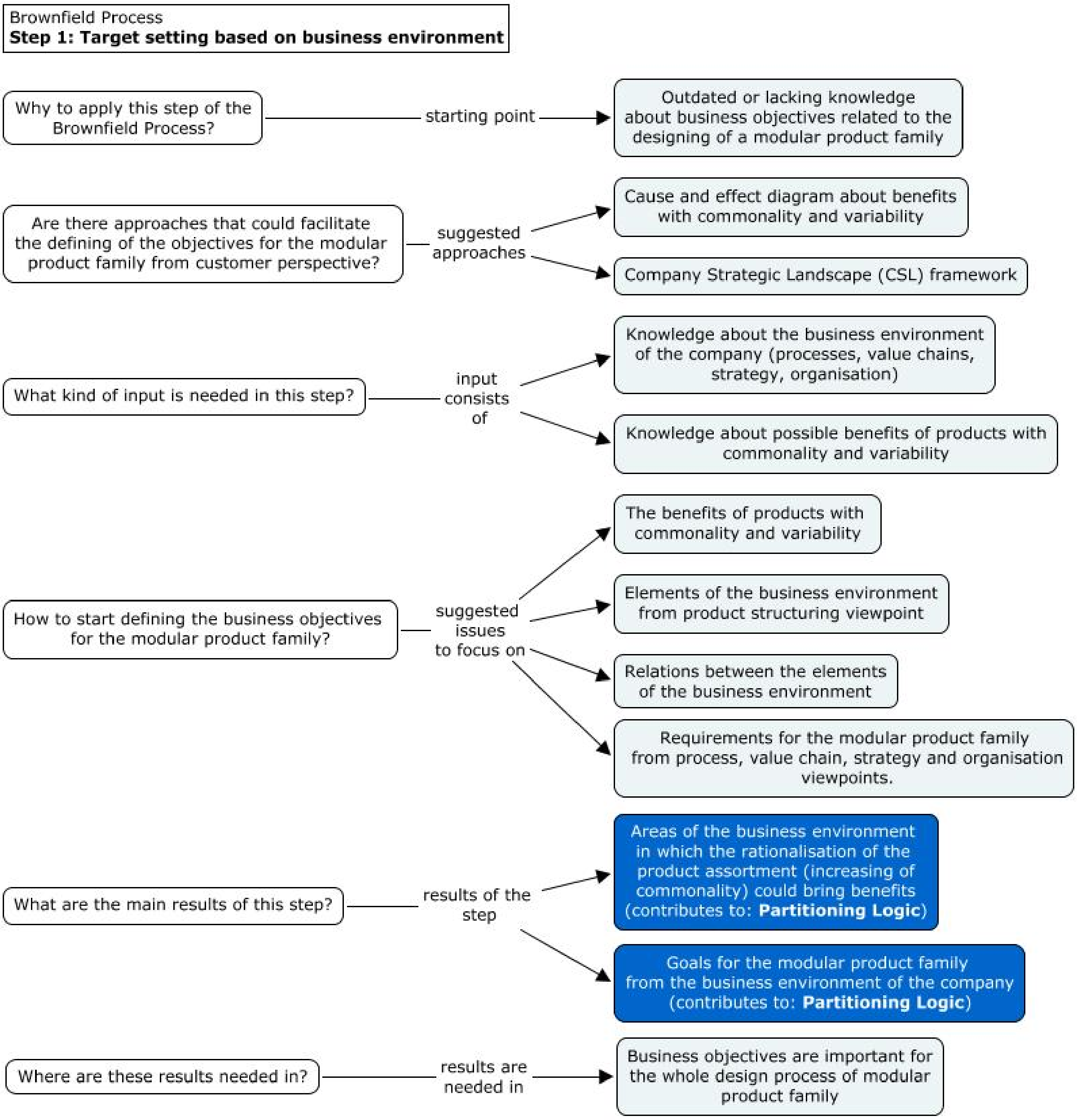


Figure 4.8. *The main content of Step 1 (target setting based on business environment) in the BfP.*

As discussed in the previous section, the BfP is meant for rationalisation of an existing product assortment towards a modular product family. The driver for using the BfP can be a recognised problem within the current product assortment. The main problem that the process aims to support is reduction of complexity in product assortment by focusing on the finding of commonalities while enabling variability.

One of the first tasks in the BfP is to select a scope. This is done by observing the existing product assortment and selecting products that should be analysed and developed further by using the process. Selecting the scope is based on the view that the company has of its product assortment. If the product assortment of the company is wide and includes several kinds of product types or classes, it might be necessary to narrow the focus of the modularisation process by selecting only specific products for the BfP. This contains both pros and cons. Decreasing the quantity and type of products to be included in the modularisation process reduces the complexity of the product development activities. This can make development of standardised or configurable interfaces and product elements easier, but by selecting only a couple of products for the modularisation it is only possible to gain good results locally. The greater the commonality of the whole product assortment is, the greater the possible benefits are.

After the scope of the BfP is defined from an existing products viewpoint, clarification of the targets can be initiated. The BfP suggests two approaches that can facilitate this task. The first approach is the cause-and-effect diagram / concept map of benefits of commonality and variability by Juuti (2008). The second approach is the Company Strategic Landscape (CSL) framework discussed e.g. by Lehtonen (2007). Both of these approaches have been already presented earlier in this thesis. The concept map has been discussed in Chapter 3.5.4 (Product Variety) and the CSL has been discussed in Chapter 3.5.3 (Company Strategic Landscape). The cause-and-effect diagram is shown again in Figure 4.9 and the CSL in Figure 4.10 for clarity.

How to decide on which approach to use for the facilitating of the target setting? The first step of the BfP can be customised based on knowledge of the design requirements. The cause-and-effect diagram shown in Figure 4.9 is suggested for ensuring the target setting in situations in which the company, including its product development team, considers that the objectives are obvious. This obviousness means that the company has a common understanding about the benefits that are sought after with modular structures. Thus the cause-and-effect diagram can be used in confirming presumptions about the objectives and possible benefits because it presents explicitly generic benefits from several viewpoints. The cause-and-effect diagram reveals also the linkages between different issues and benefits. This map could help in identification of areas in which the largest benefits could be achieved and thus it could be helpful in the defining of objectives for the BfP.

The CSL is suggested for more comprehensive target setting. It can be beneficial in cases in which the objectives for product development are somewhat unclear. The CSL describes the main elements of a business environment from a product structuring point of view. The actual product structure is considered as a black box in this step. The aim is that the requirements for modularisation are gone through in a workshop in which the areas of the CSL framework are discussed and defined using the CSL template. Examples of applying the CSL can be found in the thesis by Lehtonen (2007), in which he re-examined industrial product development cases by using the structure of the CSL.

By using the CSL, the business environment is modelled on process, value chain, and strategy and organisation perspectives. Analysis of these perspectives together can be helpful for finding relevant targets for the modular product. The content of the approach has similarities with, for instance, the checklist for defining the requirement list discussed by Pahl & Beitz (1996). The checklist they discuss considers different life phases of a product. The CSL also discusses product life, but it provides a more structured way for defining the requirements. In the CSL, product life phases are discussed in process- and value-chain areas. As a starting point, it is suggested that the design process and order/sales-delivery processes of the company be analysed from a product-structuring perspective. This requires that knowledge of the processes and also of other areas discussed in the CSL (value chains, organisation and strategy) is available when the target setting is done. One of the premises of the BfP is that it focuses on the existing products of the company. The process includes an assumption that the products have been sold earlier, and that the basic requirements the product must fulfil are known. Thus the target setting should focus on the requirements and objectives that relate to things that cause the need for variety, but also clarify in which areas commonalities would be highly beneficial.

Erixon (1998) pointed out that the module drivers are important in the designing of a modular product. The same kind of thinking can be found in the CSL. It can be said that basically the objective of the CSL is to help in the recognition of the module drivers of the business environment of the case company. As discussed, the suggestion is that the processes to be analysed include the product development process and the order/sales-delivery process of a company. The content of these processes should be defined in the CSL workshop and each process step should be discussed from the viewpoint of whether or not it sets any relevant requirements for the product structuring. Processes in which the customer uses the product are discussed in the further steps of the BfP. In the analysis of value chains, the first task is to clarify if there are different value chains in which the company wants to operate. There are different ways to classify value chains. One way to define value chains is by division of work content (Juuti 2008). Companies can have, for instance, strategic decisions made whereby some products are made completely in-house and some products are produced by selected subcontractors. Value chains can be also defined by the product process type. For example, Lehtonen (2007) and Juuti (2008) discuss standard, configurable and delivery-specific product process types. Thus the value chain and process structuring have similarities.

Target setting, the first step of the BfP, benefits from a multi-disciplinary group of participants because this kind of group broadens the understanding of the drivers for the modular product family development and the voice of all parties can be heard. These drivers can arise from several life phases of the product and from different functions of the company. Although a specific aspect might not be completely relevant to all of the participants in the target setting, acknowledgment of these aspects and the following of the definition process for targets can increase understanding about the overall decision making in product development. This is important because the product cannot be necessarily optimised from only one viewpoint but rather several viewpoints need to be considered in order to fulfil the expectations of different stakeholders. However, trade-offs are often also necessary as, for instance, Eilmus et al. (2012) have discussed.

Consequently, major input in this task is expected from different functions of the company. Participants should contribute by expressing their critical viewpoints and estimations of the requirements and possible benefits or disadvantages that products, which are based on commonality with variability, could provide.

The results of this step are needed in the other steps of the BfP. The most important instance of this, as far as who actually uses the results or output of this step, is the organisation or group that does the actual development work. This group needs information about objectives as a starting point for design activities. The type of output depends on what kind of approach is used for facilitating the step. In the BfP, the suggested output is a CSL model that defines the main elements of the business environment and requirements from a product structuring perspective in each section of the business environment framework.

This step requires active participation if the objectives for the designing of a modular product family are unclear. As discussed, there are suggested tools and frameworks with templates for this step but these approaches do not automatically define the requirements for the designing of modular products. However, the role of these tools is more to work as facilitators. Thus expert knowledge about the business environment and products are needed.

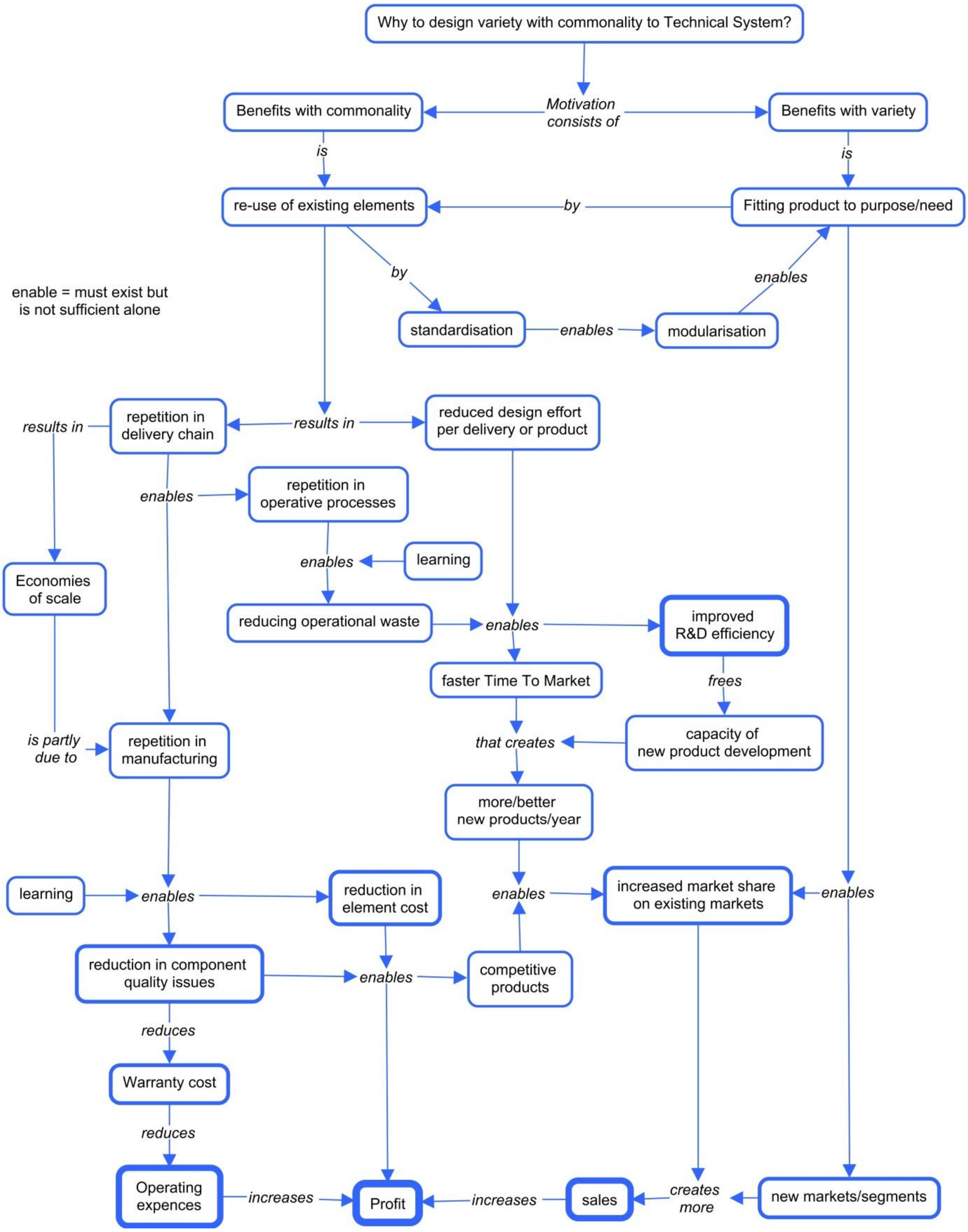


Figure 4.9. *The aim of the cause-and-effect diagram is to facilitate in the setting of a target for development of a modular product family. Possible benefits can be discussed and requirements defined by referring to the topics discussed within this map. The map was presented originally in a dissertation by Juuti (2008). This map is a result of his literature analysis regarding benefits in the field of commonality and variability.*

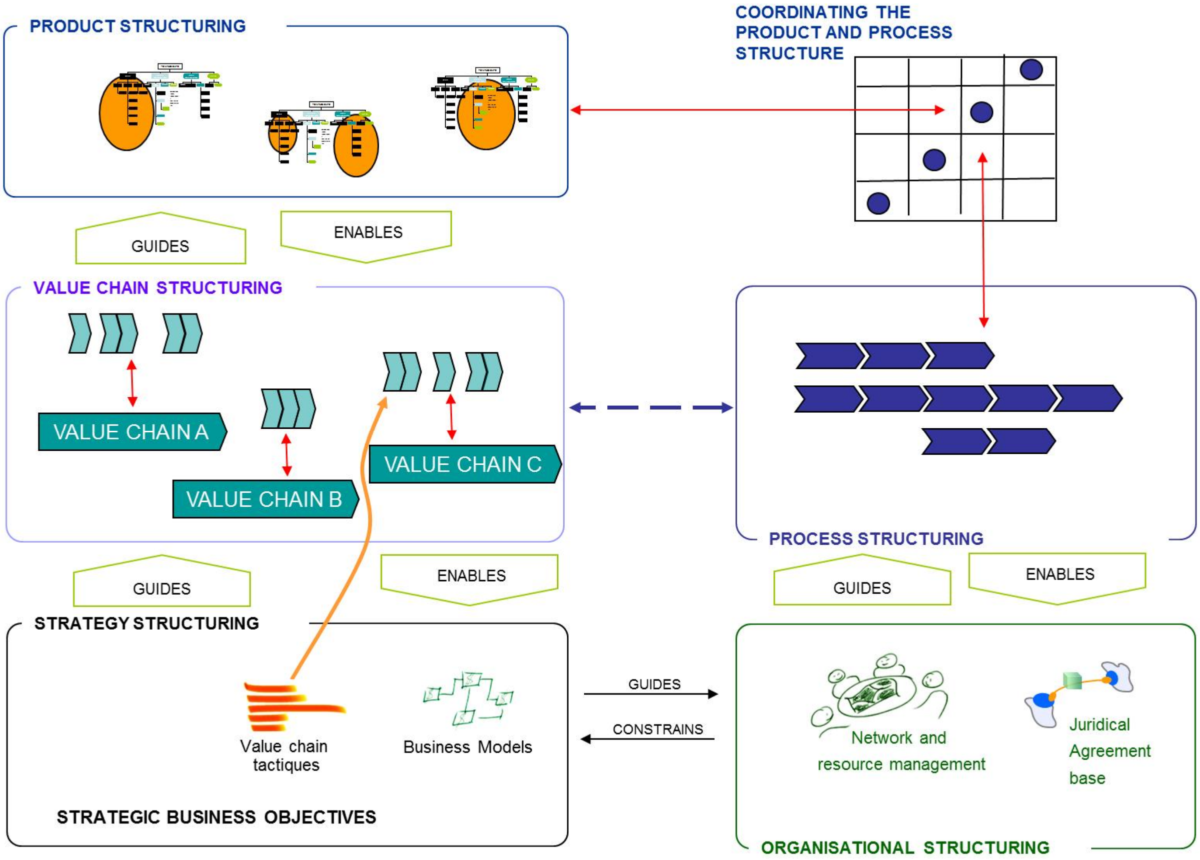


Figure 4.10. *The Company Strategic Landscape (CSL) framework (Lehtonen 2007) is suggested for facilitating the setting of a target in the development of a modular product family in a situation in which objectives are not completely defined. CSL suggests areas which should be considered in design work.*

In summary, the first step of the BfP aims to define objectives for modular product family development from a business-oriented perspective. This step provides an approach that considers important business aspects and relates these to product development and aims at helping to discover the reasoning for modularisation. It is suggested that this step be done in a workshop-type environment in which people with knowledge of different functions of the company are participating and the voice of each party can be heard. The cause-and-effect diagram from a reuse perspective and CSL discussed in this section highlight an important aspect to be considered in this step and these approaches can help in the actual selection of a scope for the BfP which is founded on the vision of the company. Referring to the five elements of the Module System, this step contributes to partitioning logic, because reasoning for partitioning of the product assortment is analysed in this step from a business environment perspective.

4.2.2 Step 2: Generic element model of the Module System

In the BfP, the preliminary module division is made according to the generic element model. A generic element is an abstract element in product structuring. Knowledge of existing products, which are selected as a scope for the BfP, is needed as an input for this step. Figure 4.11 explains the core content of this step.

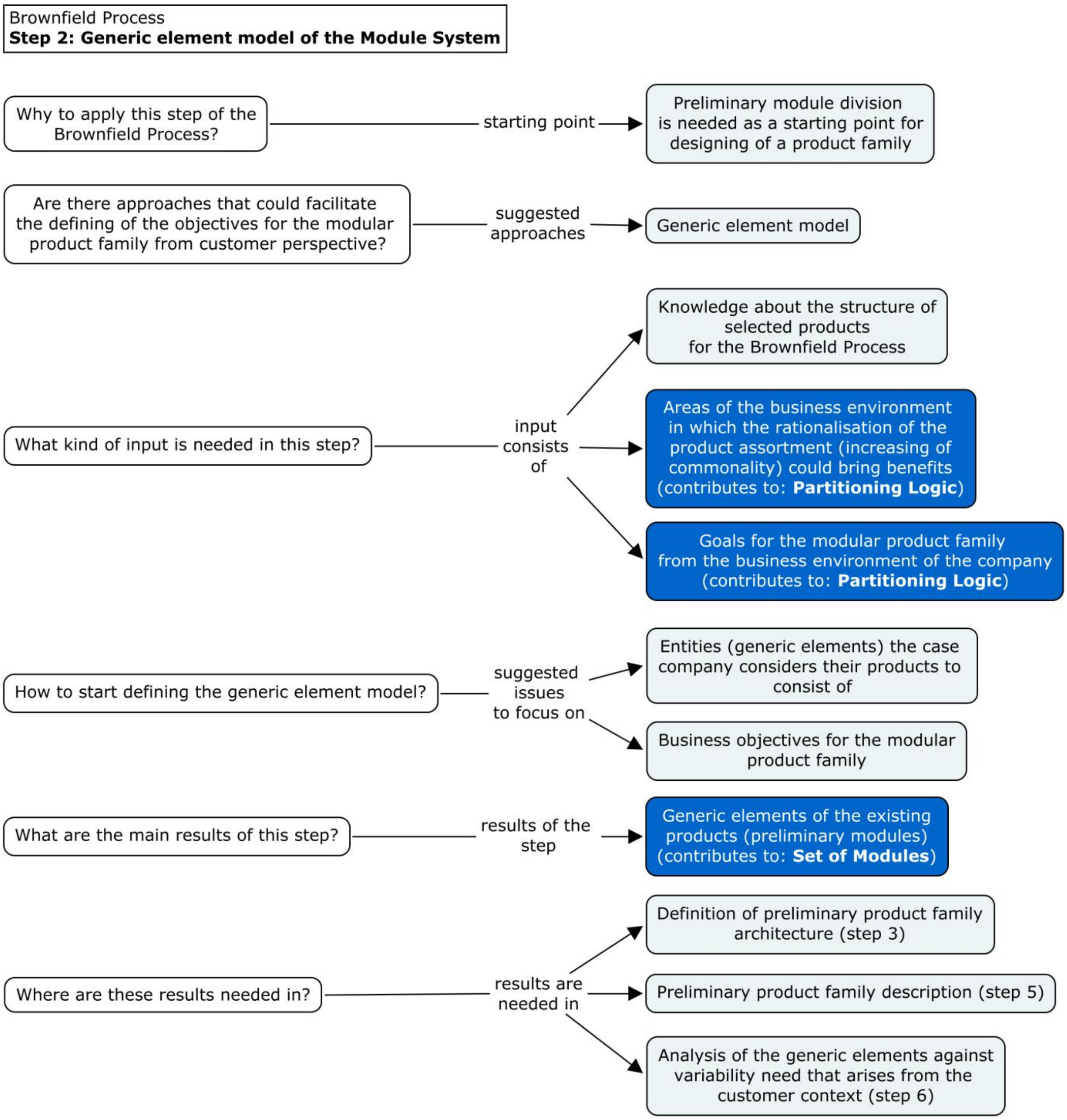


Figure 4.11. *The main content of Step 2 (generic element model of the Module System) in the BfP.*

Generic elements are determined according to which entities the case company considers their products to consist of. These can be, for instance, sub-systems, function carriers, assemblies or even single parts. Thus this definition has similarities to the definition of element by Oja (2010). The difference is that Oja does not consider function carriers in his definition of element. If generic elements are considered as function carriers, then organ thinking as discussed by e.g. Harlou (2006) is also close to this topic. Consequently in the BfP, it is suggested that natural division principles for generic elements can be, for example, functional or structural; however, other reasons are also appropriate. When the BfP proceeds, the nature of a generic element is defined in more detail. In the resulting product family, one generic element can, for example, consist of several alternative modules.

Is it clearly seen if the defined generic element model is incorrect? Business objectives should be kept in mind in this step. In the defining of generic elements, commonality between the different generic elements should be considered. If two or more proposals for generic elements have many commonalities, defining of only one generic element should be considered. If elements that have much commonality with each other are approved as different generic elements, there is a risk that the product family will eventually include unnecessary variation. This reduces the benefits that can be achieved with the modular product family. Correctness of the generic element model can also be estimated using the so-called 100% rule. This is based on the question: Does the suggested generic element model represent all the products chosen for the BfP, or are there some areas missing?

The commonality between the generic element proposals should be analysed based on business objectives. For instance, Siddique & Natarajan (2006) represent that commonalities can be found from features and their geometric properties such as forms, dimensioning and positioning. This is an example that is a valid aspect in, for example, products that consist of metal or other material structures. In these cases, benefits can be achieved in the defining of generic elements by concentrating on these kinds of issues. As an example once again, if certain support structures have only some differences, it could be considered as a starting point that one generic element could represent all of these supporting structures. It should then be analysed in the later phases of the process as to whether or not it is possible to realise all of the existing variants of the supporting structures by using only one standard structure, or are there a limited number of module variants or unique designs for every delivery needed? This is discussed in the step of designing modules (Step 7) in more detail.

As discussed earlier, commonality enables several benefits when repetitions in the operations of the company are achieved. Among industrial companies, there are companies which are able to have only low numbers of repetitions in the delivery chain because of the specific nature of their business. In these companies, benefits of commonality might not be achieved on a large scale. Nevertheless, considering the commonality aspect is not useless; however, there might be objectives that are more beneficial for their operations. Thus the emphasis in the defining of the generic element model is to consider the business objectives and the potential that the company has.

An example of generic element thinking (although this definition is not used) can be found in the research of Umeda et al. (2000; 2012). They discussed different ways to consider the structure of a product from a business objective perspective. They noted that there can be alternative structure models for the product and that each serves a different purpose. Thus their research also supports the fact that the drivers for the structuring of the product must be known and taken into consideration when the structuring division for the product is decided.

In this step, product knowledge from every product and its different disciplines selected for the scope of the BfP is needed. This kind of knowledge can be found from workers of the company, specifications, drawings, sketches or other models of the products. This step can be done in a workshop-type meeting in which people who have strong product knowledge are participating. Disciplines must be considered in a way that the generic element model does not include overlapping. For instance, hydraulic systems should not be considered as a separate element if considered as a part of some other elements also. The result of this step should be documented hierarchically because in the later phases the generic element model is analysed from a requirement perspective using matrix tools. Also the result of the step is used in the defining of a preliminary architecture for the module system.

The BfP supports the beginning of designing a module structure by suggesting a definition of generic elements which should be applied with the help of existing products in the company. In summary, the objective is to define a list of elements for preliminary module division and for a starting point for the defining of an architecture and product structure type division. The generic element model is revised when the design process advances and then, for instance, the types of generic elements are defined in more detail. For this reason the structure of the model considers tentatively what kind of elements the modular product family does consist of.

4.2.3 Step 3: Architecture: generic elements and interfaces

The third step includes drafting of the architecture in which generic elements and their interfaces are defined. This step focuses on how generic elements are located within the product. The step is important because the architecture illustrates the locations of preliminary interfaces to be managed. Thus, the generic elements that have interfaces with each other have to be identified. Figure 4.12 summarises the content of this step.

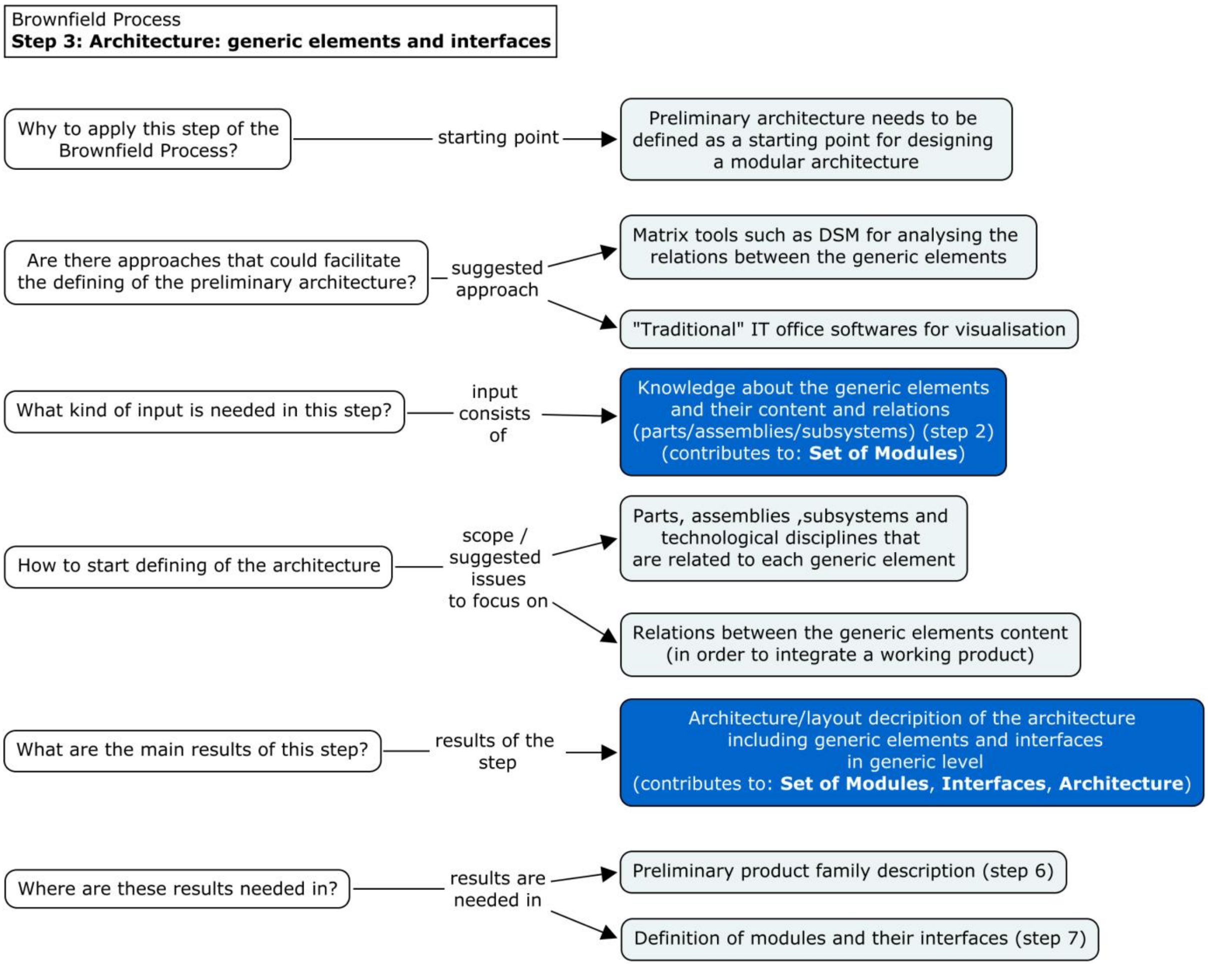


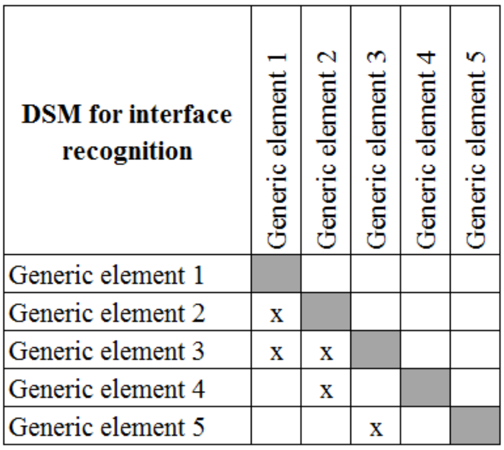
Figure 4.12. *The main content of Step 3 (Architecture: generic elements and interfaces) in the BfP.*

Different types of architectures were discussed in Chapter 3.5.6 regarding modularisation. Integral, modular, open and closed architectures (Fujimoto 2007) were recognised in that section. In the BfP, it is obvious that the aim is to design modular architecture because the design support includes an assumption that variants are needed. But how does the process consider open and closed architectures? In this step, the architecture is considered as a description of a layout of generic elements that have been defined based on existing products. In addition to generic elements, recognition of interfaces between the generic elements is an essential part of the architecture. After interfaces have been defined, they enable both closed and open modular architecture. The defining of closed modular architecture is used in describing a product family that is considered to include only certain defined modules and defined interfaces related to these modules. In this step of the BfP, recognition of interfaces is enough. In Step 7 of the process, more detailed defining of the interfaces is suggested.

It is possible that after the product family has been developed and taken into use in the sales-delivery process, it might be found at some point in the future that the product family no longer satisfies all the needs of customers. In this case, the definitions of interfaces enable introduction of new elements to the product family. If this new element is considered important to several customers, a new module can be introduced without losing the benefits of modularisation. The other choice is that the new element is designed as a unique element only for a specific single purpose. Thus the prerequisite for efficient modifications is that the interfaces related to the modules are defined and can be utilised.

Thus the open modular architecture would also consider possible needs in the future by considering the existing interfaces in the product family. This includes challenges. One challenge can be that in the open modular architecture, attention has to be paid to space requirements and other properties of possible future modules. These can be difficult to consider. The BfP does not cover the forecasting of future needs but it is suggested that the interfaces of the product family be clearly defined. The issue of future product elements is typically considered as road-mapping of platforms and architectures. Road maps would consider what product elements each product family architecture and platform would include, and when new architecture or a platform is designed and taken into use and which product elements such as alternative modules are included in those.

There are several possible approaches that could be used in this step for describing the preliminary architecture with generic elements and their interfaces. First of all, the relations between the generic elements must be clarified. For this purpose, matrix tools such as the Design Structure Matrix (DSM) (Steward 1981) can be used. In this matrix, generic elements could be listed and relations between the elements could be analysed from an interface perspective. A generic example of this kind of DSM matrix is shown in Figure 4.13.



DSM for interface recognition	Generic element 1	Generic element 2	Generic element 3	Generic element 4	Generic element 5
Generic element 1	▨				
Generic element 2	x	▨			
Generic element 3	x	x	▨		
Generic element 4		x		▨	
Generic element 5			x		▨

Figure 4.13. *DSM can be used as a supporting tool for recognition of interfaces between the generic elements. This example shows that, for instance, generic element 1 would have an interface with generic elements 2 and 4. Duplicates are not marked in the matrix.*

CAD tools can be too steep for visualising the product family architecture because accurately designed product elements describing the final structure of the product family are probably not available in this step, although drawings from the existing products could exist. Generic elements are on a more abstract level and thus traditional office software used in the industry can be also used in this step instead of or in addition to matrix tools. For example, Bruun et al. (2013) have presented an example in which Microsoft Visio has been used in the drafting of product architecture and interfaces. They explain that this kind of description can be linked with PLM systems by using additional applications. Bruun et al. also explain that it can be useful to keep some typical outline of an existing product as a background on which the modular architecture is drafted. Other examples of architecture descriptions can be found in the modularisation chapter (Chapter 3.5.6), Harlou's suggestions (Chapter 3.8.6) and also from the Integrated PKT-approach (Chapter 3.8.5), although authors of this approach did not speak directly about architecture but rather about the module interface graph. In the BfP, the basic idea to present the architecture is similar. The aim is to define how generic elements are located in the product and which elements have interfaces with each other. An example description of architecture in the BfP is presented in Figure 4.14. In this example the interfaces are not explained in detail.

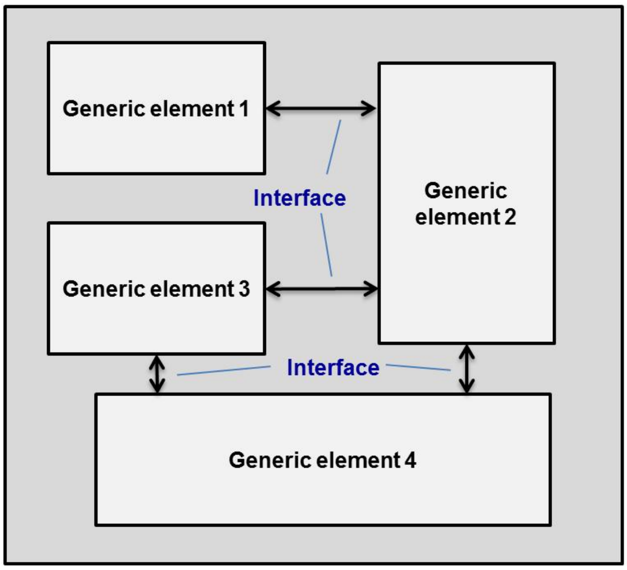


Figure 4.14. *An example of a preliminary architecture visualisation of an imaginary product includes generic elements and recognised interfaces between them. Figure modified from Fujimoto (2007).*

To conclude, this step needs information about generic elements and their practical realisations as an input. This step brings out the interfaces that exist between different generic elements for the design team. In this case, this step can be considered as a starting point for the designing of interfaces. Workshop-type working can also be done in this step. The result of this step (layout description of generic elements and their interfaces) is needed in Step 7, in which modules and their interfaces are designed in more detail. When considering the five main design information elements of the Module System, the contribution of this step is obvious. This step considers architecture, modules and interfaces on a generic level.

4.2.4 Step 4: Target setting based on customer environment

The BfP focuses on existing product designs and is not meant primarily for the designing of a completely new product family. When designing a modular product family, this means that there are old products that have been produced and delivered against some customer requirements. Studying of the customer environment is important if the company wants to change its operating mode from project delivery with delivery-specific solutions to configurable product delivery with predefined solutions. The reason for this is that formalised customer requirements are needed in the defining of configuration rules, which explain what kind of product will be delivered to the customer with certain requirements. It is possible that all of the requirements cannot be described formally. In this case, the part which these requirements relate to could be left outside the systematic configuration, thus being partly configurable. If customer requirements are not analysed, benefits with configurations are difficult to enable. The main content of this step is shown in Figure 4.15.

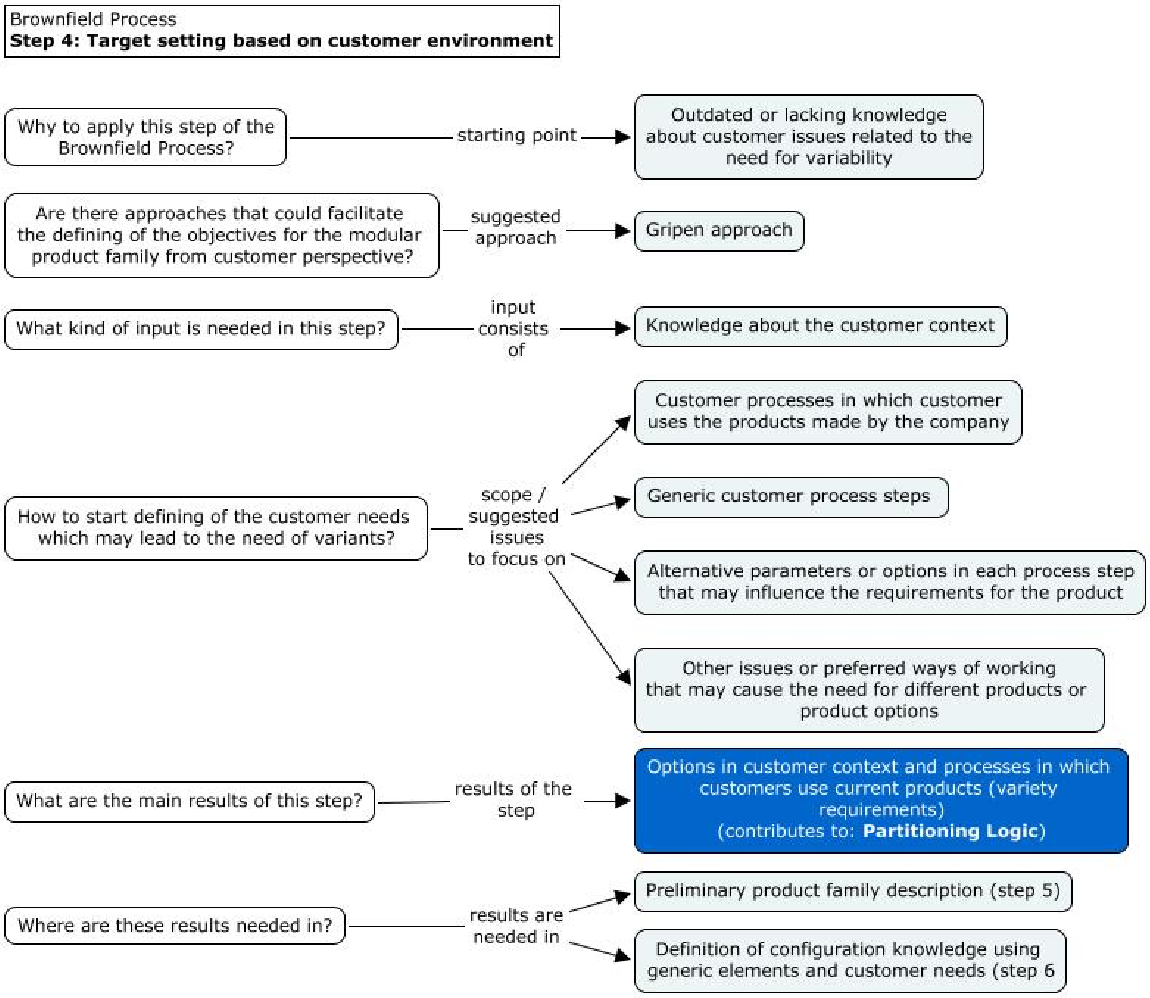


Figure 4.15. *The main content of Step 4 (target setting based on customer environment) in the BfP.*

The BfP includes a presumption explaining that the very basic requirements that the product must fulfil are well known within the company (e.g. a ship has to float) and that the emphasis of focusing on these requirements is low in the process. More specific requirements can include information that is not relevant anymore for the existing technological implementations. This may lead to traditions that actually harm the product and thus also the business. The BfP suggests analysing the customer context in order to ensure that the product requirements and needs are real and up to date and not according to old products. Consequently the aim of this step is to define valid customer requirements for the designing of a modular product family.

The BfP suggests that the so-called Gripen approach can be used for the clarification of customer requirements. This approach has background in the defining of the product structure of a truck by configuration (Lehtonen 2007). In that example, a truck is configured based on a set of questions and topics that decide what options in each area of the product would be the most suitable for the customer. This kind of thinking is also used in the BfP.

The Gripen approach suggests that the starting point in defining valid customer requirements is to understand the processes of customers when they use the products of the company. In defining the requirements from a customer perspective, the scope is to focus on variability issues. The seeking of answers to the four questions discussed below can facilitate this step in finding drivers for variability:

- What kind of processes can be recognised in which the customers use the company's products (products which are chosen as a starting point in the BfP)?
- What kind of generic process steps and segmentation can be identified from the way in which customers use products?
- What kind of alternative parameters or options, that have an effect on the definition of the product, are related in each process step?
- Are there any other issues or preferred ways of working that cause the need for different products or product options?

The Gripen approach can be used as a basis for segmenting similar variety needs of technical solutions to the same segment. The segmentation model can be useful in, for instance, the directing of specific solutions to a certain group of potential customers. The BfP does not consider segmentation in more detail. Instead, linkages between customer context and technical solutions are considered from a configuration knowledge perspective in the later steps of the process. The Gripen approach suggests offering larger assemblies or solutions instead of selling individual components. The reason for this is that from a company viewpoint it is easier to be sure of the compatibility and functioning of a limited amount of variants than compatibilities or correct functioning of larger numbers of single parts or assemblies. Sizing of the product elements from a modularisation perspective depends on the reasoning for the modularity and the resulting architectural decisions.

As discussed, this step focuses on analysing the need for variability from a customer perspective. The questions discussed above can be exploited in the analysis. Accordingly, the aim is to clarify the context in which the customers are using the products and to find sources for possible options from their processes and ways of working that need to be considered in the designing of a modular product family. The presumption in this phase is that the company has existing products, and customers who have bought them. Thus knowledge of the customers is needed in this step. It is suggested that at least the sales function participate in this step of the BfP. The result of this step is a description of the customer context and options and ways of working that are related to it. This resulting information is important when variability issues are considered. In the introduction of the BfP, the five main design information elements of the Module System were suggested. The result of this step contributes to the information element of partitioning logic because customer context has to be considered when designing the structure of the modular product family. Otherwise there is a major risk that the benefits of modularity are not achieved. The requirements and needs of the customers affect the reasoning of why the structure of the product assortment should be partitioned in a specific way.

4.2.5 Step 5: Preliminary product family description

The aim of the fifth step is to continue defining rationale for the product family and to analyse what kinds of possibilities exist for standardisation of parts and assemblies related to generic elements. The main content of the step is visualised in Figure 4.16.

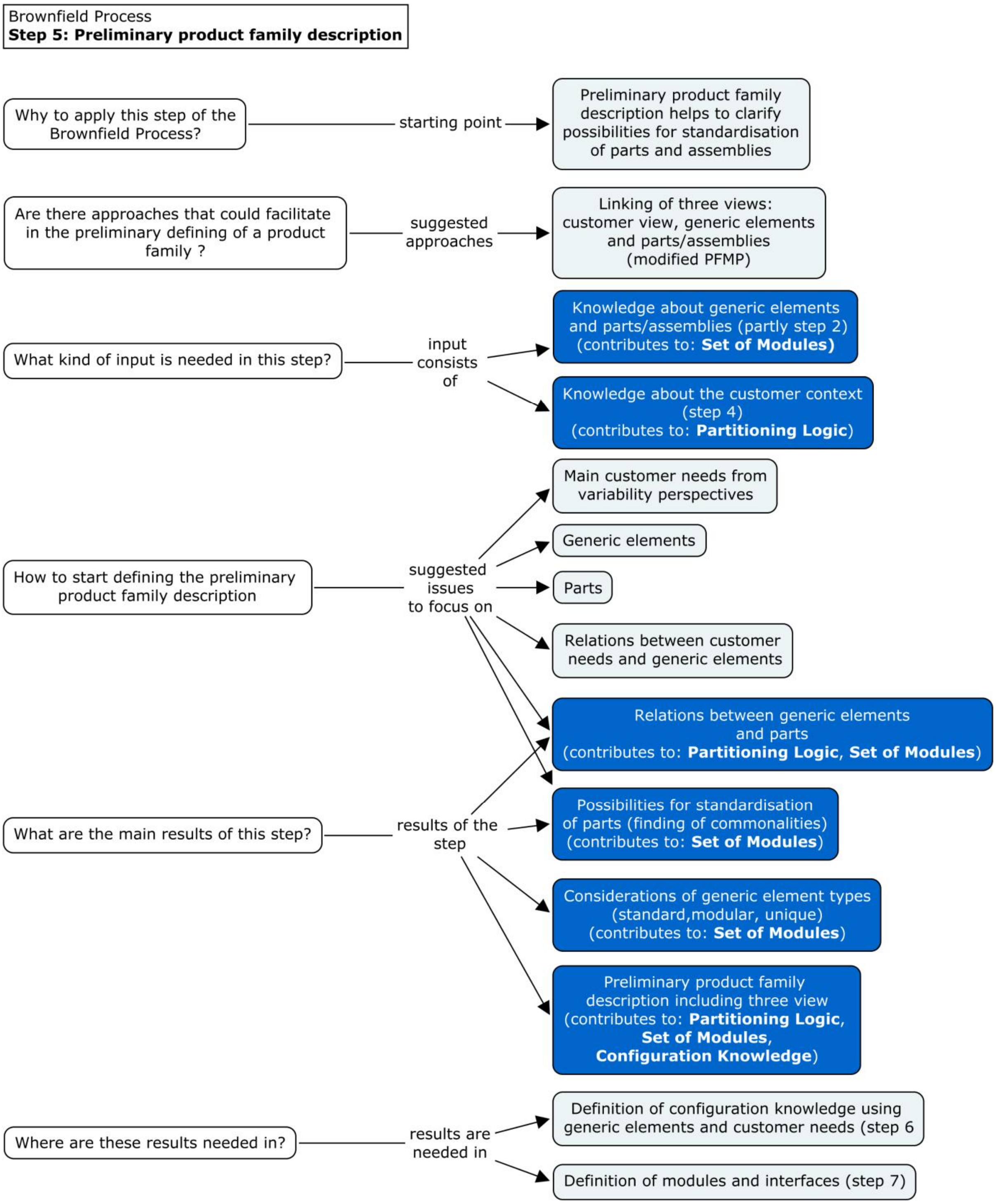


Figure 4.16. *The main content of Step 5 (preliminary product family description) in the BfP.*

Harlou (2006) mentioned that three views, including customer, engineering and part view, are important when describing a product family. He also suggested that the customer view should show variety for the markets, the engineer view should describe the product family and the part view should be related to the production system. In this step of the BfP, the customer view includes those main customer need groups that drive variability need for the products. In Harlou's examples, he presents the idea that the engineering view focuses on organs. In our approach, we understand the engineering view to include generic elements. Thus the PFMP approach is used in this step of the BfP in a slightly modified way. Figure 4.17 presents a generic example that is suggested for use in this step.

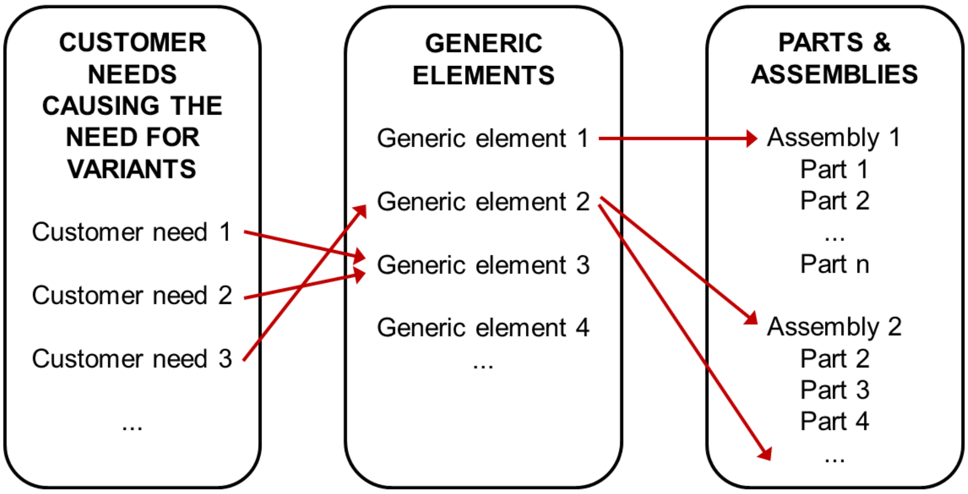


Figure 4.17. *Preliminary product family description is done by focusing on three views. This approach follows principles discussed in PFMP by Harlou (2006). The aim is to define what issues these views include, what kind of relations exist between different views and what kind of possibilities exist for standardisation.*

Knowledge regarding the customer context and parts and assemblies is needed in this step. Variability drivers from the customer environment were studied in Step 4 of the BfP. One task in this step is to list the main customer needs or requirements that include the possibility for the need of product variants from the customer perspective. Then generic elements are listed in the middle of the template as shown in Figure 4.17. These were studied in Step 2 of the BfP. The aim is also to list parts and assemblies related to the generic elements on the right-hand side of the template and then to analyse the relations between these different views.

There are two possibilities for beginning the analysis in this step. The first is to analyse the relations between the customer needs and the generic elements, and the second is to analyse the relations between the generic elements and parts and assemblies. In this step, types of relations are either yes or no.

One of the objectives in analysing the relations between customer needs and generic elements is to be sure that there is at least one generic element for each customer need. This step is done by going through each recognised customer need related to variability aspects and linking this need to each generic element that it relates to. If there are generic elements which have no relations to customer needs related to variability, these generic elements have good potential for standardisation. Generic elements to which several customer requirements are related are a challenge for modularisation.

In analysing the relations between the generic elements and parts and assemblies, the aim is to raise discussion regarding the extent of part assortment in the existing products and possibilities for standardisation of parts or assemblies. This means that parts and assemblies that are related to each generic element must be defined. The relation mapping between customer needs, generic elements and parts and assemblies can be an eye-opener if current products do not include plenty of commonalities and thus there exist multiple solutions for almost similar needs. Every variant part or module should have a connection to a specific customer need that explains why there needs to be variation. This is a basic rule for reasoning of variation but there can be exceptions. The business environment can cause the need for variation from inside the processes of the company. As an example, the existing production equipment can create a situation where the exact same kinds of parts cannot be manufactured for the same purpose. So the parts should be organised according to which elements they are related to. This gives an overview regarding existing products and their commonalities and also regarding complexity of the whole product assortment chosen for the BfP. This presentation can be helpful in the consideration of possibilities to enable different product structuring tactics.

If a part set that is related to a specific generic element can be formed with a small number of standard bills of materials (BOM), those are good candidates for modules (presuming that there exist variability needs from the customer context related to the generic element in question). In this case, these standard BOMs can be defined as modules and the variability need is fulfilled by selecting a suitable module (standard BOM) for the product in the sales-delivery process.

If most of a part set of a generic element could be standardised and only a minor part varies, a generic element could be considered as a configurable element. Thus most of the configurable element would be founded on a standardised base unit.

If standardised BOMs cannot be found for a generic element, it is difficult for the generic element to be considered as a module without large modifications. Thus there are still some options that should be considered, such as dividing the element further, changing the element division or changing the technical solution. If a standardised part set is not found by performing any of these modifications, the generic element could be considered as a unique element which is not part of the product family.

When the different views are clarified and relations are analysed, it is also possible to discover possibilities for using the same parts or assemblies in generic elements that as a whole serve different functions. This would improve the commonality in the product family. When considering the level of commonality there can also be negative side effects. One risk is that the customer understands the product variants as being too similar. This can be a problem in, for instance, products with strong brand image where the customer pursues high differentiation.

There can be different types of generic elements, as discussed above. Thus one interesting issue to consider is their ability to handle complexity. Complexity in this situation is understood by the definition of a system consisting of elements and their relations. The complexity of a system is directly proportional to the number of elements and relationships to be managed. Consequently, it is easier to manage and develop a generic element that should consider a reasonable number of different customer needs. In addition to this, content of a generic element is easier to define if the variability need from the customer relates to only a specific area of the generic element. If there are different requirement needs falling upon the same area of the generic element, defining of a minimum number of variants is more difficult. Independence of a generic element is supported by non-overlapping parts from the other generic elements. The module should not completely surround another module. Complexity of the generic elements is also reduced by avoiding redundancies and duplications between generic elements. One example of this is where a same part set is included in several generic elements as a major partition.

In summary, this step highlights the considerations of possibilities to add more commonality to the existing products and considerations of numbers of variants needed for matching the customer needs that cause the need for variability. The result of this step presents the preliminary structure of a product family, including the links between customer, generic element and part and assembly views. Thus this step contributes to partitioning logic, set of modules and configuration knowledge of the Module System elements.

4.2.6 Step 6: Configuration knowledge: generic elements and customer needs

The sixth step focuses on preliminary configuration knowledge. In this phase, configuration knowledge consists of the relations between the generic elements and customer needs that cause the need for variety. Figure 4.18 represents the core aspects of this step.

As discussed in earlier sections in this thesis, there are several justifications for clarifying configuration knowledge. Separate modelling of configuration knowledge was, for instance, considered beneficial in the implementation of configurator software for the defining of product configurations in the sales-delivery process (see e.g. Haug et al. 2012). Clear representation of configuration knowledge can, moreover, be useful when modifications, updates or a completely new version of the product family is designed in the future. In the previously mentioned case, the reasoning for the content of the existing product family can be partly seen from the configuration knowledge (also business drivers for the product family should be well documented).

This step of the BfP facilitates the designing of modules in Step 7 and the formation of the final configuration knowledge in Step 8. The aim of the step is to clarify relations between generic elements and customer needs that present the variability needs. In other words, which customer needs must be considered in each generic element when solution principles and product structuring strategies for generic elements are defined? Thus knowledge of the generic elements and customer context is needed in this step of the BfP.

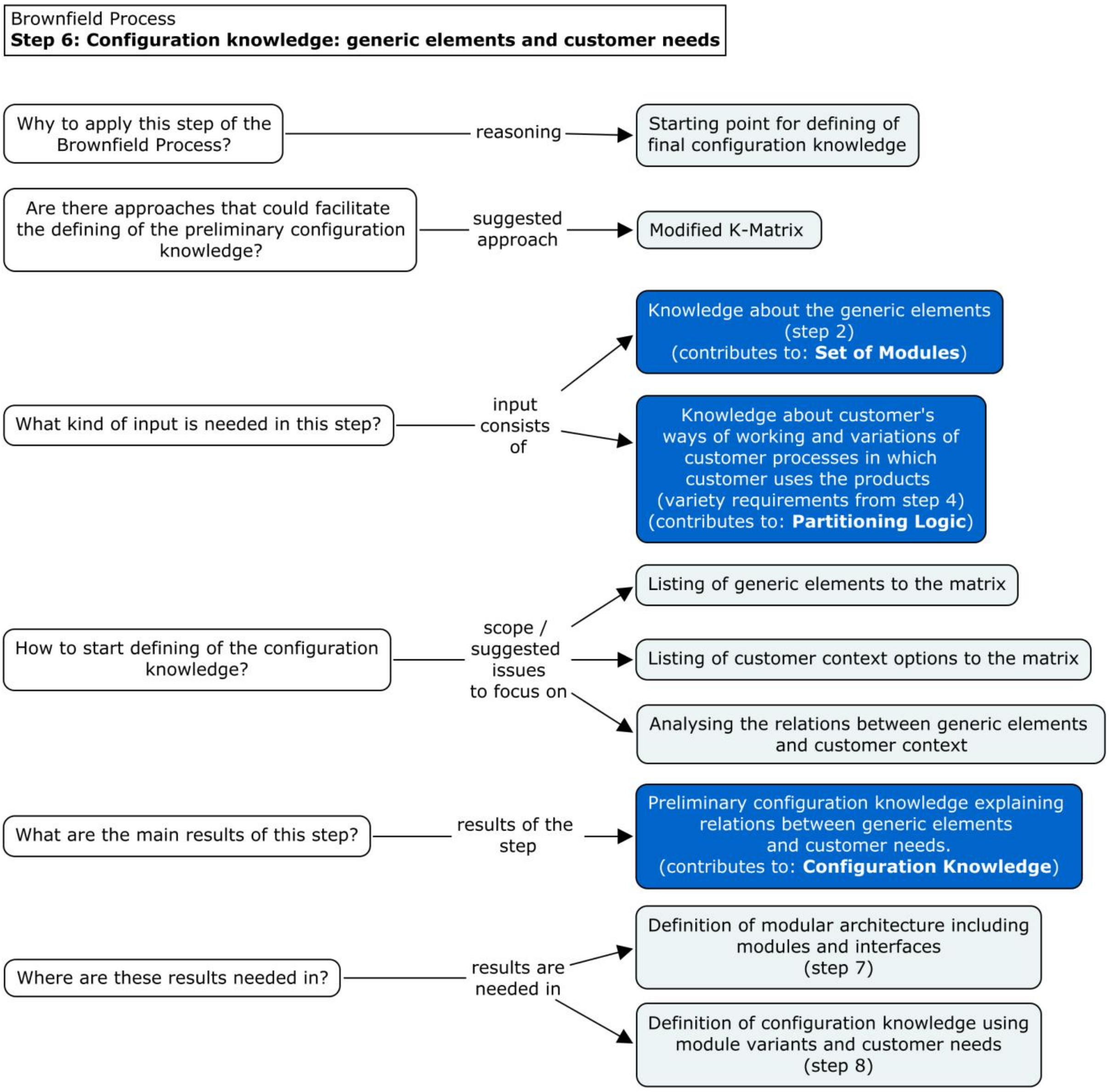
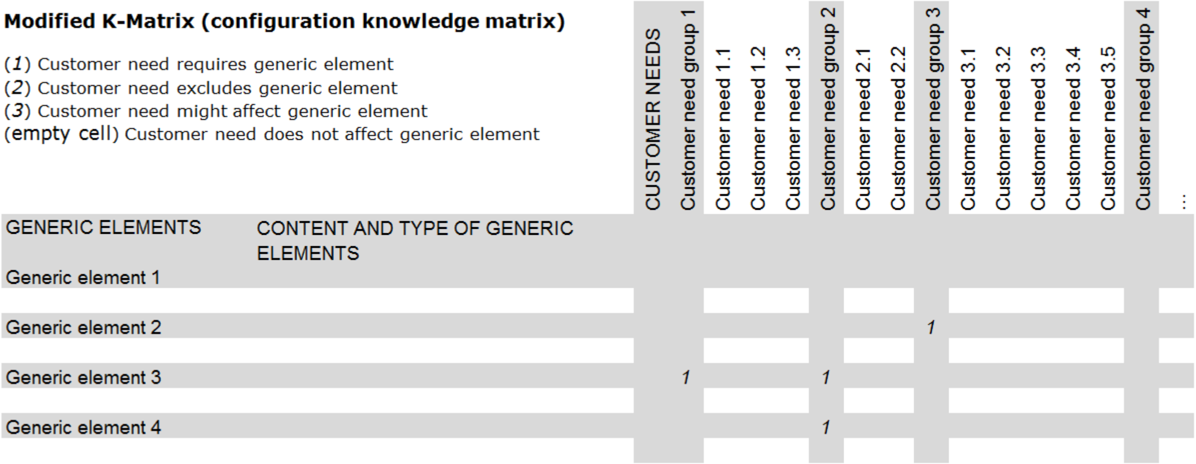


Figure 4.18. *The main content of Step 6 (Configuration knowledge: generic elements and customer needs) in the BfP.*

A modified version of the K-Matrix is a suggested tool in this step. The original K-Matrix is part of the K- & V-Matrix method discussed by Bongulielmi (2003) (see Chapter 3.8.7). The original K-Matrix is a configuration matrix in which studying of the relation between the technical view and the customer view is suggested. In the original method, relations are marked using only yes (there is a relation between technical view and customer view) and no (there is no relation) type of markings. Because the technical view is not defined in detail in this phase of the designing of a product family, more diverse types of relations can be used. Consequently, in the version used in the process, the following alternatives are analysed. This step suggests that there can be at least four types of relations between technical and customer view:

- Customer need requires generic element
- Customer need excludes generic element
- Customer need might affect generic element
- Customer need does not affect generic element

An example of the matrix used in the BfP is presented in Figure 4.19. In the later steps of the BfP, the aim is to use this matrix for representing the final configuration knowledge when the technical view is designed in more detail. Hereby the matrix shown in Figure 4.19 includes areas that are not considered in this step but should be considered if using the suggested tool template. Later on, solution principles for the generic elements and their type (standard, modular, unique etc.) can be added to this matrix and the relations can be defined in more detail. Thus in this step of the process the aim is to define configuration knowledge at a higher level. The goal is to define links of customer needs to generic elements, as discussed.



Modified K-Matrix (configuration knowledge matrix)

(*1*) Customer need requires generic element
(*2*) Customer need excludes generic element
(*3*) Customer need might affect generic element
(empty cell) Customer need does not affect generic element

GENERIC ELEMENTS	CONTENT AND TYPE OF GENERIC ELEMENTS	CUSTOMER NEEDS	Customer need group 1	Customer need 1.1	Customer need 1.2	Customer need 1.3	Customer need group 2	Customer need 2.1	Customer need 2.2	Customer need group 3	Customer need 3.1	Customer need 3.2	Customer need 3.3	Customer need 3.4	Customer need 3.5	Customer need group 4	⋮
Generic element 1																	
Generic element 2										*1*							
Generic element 3			*1*				*1*										
Generic element 4							*1*										

Figure 4.19. *Example of the modified K-matrix (original discussion by Bongulielmi 2003) for analysing preliminary configuration knowledge. Generic elements and customer needs that need to be considered from a variation perspective are organised using this matrix. For instance, one customer need group can consider different types of suspensions that customers have requested for their bicycles. In this case, customer needs of this group would describe the possible alternatives from a suspension-need viewpoint. Because content and type of generic element is not defined yet in detail, it is sufficient to analyse only the relations between the generic elements and customer need groups to get an overview of the variation reasoning for the product family.*

Generic elements are listed in the rows of the matrix, and customer needs are added to the columns, as shown in Figure 4.19. After this, the relations between the elements and the needs are defined by using the classification of relations discussed above.

The result of this step explains which generic element is compatible with a certain customer need. The result is needed in the defining of modules and interfaces (Step 7) and in the defining of final configuration knowledge (Step 8). Step 7 needs the results of this step because these results must be considered when defining the solutions for the generic elements. Thus when defining the solutions, it must be verified that these solutions (possibly modules) consider all the relevant customer needs. In Step 8, where modules are clarified, these modules and other types of product elements are added to the matrix begun in this step and the final configuration knowledge is then modelled. Related to the five elements of the Module System, this Step 6 contributes to the design information element of configuration knowledge.

4.2.7 Step 7: Modular architecture: modules and interfaces

Modular architecture is an important element in modularisation because it enables major benefits of configuration. Thus the seventh step focuses on the defining of modules and interfaces. In this step, structure of the modular product family is defined in more detail. Until modules can be defined in more detail, types of generic elements need to be clarified. This means that standardised, configurable, partly-configurable and one-of-a-kind elements have to be recognised from the architecture in the step. Figure 4.20 summarises the core of this step.

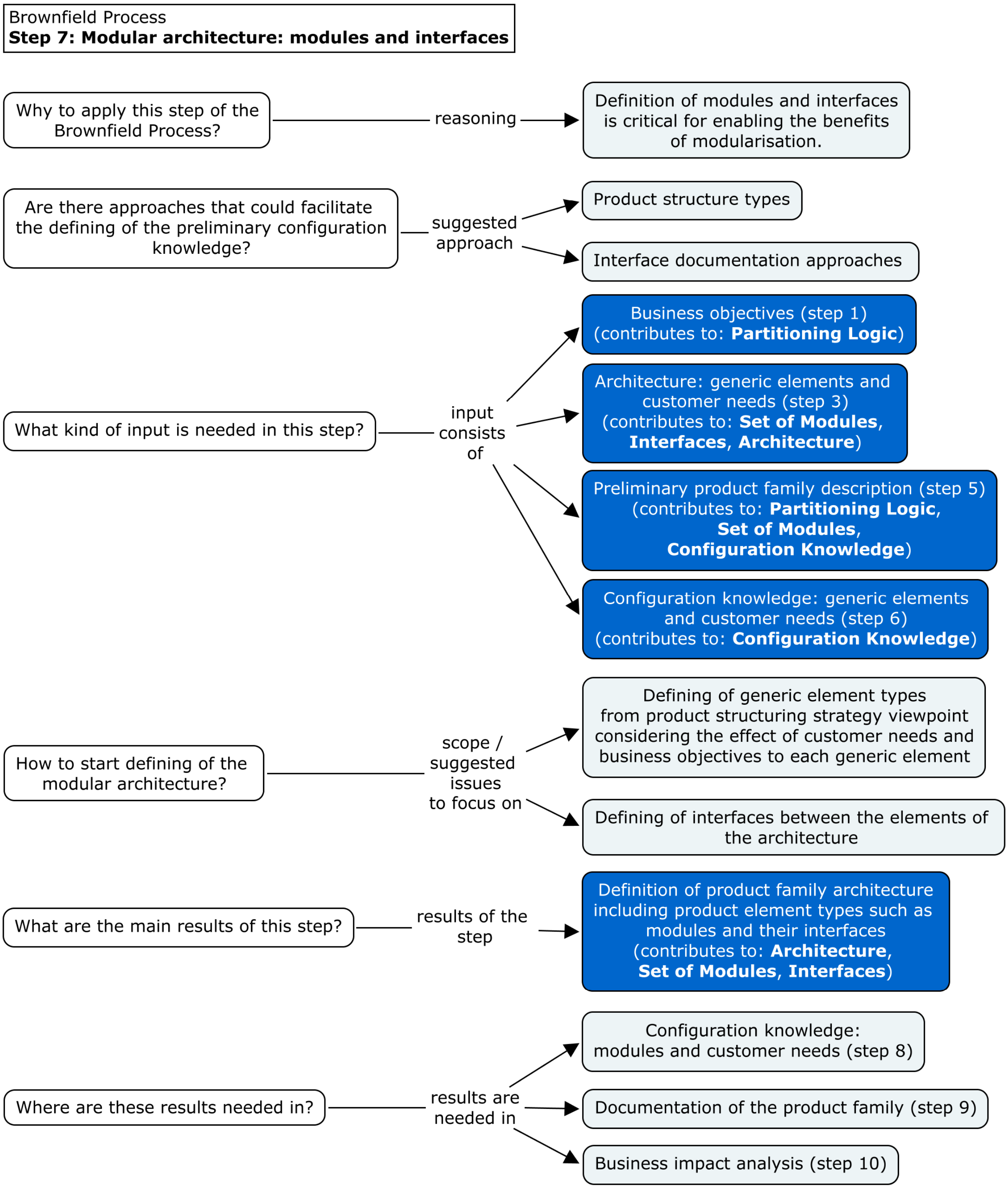


Figure 4.20. *The main content of Step 7 (Modular architecture: modules and interfaces) in the BfP.*

What kind of information has been accumulated from the previous steps? In the earlier steps, reasoning for modularisation has been collected from the business and customer environment. The structure of the existing products has been studied and preliminary considerations of the product family have been made. This step focuses on defining the architecture and its generic elements and interfaces in more detail. Thus the results of the previous steps are needed in this step. Consequently, until defining the product family in more detail, we have to know what kinds of requirements and limitations exist for the product family structure, what kind of possibilities there are for standardisation of parts and what kind of architecture the product family could have at a generic level and which generic elements would have interface with each other. Thus earlier steps of the BfP have aimed at dividing the drafting of the product family into manageable tasks.

In academic publications in which modularisation of industrial products are discussed, the detailed activities that have been carried out in the designing of successful modular products are seldom explained. Moreover, there are limited numbers of publications in which results of modularisation such as interface documentation of technologically multidisciplinary products are explained in detail. The author’s impression is that knowledge related to the design and management of products with variability and commonality is often considered as a core competence in each company and thus it is not revealed to the competitors on a large scale. This creates challenges for validating modularisation methods because all the details cannot necessarily be published. Method-like guiding principles have, however, been presented in several modularisation publications as already discussed in this thesis.

As a starting point in the designing of the architecture in more detail, the BfP suggests recognising different product element types from the generic architecture discussed in Step 3. The element types of the product structure are discussed based on a generic example of a product structure model of a partly-configurable product, as explained by Juuti (2008). This model was presented in Figure 3.37. Thus one of the aims of this step is to recognise which of the generic elements are standard, configurable, partly-configurable or one-of-a-kind (synonyms: unique, delivery-specific, project-specific). In the BfP, it is understood that the standard element is the same in every variant of the product family. Configurable elements include standardised variant options. Unique elements are compromise if standard or configurable elements cannot be defined for some area of the product family. According to this division, a product family might not be fully configurable when consisting not only of standard elements and modules with standardised options, but if unique elements are needed in some areas of the product in order to fulfil the customer needs in a reasonable way. This results in partly-configurable overall structures. From the re-use perspective, the aim is to naturally avoid delivery-specific elements because they behave differently in the sales-delivery process since they need to be designed separately in each product delivery case.

Thus the aim is to **recognise different elements from the architecture** and in addition to this, also to **define part sets for generic elements** and to **clarify the overall architecture of modular product family including interface definitions** as illustrated in Figure 4.21.

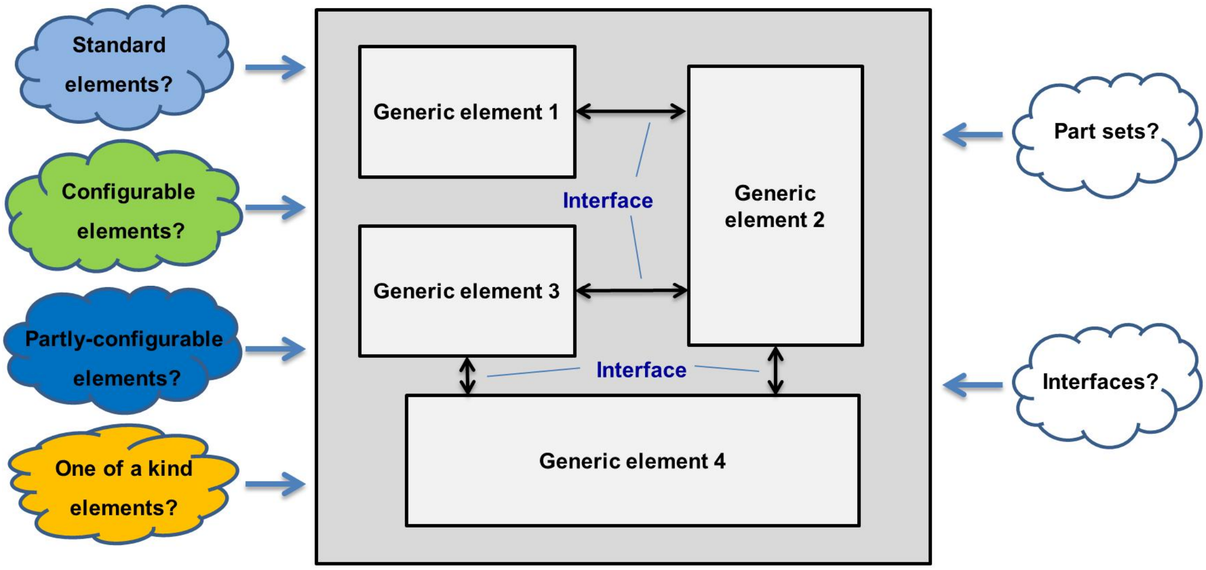


Figure 4.21. *Generic elements and their interfaces must be defined in more detail.*

When discussing variable products in general, the aim is for these products to include standard solutions as much as possible, and to include a minimum number of interchangeable standardised modules in the areas in which one standardised element is not reasonable from a variation-need perspective. Interfaces between the elements should also be standardised in order to enable effective variation.

If variation needs from customer perspective are not related to a generic element and the element could be realised with one solution, the element is good candidate to be **standard element**. This kind of element is included in every product variant of the product family. A part set for standard element is selected or re-designed if needed based on the existing part sets. Standardisation relates also to interfaces of product solutions in order to support their interchangeability and independence. Interfaces are discussed later on in this section in more detail.

Generic elements which need to consider variation in order to satisfy customer and business needs are challenge for development of modular product family. It is beneficial if variation needs can be fulfilled with minimum number of standardised modules from company viewpoint because this supports benefits of design by reuse (Juuti 2008). It might be possible to design a single standard solution for a given set of different needs but this kind of element might become too expensive because the solution would have to include the potential for adapting to different needs although only a fraction of the potential and performance would be possibly used in a customer variant.

When a single standard solution is not reasonable for the variation need, a set of interchangeable modules which are standardised within a company and product family should be considered. We name these as **configurable elements**.

If a reasonable number of standardised modules cannot be defined for a generic element, dividing the generic element or changing the generic element division or solution principle is needed. This can lead to **partly-configurable elements** that might include also **one of a kind elements** in addition to standardised and configurable sections. If restructuring of generic element does not help in recognising standardisation possibilities, element can be considered as one of a kind element. These elements are compromise and should not be aimed for in modularisation because these do not support benefits with design re-use. It might not be sensible though to design re-usable and interchangeable modules for business areas which have low sales potential if the designing of reusable elements is more complex than the designing of one-of-a-kind elements for each rare case.

When requirements that justify the variation need and relations of these requirements to specific generic elements are known (this information is considered as preliminary configuration knowledge in Step 6), the rational number of existing **part sets** or solutions can be analysed. Based on existing solutions, the following issues can be recognised:

a) Existing solutions and part sets that are related to a specific generic element meet the variation needs well. Clear and different variation needs are related to existing solutions and part sets include similar interfaces. Thus existing part sets are justified.
b) There are too many part sets with different interfaces related to a specific generic element for matching the defined variation needs. Thus the number of different part sets should be decreased for example because of redundancy and overlapping and cost reasons.
c) There is not enough part sets related to a specific generic element for matching the defined variation needs. This means that new part sets are needed.

In the background of the BfP, there is the thought that the company has operated in a projecting business area in which solutions have often been designed to fit every customer need and thinking regarding re-use aspects has been low. The reason for this might have been a strict delivery schedule that caused low possibilities for the designing of re-usable assets. The situation in the company could have been that out of a large number of different solutions significant numbers of product deliveries were made. By using the BfP, the situation is hoped to develop in the direction in which, with smaller sets of solutions and their parts, the same customer needs (compared to the existing situation in the company) could at least be fulfilled.

If there are completely different part sets for every variation need, this cannot be considered as the best situation. If the product family includes parts and solutions that can be used in different variants, this is as a better situation. According to Martin & Ishii (1997), commonality indices illustrate how well the design uses standardised parts. The BfP does not highlight calculation of indices but standardisation at least within the analysed product variety is emphasised. A reasonable number of part sets is affected for instance by the variety of customer needs the same product family have to fulfil, possibilities, skills and resources for recognition of commonalities from existing solutions and standardisation. Redundancies between part sets should be avoided because of unnecessary costs. In reducing unnecessary part sets, recognition of commonalities and realisation of the same kinds of solutions with fewer physical realisations should be aimed at. As stated, this can lead to partly-configurable product structures.

The focus of the BfP is in rationalisation of existing product variety. The BfP presumes that there are customers and markets that have bought certain kinds of products against specific requirements. Thus methodological suggestions for designing of radically innovative products or part sets are not discussed in this section in greater detail but tools for finding new ideas can be found for example in publication by Pahl & Beitz (1996). Surely the innovativeness is not declined in, for instance, the defining of the solutions for the generic elements if the resources exist and it is not considered to be too large a threat from a risk point of view. As discussed earlier, Oja (2010), for example, noted that one reason for incremental designing in the industry is to avoid risks with new product development.

Goal of the BfP is not only to find suitable solutions and part sets for each variation need but also to consider architecture of a modular product family. If division of generic elements changes then the architecture of the modular product family also changes. As discussed, generic elements can be divided into smaller entities because of easier possibilities to manage variation. This increases number of interfaces to be managed if standardised elements cannot be combined with other standardised elements to form a single larger standard element. Figure 4.22 shows an example of how the architecture might have changed during the designing. Interface between two or more generic elements should always be standard within a product family, although generic elements would include module options or even unique elements with different space reservation needs. In ideal situation, all the interfaces and space reservations for solutions are recognised and defined in modular architecture. When comparing Figure 4.22 to the preliminary architecture description in Figure 4.14, this example shows that one generic element has been divided into two different elements, of which the left hand side can be standardised and the other section needs a variable section including a set of standardised modules. In addition to this, one element has been defined as a delivery specific element and the element at top right includes optional variants in this example.

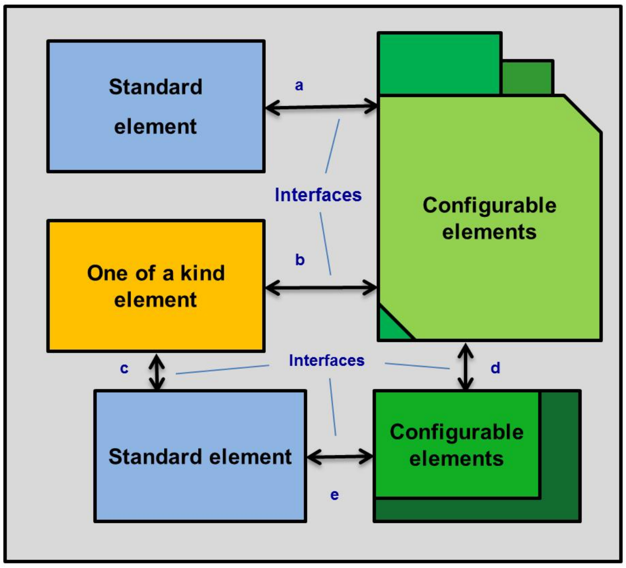


Figure 4.22. *An example of how product family architecture might have changed compared to preliminary architecture as shown in Figure 4.14 and 4.21.*

In the designing of a product family, the aim is not only to find suitable solutions for each variation need, but also the overall architecture of the product family must be considered. In this case, the task is to analyse each part set entity related to generic elements in order to ascertain whether or not it would have similar **interfaces** with part sets of other generic elements. Based on the earlier discussions, standardised interfaces maintain a central role in the designing of modular architecture for a product family. In the modularisation chapter, it was discussed that standardised interfaces enable interchangeability and independence of the modules. Drafting of product or product family architecture can help in recognition of important interfaces, as Step 3 of the BfP suggests.

The BfP is open for different interface definitions. Therefore approaches from literature are discussed in following. Interfaces can be defined from several perspectives such as spatial, structural, geometry, material, energy, signal and information (Avak 2006; Rahmani & Thomson 2009; Sosa et al. 2007). Separate interface control documents are also suggested for defining of interfaces (Stevens et al. 1998). Existing research includes also categorisation of different levels of interface standardisation (Cabigiosu et al. 2013; Fujimoto 2007). For example it can be beneficial to define whether interfaces are model specific, company specific or can industrial standards be applied. Also potential and need for substituting the interface must be considered. In redesigning situations, considering of modularity types (Pine 1993; Ulrich & Tung 1991) can be also helpful in finding suitable approaches for defining of interfaces for product solutions. Interface standardisation and defininions facilitate the designing of module variants for the product family because definitions explain what kind of restrictions modules have to fulfil.

Erixon (1998) explained in MFD (see Chapter 3.8.4 and Figure 3.66) that there are at least two basic principles for assembling the product: "hamburger" assembly and base part assembly. Signs for these kinds of assembly principles can be recognised from layout or architecture definition of the product family and obviously also from existing products. For instance, if an element has interfaces with several elements and those other elements would have only interfaces with this specific element, this could mean that this specific generic element could follow the base part assembly principles. On the other hand, if generic element has interfaces with only two generic elements at most and those two would not have common interfaces, this could refer to "hamburger" assembly if the layout enables this kind of assembly. This can be an important issue to recognise if production and assembly reasons are major drivers for modularisation.

Holmqvist (2004) discussed the defining of areas for the product of which the variants dedicated for each section are not allowed to cross. This kind of suggestion for the designing of modules can be especially relevant in an environment in which space is a critical design criterion. In that case, the defining of these kinds of limits would give clear rules for designers for avoiding possible disturbances of a module in regard to other sections of the product. The module would be designed based on the layout criteria. In some cases, this could result in unused space in the variant. In analysing the rationality of this kind of suggestion, strictness of space limitations must be considered in each case.

From a management point of view, ownership of the elements and interfaces is also an important topic. If this topic is neglected, the risk is that the modular architecture deteriorates during the time frame and the benefits of re-use are lost. Harlou (2006) explained that there is no one ownership solution for all companies, but that each company should clarify its motivation and consider how advanced it is from an architecture perspective and then make the decision about the ownership issue of interfaces and the whole product family architecture.

In summary, this step focuses on the defining of modular architecture of the product family. This architecture defines what kinds of elements and interfaces the product family includes. Thus this step contributes to the architecture, modules and interface information elements of the Module System. Results of this step are needed in clarification of the final configuration knowledge which is essential in order to define product variants efficiently based on customer needs. Results of the step are also needed in documentation of the product family and in estimating the business effects of the product family.

4.2.8 Step 8: Configuration knowledge: module variants and customer needs

The eighth step of the BfP includes the defining of configuration knowledge. Configuration knowledge was already discussed in Step 6 but in that step the defining of configuration knowledge was done in regard to generic elements and customer needs. In this step, the knowledge is defined using actual solutions for the generic elements that were defined in the previous step. Figure 4.23 summarises the content of this step.

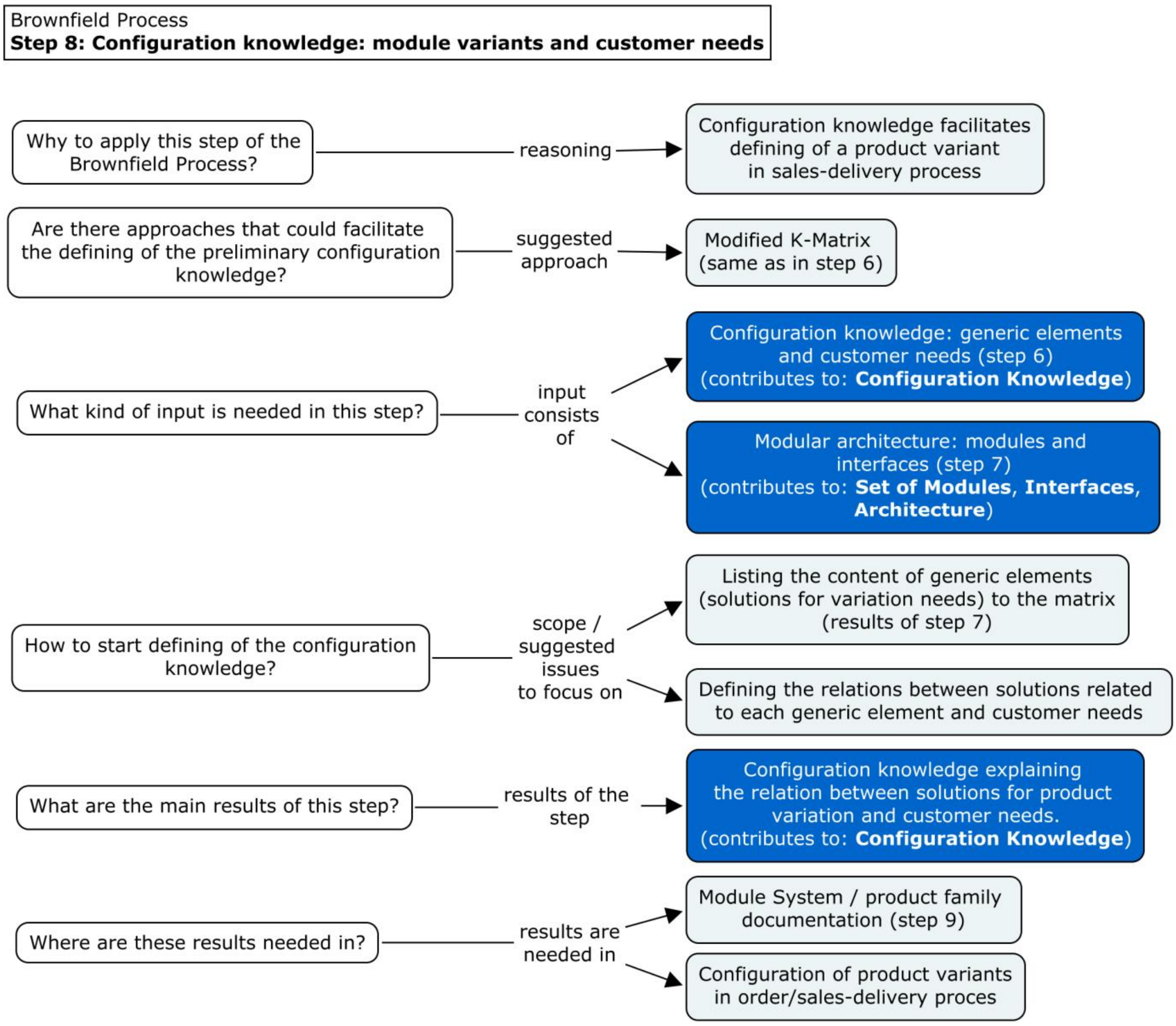
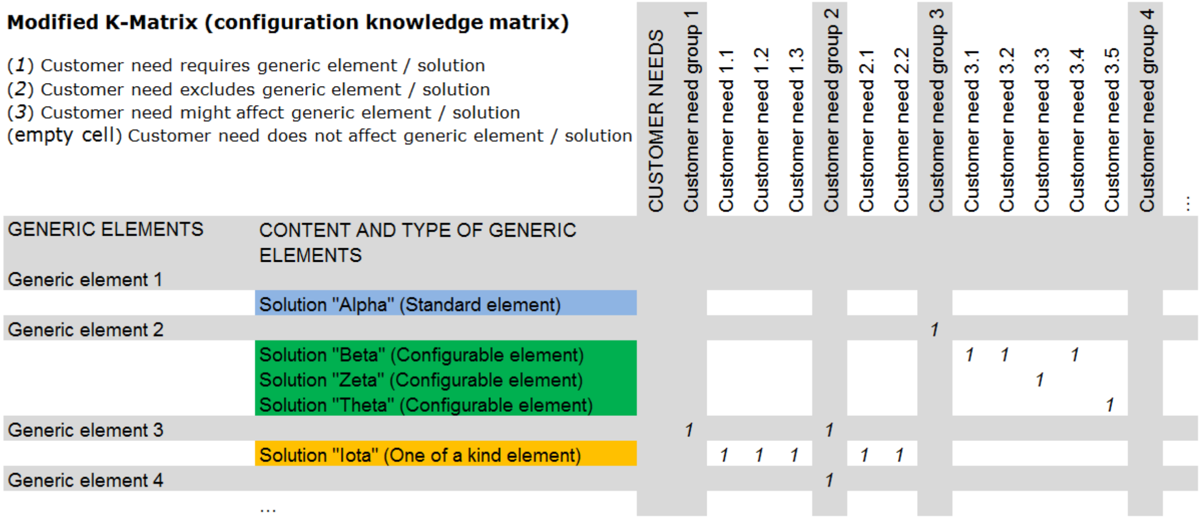


Figure 4.23. *The main content of Step 8 (Configuration knowledge: module variants and customer needs) in the BfP.*

This step is important because results of the step explain clearly which technical solutions and customer needs match. Thus configuration knowledge that includes final solutions helps with the defining of variants later on in the sales-delivery process. As discussed earlier by Haug (2007) and Haug et al. (2012), separate representation of the configuration knowledge can be useful when implementing software-based configurators because product experts can easily refer to this kind of representation and, for instance, suggest corrections to the configurator if necessary. The results of the step can be used also in the documentation of the product family in which the reasoning chain is presented. This is discussed in the next step of the BfP. Moreover, this kind of representation of the configuration knowledge can be used as a reminder when business impact analysis is performed in Step 10. Representation made in this step gives an overview of the designed product family and can be helpful when estimations of its business effects are made.

The suggested approach for this step is the same as in Step 6, in which preliminary configuration knowledge was studied. In the previous step, solutions for generic elements were defined. These are needed as an input for this step. Figure 4.24 shows a template and example results for this step. If compared to Step 6, the content and type of generic elements have now been added to the matrix and the relationships of these to customer needs are presented.



Modified K-Matrix (configuration knowledge matrix)

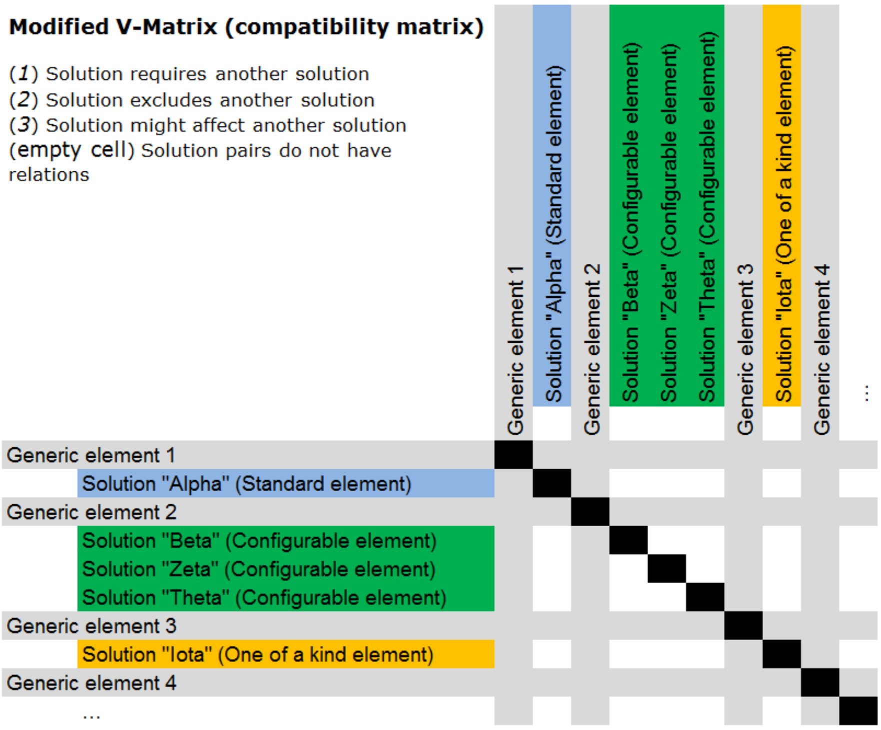
(*1*) Customer need requires generic element / solution
(*2*) Customer need excludes generic element / solution
(*3*) Customer need might affect generic element / solution
(empty cell) Customer need does not affect generic element / solution

GENERIC ELEMENTS	CONTENT AND TYPE OF GENERIC ELEMENTS	CUSTOMER NEEDS	Customer need group 1	Customer need 1.1	Customer need 1.2	Customer need 1.3	Customer need group 2	Customer need 2.1	Customer need 2.2	Customer need group 3	Customer need 3.1	Customer need 3.2	Customer need 3.3	Customer need 3.4	Customer need 3.5	Customer need group 4	⋮
Generic element 1																	
	Solution "Alpha" (Standard element)																
Generic element 2										*1*							
	Solution "Beta" (Configurable element)										*1*	*1*		*1*			
	Solution "Zeta" (Configurable element)												*1*				
	Solution "Theta" (Configurable element)														*1*		
Generic element 3			*1*				*1*										
	Solution "Iota" (One of a kind element)			*1*	*1*	*1*		*1*	*1*								
Generic element 4							*1*										
	...																

Figure 4.24. *Complete configuration knowledge of the modular product family is presented using the same matrix tool as in Step 6. Now the content and type of generic elements is added to the matrix. After that, more detailed configuration knowledge can be defined to the matrix.*

In the BfP, it is suggested that the relation between generic elements and their content and customer needs can be defined from four perspectives as shown in the top left corner in Figure 4.24. In this figure, the reason for why the relation is a certain type is not, however, discussed. This kind of knowledge remains tacit if it is not visualised. One solution for this would be to add comments to each relation field in which the reason for a specific relation is explained. The storing of this knowledge would be very important in, for example, the furthering of developments of the product family. The tool that is shown in Figure 4.24 is done with traditional office software.

In this step, compatibilities between generic elements and their content can also be visualised. There also exist matrix tools for this purpose. For instance, the V-Matrix discussed by Bongulielmi (2003) is meant for this task. In our case, both the rows and columns of the matrix would include generic elements and their content. An example of this kind of template is shown in Figure 4.25. Matching combinations are defined in the matrix. Basically, the matrix suggested by Nummela (2006) could also be used in this step as an alternative tool. By using this kind of matrix, the base product would include standard elements and saleable options would be understood as a customer need causing the variety need. Matrices are suggested because they are easy to read when the reader knows what element or pair he needs to analyse. If building a configurator, there has to also be knowledge of compatible customer needs. This means that if a customer chooses some option, this selection can exclude another customer option. Thus a well-made configurator would guide the customer in choosing only technically compatible options. For defining customer need compatibilities, a matrix with the same idea as presented in Figure 4.25 can be established for the customer needs as well. This kind of template is shown in Figure 4.26.

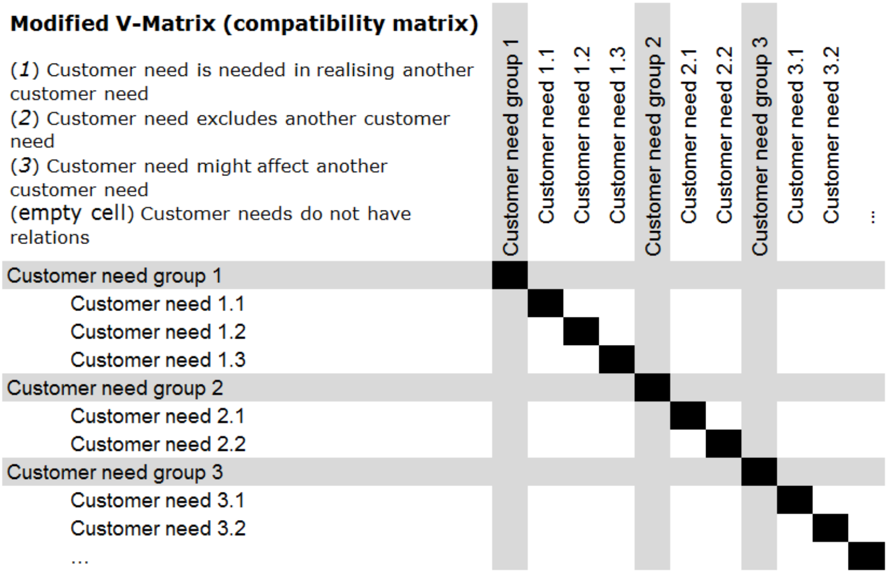


Modified V-Matrix (compatibility matrix)

(*1*) Solution requires another solution
(*2*) Solution excludes another solution
(*3*) Solution might affect another solution
(empty cell) Solution pairs do not have relations

	Generic element 1	Solution "Alpha" (Standard element)	Generic element 2	Solution "Beta" (Configurable element)	Solution "Zeta" (Configurable element)	Solution "Theta" (Configurable element)	Generic element 3	Solution "Iota" (One of a kind element)	Generic element 4	...
Generic element 1	■									
Solution "Alpha" (Standard element)		■								
Generic element 2			■							
Solution "Beta" (Configurable element)				■						
Solution "Zeta" (Configurable element)					■					
Solution "Theta" (Configurable element)						■				
Generic element 3							■			
Solution "Iota" (One of a kind element)								■		
Generic element 4									■	
...										■

__Figure 4.25.__ Matrix example for the defining of compatibilities between generic elements and their solutions, following the principles presented by Bongulielmi (2003).



Modified V-Matrix (compatibility matrix)

(*1*) Customer need is needed in realising another customer need
(*2*) Customer need excludes another customer need
(*3*) Customer need might affect another customer need
(empty cell) Customer needs do not have relations

	Customer need group 1	Customer need 1.1	Customer need 1.2	Customer need 1.3	Customer need group 2	Customer need 2.1	Customer need 2.2	Customer need group 3	Customer need 3.1	Customer need 3.2	...
Customer need group 1	■										
Customer need 1.1		■									
Customer need 1.2			■								
Customer need 1.3				■							
Customer need group 2					■						
Customer need 2.1						■					
Customer need 2.2							■				
Customer need group 3								■			
Customer need 3.1									■		
Customer need 3.2										■	
...											■

__Figure 4.26.__ Matrix example for the defining of compatible customer needs, following the principles presented by Bongulielmi (2003).

To conclude, the result of Step 8 illustrates the compatible solution and customer need pairs by explaining, for instance, which module variants are compatible for certain customer needs. If it is discovered in this step that the defined customer needs do not cover important markets for the company, this can result in iteration needs for the designing of the modular product family architecture and result in the need to return to previous steps of the BfP.

4.2.9 Step 9: Product family documentation

In the earlier steps, the basic structure of the modular product family for configurable products has been defined. Suggested approaches in the BfP document the main results of each step in themselves. In addition to this, the process includes a separate documentation step (this step) in which documentation of the product family is discussed from the design reasoning chain viewpoint. Documentation aims at describing the content of the product family and explaining which customer needs each element and solution corresponds to. Content of the step is shown in Figure 4.27.

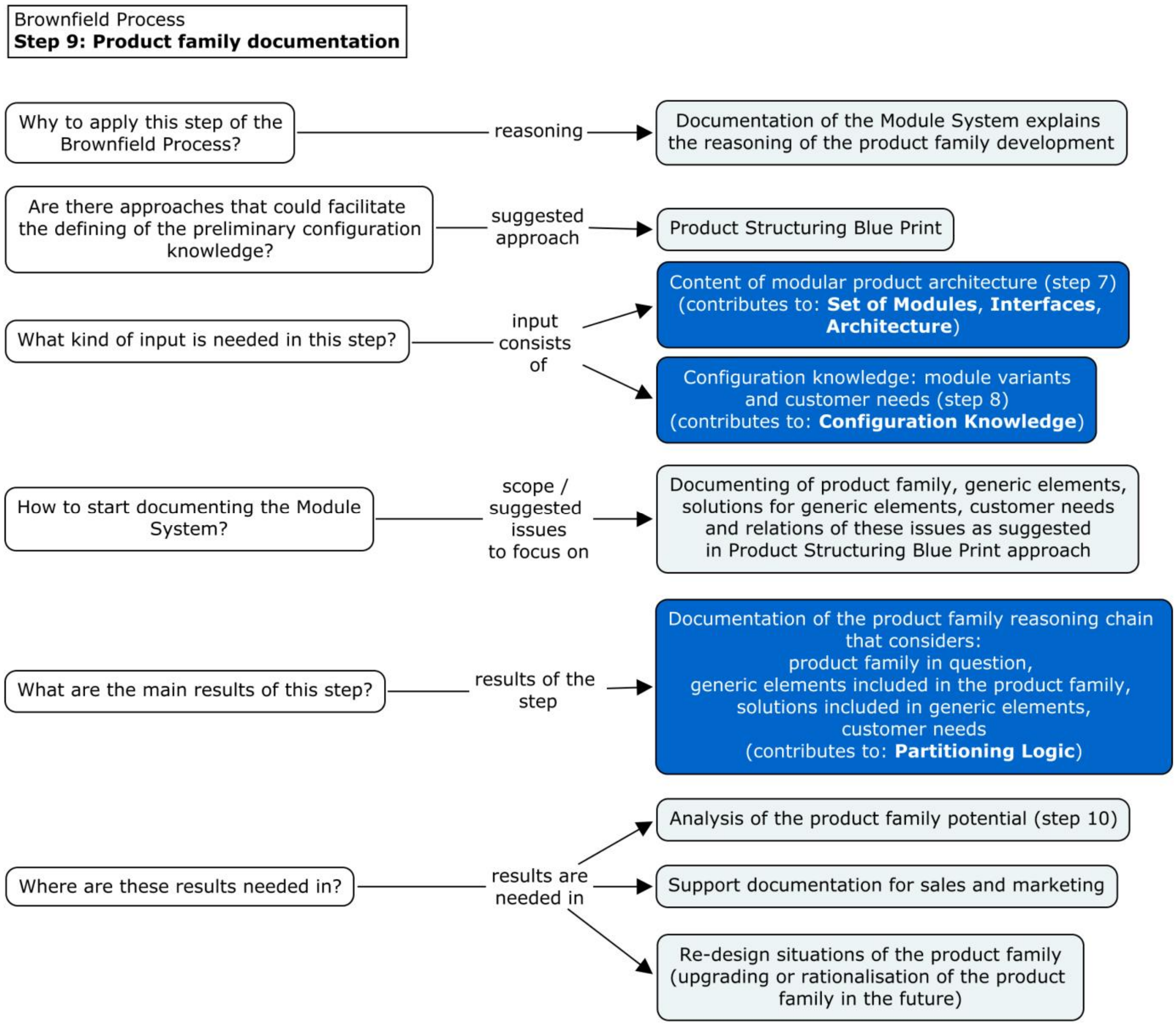


Figure 4.27. *The main content of Step 9 (Product family documentation) in the BfP.*

In the BfP, the graph known as the Product Structuring Blue Print (PSBP) is suggested for documentation. This aims at representing partitioning logic and design reasoning aspects of the product family. A generic example of the PSBP is presented in Figure 4.28. The leftmost side describes the product family in question. When moving towards the right-hand side, generic elements are described next. Then the solution principles that describe how generic elements are realised are shown. This example in Figure 4.28 shows that realised generic elements can include several types of solution principles. In this generic model of the PSBP, three different product structuring tactics are available. In this example, solution principles can be standard, configurable (based on a set of standardised optional modules) or one-of-a-kind elements. If all of these exist, the product family can be considered as partly-configurable. Finally, on the right hand side, variation needs from the customer need perspective are presented. They are linked with corresponding solutions of generic elements.

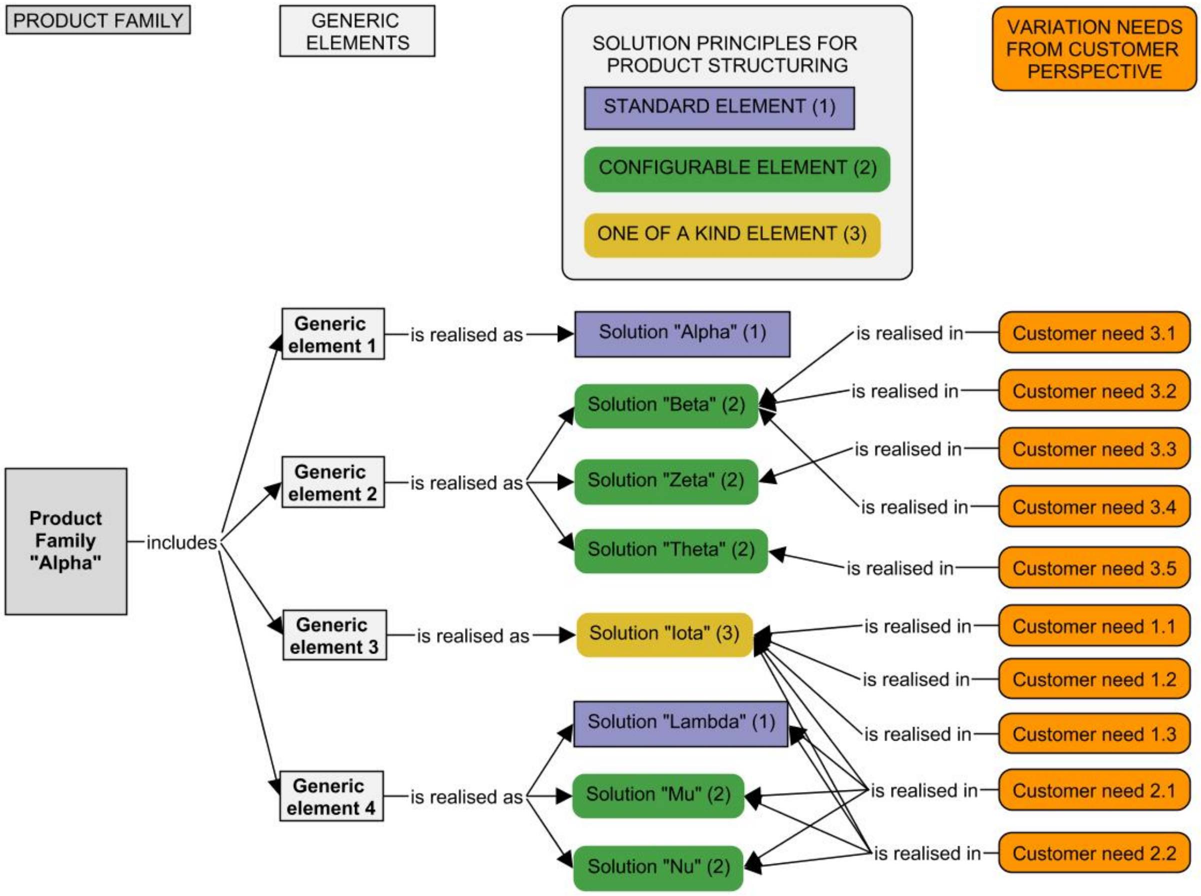


Figure 4.28. *The PSPB documentation approach for the product family describes the reasoning chain visually.*

Figure 4.28 describes, for example, that Generic element 2 is realised using solutions Beta, Zeta, Theta, which are alternative configurable elements. In this example, customer needs 3.1 - 3.5 are fulfilled with these optional solutions.

To conclude, PSBP documentation can be helpful in the support of design work and for increasing design re-use because it makes the reasoning of the content of the product family visible. Documentation is important if, for instance, changes are made to the product family because of technological evolution or changed variation needs.

4.2.10 Step 10: Business impact analysis

As discussed in the literature section by, for instance, Juuti 2008, consideration of variability with commonality in the products is regarded as a way to increase the competitiveness of the company if the company aims to deliver products for different customer needs. Analysing the results of the product development is important in order to gain understanding about how well the objectives are met with the designed solution and whether or not the new product family suggestion could be competitive. In the BfP, an estimation of the business effects of the modular product family in relation to the different life cycle phases is made. Summary of the step of business impact analysis is made in Figure 4.29 and discussed in this section in more detail.

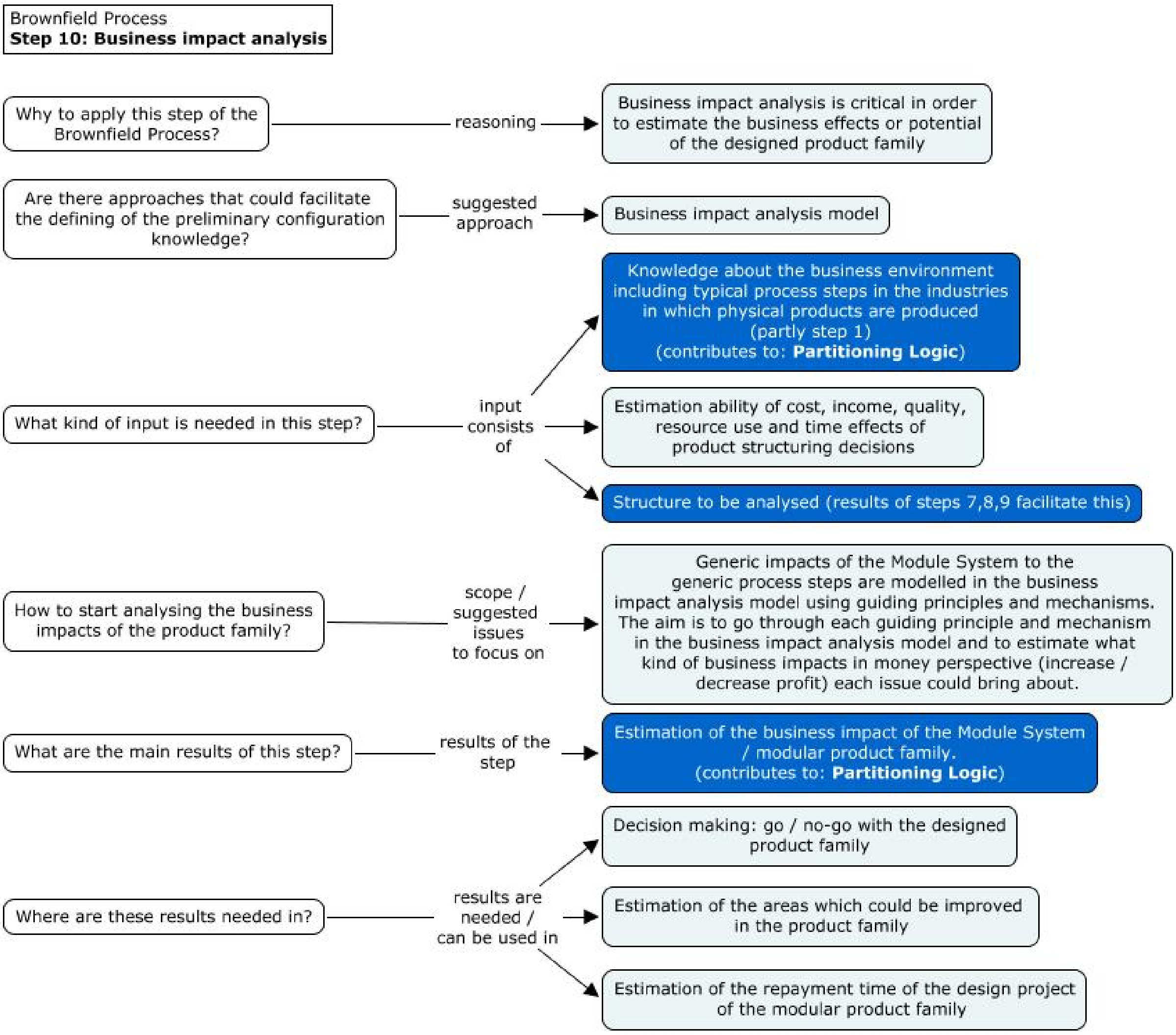


Figure 4.29. *The main content of Step 10 (Business impact analysis) in the BfP.*

Based on the modularisation experiences discussed in the literature, a model for business impacts of modularisation has been created. Basic idea of the analysis is presented in Figure 4.30 and the overall model in Figure 4.31. The structure of the model has some similarities with the model discussed by Fixson (2006), in which he described the relations between product architecture dimensions and cost and time issues in different product life cycle phases (see Chapter 3.8.9). In our model, the product is defined using different dimensions; recognised mechanisms are not completely similar and there can also be effects other than cost and time. The business impact analysis model suggested in this step is described below.

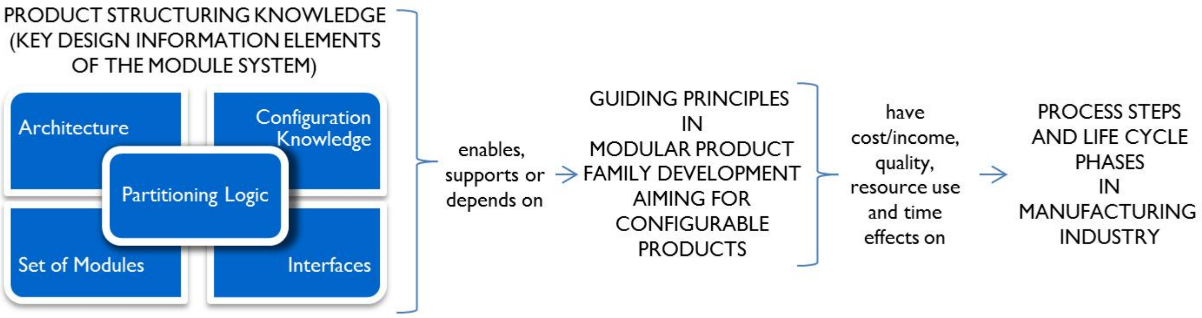


Figure 4.30. *The main idea of the business impact analysis model in the BfP.*

The left side of Figure 4.31 includes the product view, which considers the Module System. In the BfP, partition logic, architecture, sets of modules, interfaces and configuration knowledge are considered important design information elements in modularisation. It is stated that this kind of division into five elements can help in understanding what kind of information has to be considered when designing a modular product family. The steps of the BfP seek to define the content of these five elements, as discussed earlier. Each step aims at contributing to one or more elements of the Module System.

Guiding principles and mechanisms have been presented in the middle of the business impact model in Figure 4.31. These principles describe the possible objectives, phenomena and problems that modularisation can have an effect on. Table 4.1 presents an overview of the guiding principles and mechanisms, their descriptions or arguments and examples from the publications that relate to each principle or mechanism. There are several publications in which possible impacts of the modularisation are discussed. In the literature, both positive and negative effects have been presented. In Table 4.1, the aim has been to define references in which supporting definitions can be found beside each guiding principle and mechanism.

Guiding principles and mechanisms have similarities with, for example, the module drivers discussed by Erixon (1998). Module drivers by Erixon were discussed in greater detail in Chapter 3.5.6 of modularisation and in Chapter 3.8.4, in which Erixon’s MFD method was presented. It can be stated that these kinds of module drivers, guiding principles or mechanisms aim at reflecting the causality between the modular structure of the product and the business objectives. Not all the guiding principles and mechanisms discussed in Figure 4.31 can be found from the publication of Erixon (1998). Thus Table 4.1 also includes other opinions and observations on this issue. Not all of these have been discussed in great detail earlier in the literature review of this thesis but the content of these has been summarised in Table 4.1.

Relations have been modelled between the product structuring knowledge and guiding principles and mechanisms in Figure 4.31. Relations describe basically which elements of the Module System might have an effect on which guiding principles and mechanisms. All the five elements of the Module System are necessary in order to develop a rational modular product family but in the business impact analysis model an attempt to define the most important elements of the Module System for each guiding principle and mechanism have been made. Thus most of the relations describe the fact that certain product structuring knowledge is necessary but not enough on its own.

The right-hand side of the business impact model shown in Figure 4.31 describes generic process steps of the manufacturing industry. In this model, process steps include product development, marketing and sales, production, transport, installation & implementation, use, service, revision and retirement / recycling. Product development can include the designing of new products or features or the re-designing of existing products because of, for example, updates, corrections or part changes. In marketing and sales, supporting elements have also been explained. These highlight supporting documentation and information systems and the level of product knowledge that sales persons have. This is because modularisation may have important effects on these areas. Production includes procurement of parts and materials, possible subcontracting, own manufacturing of the company, testing of parts, modules and final product and assembly.

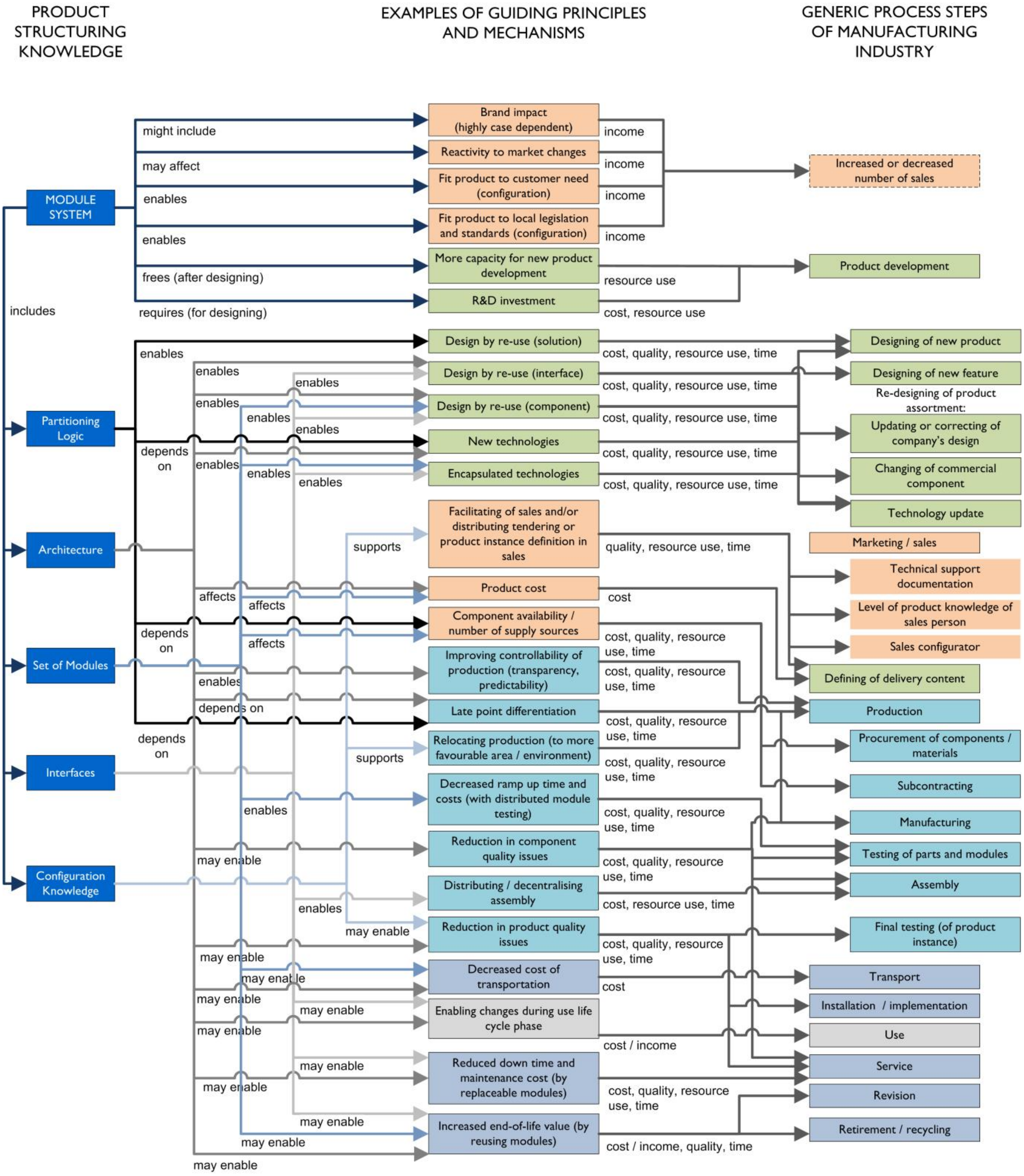


Figure 4.31. *Model for estimating business impacts of the Module System. In this step, guiding principles and mechanisms are gone through and their possible cost, income, quality, resource use and time effects in money are estimated in relation to the process steps.*

Figures 4.32 – 4.37 present sections of Figure 4.31 in order to simplify reading compared to the whole model shown in the figure above. As discussed earlier, Table 4.1 includes descriptions of guiding principles and mechanisms with supporting reference examples related to these figures.

Figure 4.32 presents the module system as a main element of product-structuring knowledge and its related guiding principles and mechanisms and process steps. The main mechanisms include brand impact, reactivity to market changes, fitting product to customer need (configuration), fitting product to local legislation and standards (configuration), more capacity for new product development and R&D investment. These mechanisms especially affect sales and product development.

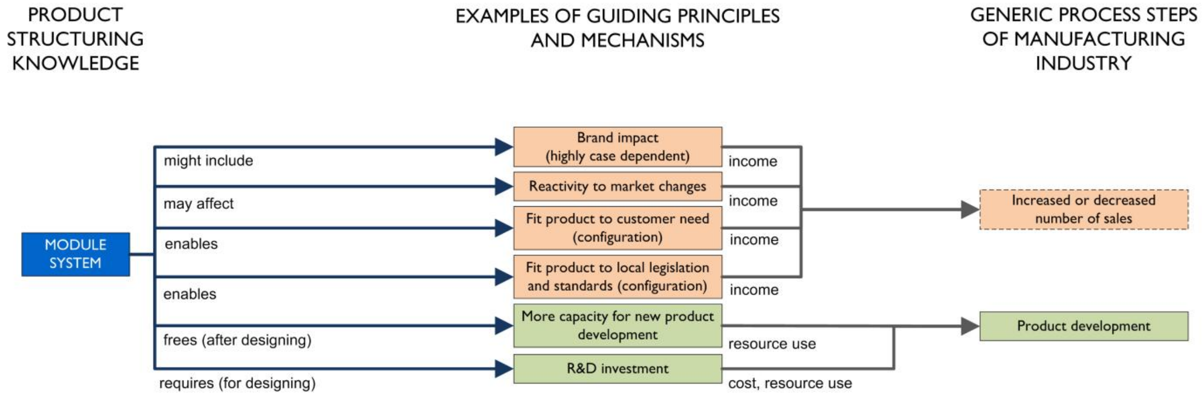


Figure 4.32. Business impacts of module system.

Figure 4.33 presents the business impact model from a partitioning logic viewpoint. Here the suggested main guiding principles and mechanisms include design by re-use (solution), new technologies, component availability / number of supply sources and late point differentiation. These affect design and production aspects.

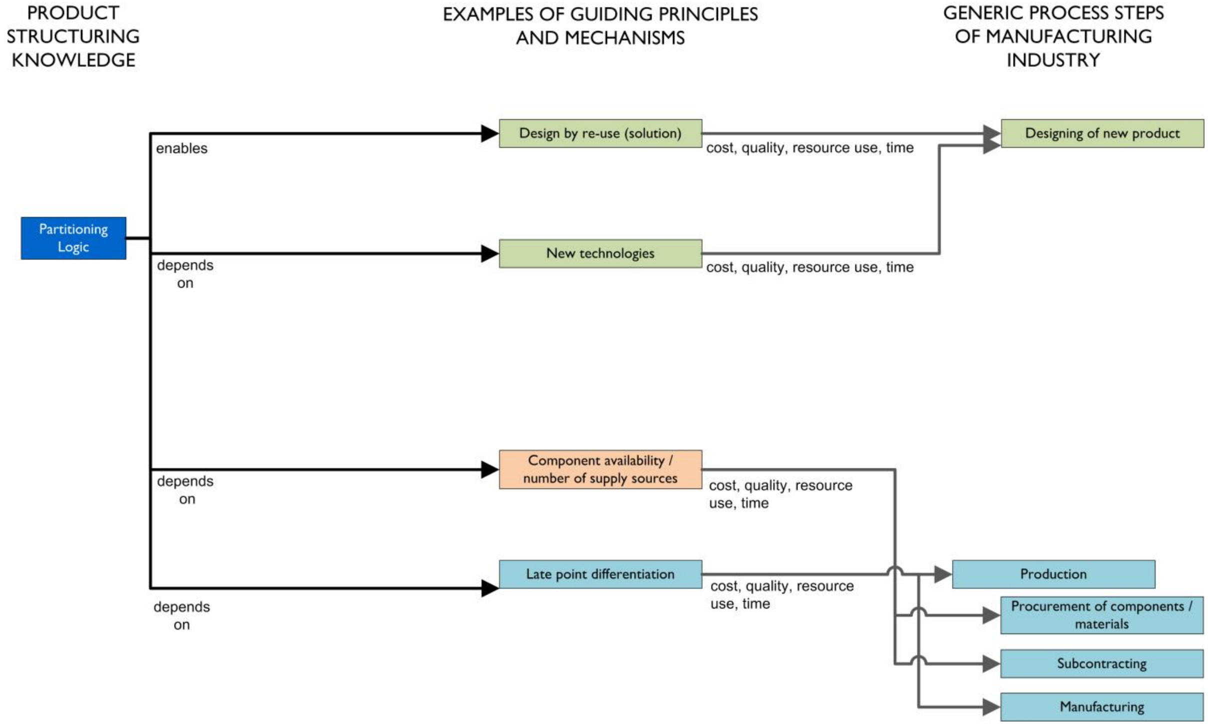


Figure 4.33. Business impacts related to partitioning logic.

Figure 4.34 presents the business impact model from an architecture viewpoint. Several guiding principles and mechanisms have been related to architecture. These include design by re-use aspects, new technologies, product cost, improving controllability of production, late point differentiation, reduction in component quality issues, decreased cost of transportation, enabling changes during use life cycle phase, reductions in down time and maintenance cost and increased end-of-life value. These guiding principles and mechanisms can be linked with a number of process steps as the figure explains.

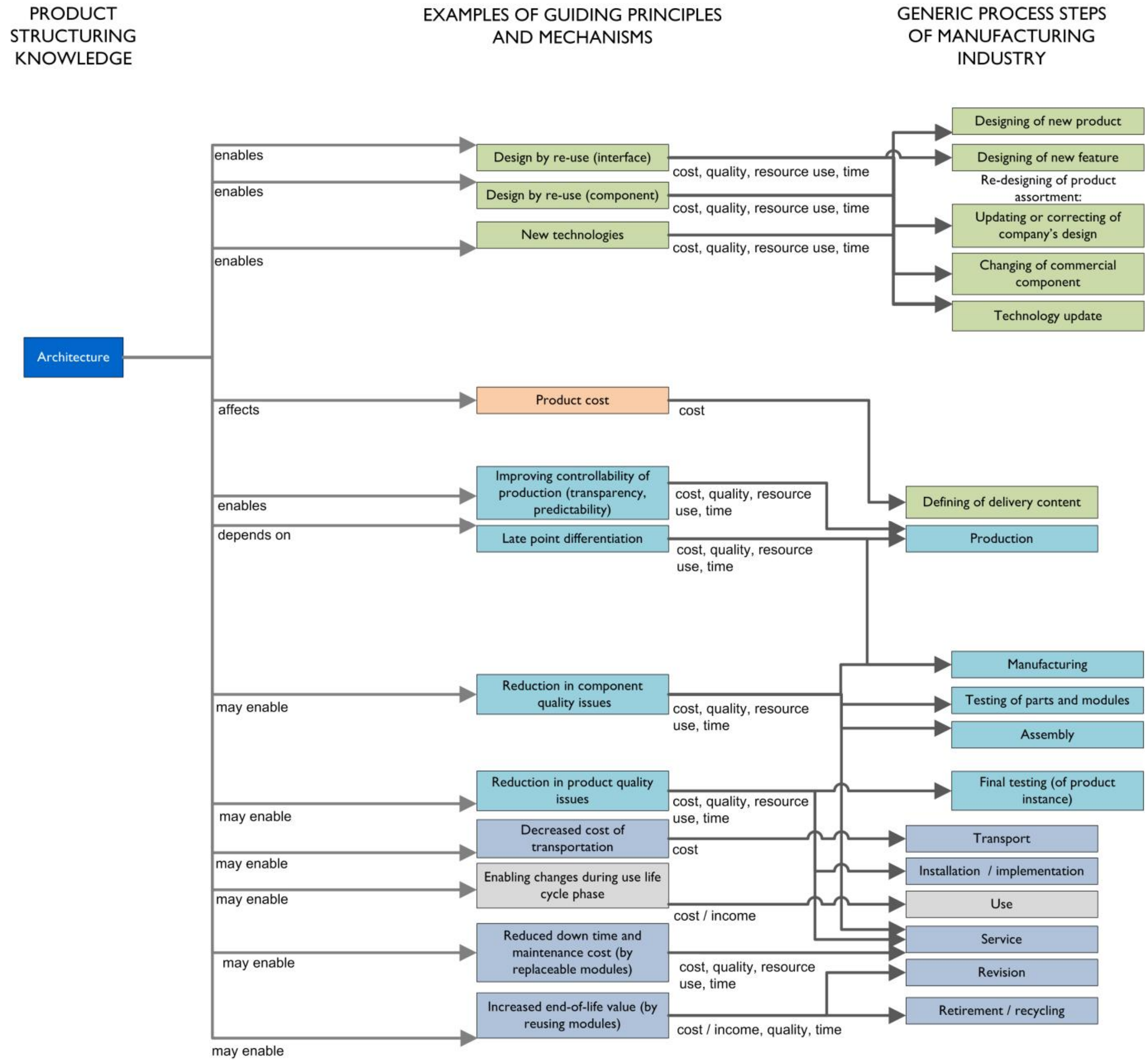


Figure 4.34. *Business impacts related to architecture.*

Figure 4.35 presents the business impact model from a module viewpoint. Related guiding principles include design by re-use (component), encapsulated technologies, product cost, component availability / number of supply sources, decreased ramp up time and costs, decreased cost of transportation and increased end-of-life value. These mechanisms also have connections to several process steps.

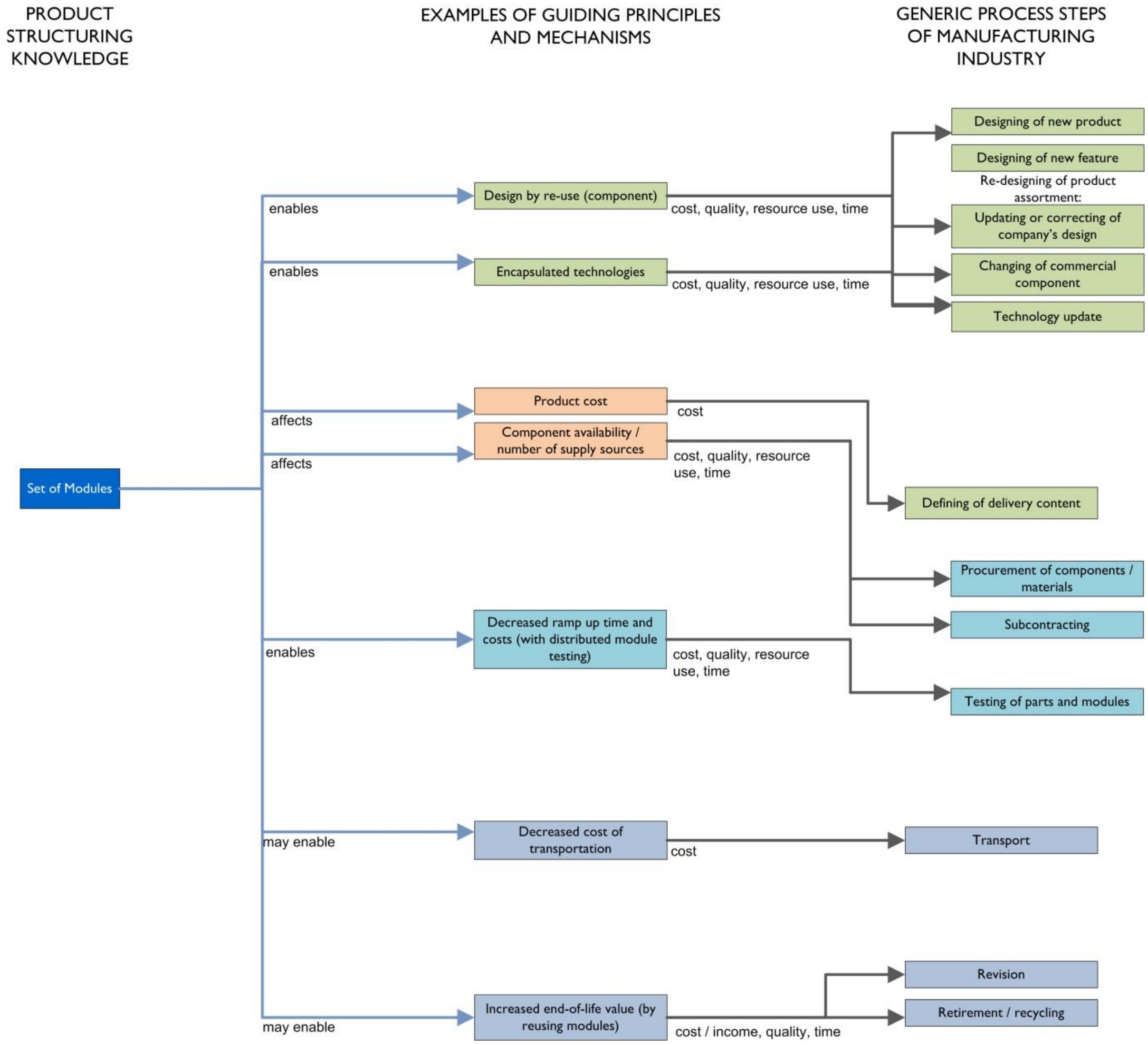


Figure 4.35. *Business impacts related to set of modules.*

Figure 4.36 presents the business impact model from an interface viewpoint. Guiding principles and mechanisms include design by re-use aspects, new technologies, encapsulated technologies, distributing / decentralising assembly, enabling changes during use life cycle phase, reduced down time and maintenance cost and increased end-of-life value. These principles and mechanisms have effects on designing, assembly, use, service, revision and retirement / recycling steps.

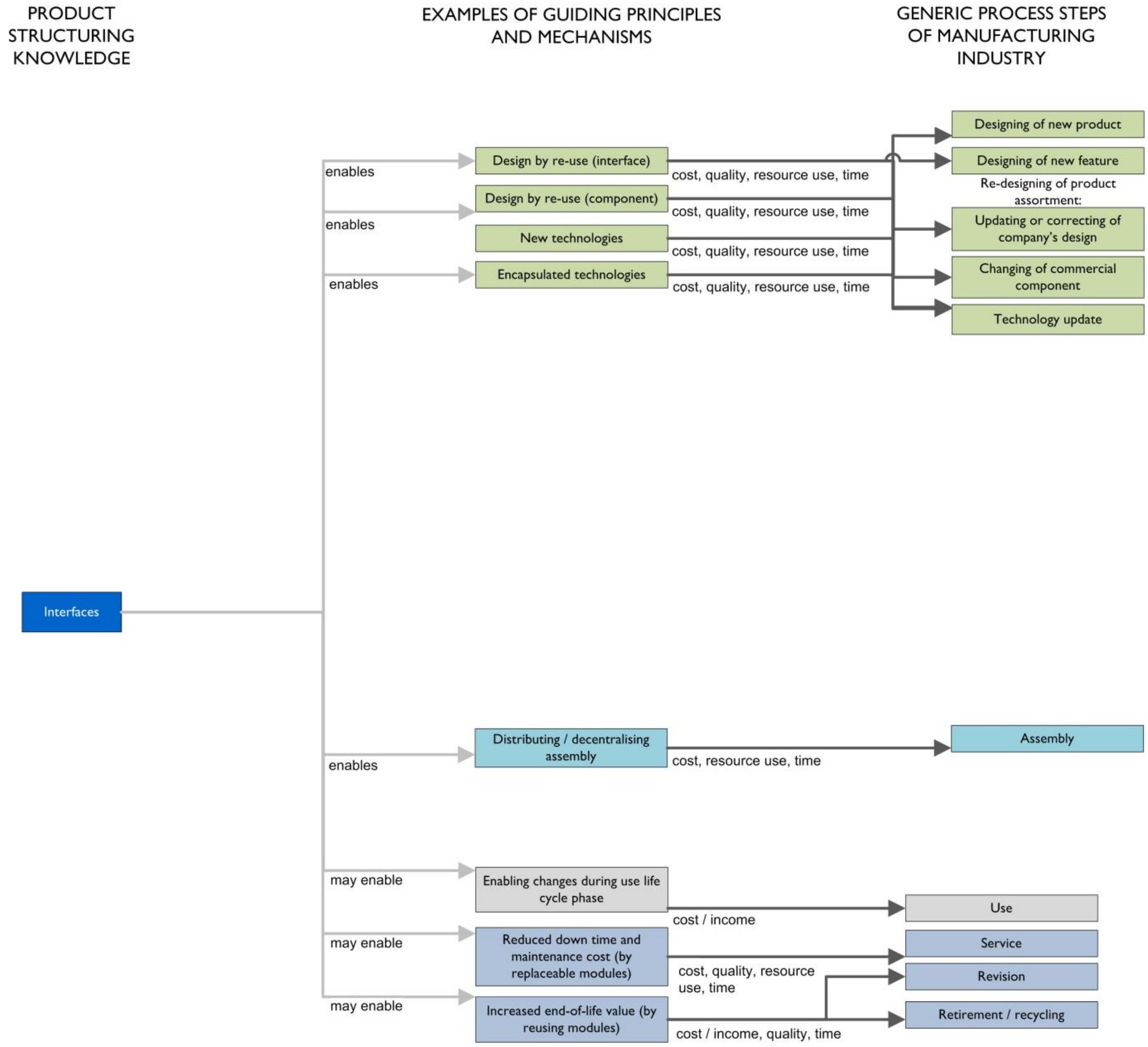


Figure 4.36. *Business impacts related to interfaces.*

Figure 4.37 presents the business impact model from a configuration knowledge viewpoint. In this model, configuration knowledge is connected to three guiding principles and mechanisms, which include the facilitating of sales and/or distributing tendering or product instance definition in sales, relocating production and reduction in product quality issues. These may affect sales, production (including testing), installation / implementation and service.

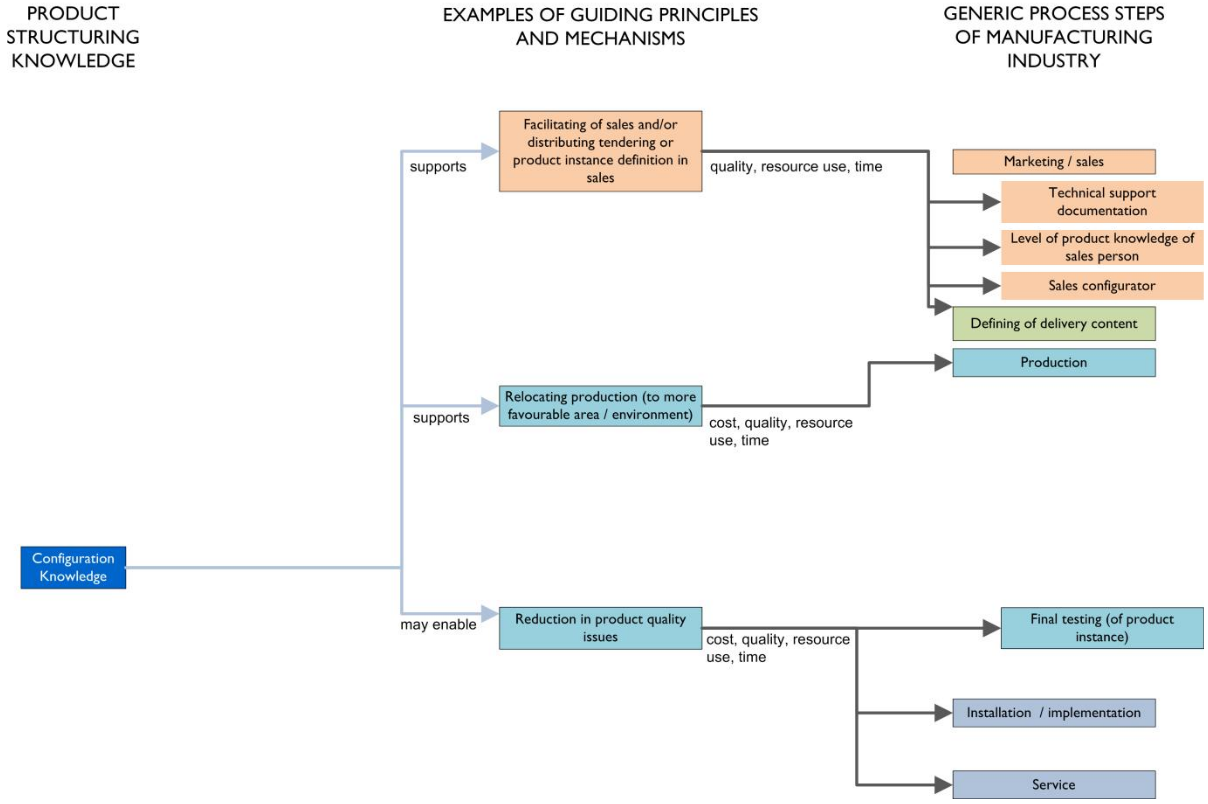


Figure 4.37. *Business impacts related to configuration knowledge.*

As can be seen from these figures (Figures 4.31 – 4.37) of the business impact model, the aim has been also to consider the type of relation (cost, quality, resource use, time) between guiding principles and mechanisms and process steps. These types are defined by reasoning, based on the supporting references discussed in Table 4.1, but some of the relation types are assumptions. This means that although some relations have been defined with cost, quality, resource use and time effects, all of these relation types might not exist or it is difficult to estimate all of these separately in real life cases.

Fujimoto (2007) discusses the idea that quality, cost, delivery and flexibility are typical views on product competitiveness. Lau Antonia (2007) states that product quality, low price, flexibility and customer service can be found in the work of several authors. These considerations were discussed in Chapter 3.3 regarding product competitiveness and the competitive company. In this step of the BfP, cost, income, quality, resource use and time effects are considered from a money perspective. The idea is that these effects can either increase or decrease profitability. Cost effects describes impacts of modularisation other than those effects related to quality of the final product, use of (human) resources or (lead) time effects. Thus cost effects can include, for example, costs of parts and materials, possible needs for equipment investments or effects of possibility for reducing the needed equipment. Income effect is estimated because guiding principles also have a positive nature instead of a burden, although these issues could also be understood as cost issues with increasing profit effects instead of reduction. Quality effects are estimated from a product quality perspective. Product quality describes how well the resulting product matches the specifications. Fujimoto's delivery aspect is considered as a time effect in our model. Time effects especially relate to lead time issues. Estimation of flexibility issues is left outside this analysis. This is because estimation of flexibility as a separate element in relation to guiding principles and mechanisms is difficult. In the model shown in Figure 4.31, the premise is that successful modularisation improves flexibility based on increased commonality without excluding possibilities for product variations and flexibility, and is included in estimation of other aspects such as cost, income, quality, resource use and time effects.

The result of the business impact analysis is an estimation of the effects of the successful modular product family development project. Thus it represents the estimate of the largest benefit of the Module System. When doing the analysis, the premise is that both the development project of modular product family and development of operative issues will succeed. Designing of operative issues is outside the scope of this thesis. Consequently, the result of the business impact analysis is the most positive realistic estimation, but it is not certain that it is achieved. Fixson (2006) states that detailed cost estimations rarely exist early in the design process. In the BfP, the suggestion is that the business impact analysis of modularisation is done using "decades" of money (thousands, tens of thousands, hundreds of thousands etc.) because analysis with definitive values might be too challenging. Effects can either increase or decrease profit, as discussed earlier. The period under review should be long enough so that the evaluating of effects related to the later life cycle phases such as possible product revisions could also be considered. Additionally, the number of the product deliveries should be greater than one or two because of the characteristics of the effect mechanisms. Repetitions in the delivery chain can be considered as fundamental aims because repetitions enable several other benefits. This was discussed by, for example, Juuti (2008).

Guiding principles and mechanisms that are related to process steps are analysed one by one in this step. As discussed, there is a possibility that some of the guiding principles and mechanisms are not relevant in every business case. Thus when doing the business impact analysis, original objectives set in the first step of the BfP must be considered in this step. For example, was there a specific objective set from some process steps? In this step, all of the process steps are discussed and the analysis considers the whole process from product development to retirement / recycling. Thus the business impact analysis can also explain other effects of the modular product family that were not perceived at the beginning of the design process. Because only the decades of money are estimated, the largest decades are in a dominant role when analysing the results of the business impact analysis. The largest decades can be studied in more detail if necessary. It is possible that impacts of some principles and mechanisms are impossible to evaluate. This is also a result. It should be taken into account when evaluating the effects of modularity that some areas are not well-enough known so that the analysis can be done.

The objective in the analysis is to consider the product family as one entity, with the premise that common objectives (not only variant specific) have also been set at the beginning of the design process. If the designed product family being analysed includes areas that have completely different sets of characteristics, challenges for this kind of business impact analysis exist. This is because some variants might cause different, even opposite, effects from others. In this case the analysis can be difficult to do and the results might turn out insignificant. The solution in this case is to split the product family into two or more portions and to do separate evaluations for each portion. This step can reveal whether or not the partitioning logic and the architecture should be reconsidered. The result of this step can also be used in estimating repayment time for a modular product family design project.

Table 4.1. *Guiding principles and mechanisms related to the modularisation.*

Guiding principles and mechanisms	**Description / argument**	**Supporting reference examples**
Brand impact (highly case dependent)	Marketing a product as a modular might affect to the decision making of a customer about buying the product.	Tiihonen et al. (1999) discuss that configuration contributes to brand management issues. Hopp & Xu (2005) discuss about brand effect being one factor in analysing the demand for offering variants with modularity.
Reactivity to market changes	Market requirements can change and cause change pressure to the properties of the products.	Harlou (2006) discusses that in designing of a modular product family, attractiveness of the products also in the future is decided. Erixon (1998) discusses that consideration of styling possibilities can be important driver for modularisation in the products whose purchasing decision trends and fashion affects strongly.
Fit product to customer need (configuration)	Modular product family enables configuring the product to customer needs using pre-defined product elements.	Pulkkinen (2007) and Juuti (2008) discuss that modularisation facilitates fitting of product to customer needs by configuring.
Fit product to local legislation and standards	Fitting of product to local legislation and standards is important in order to operate in multiple markets and countries.	Pahl & Beitz (1996) discuss that adhering of relevant legislation and standards is prerequisite in all type of designing.
More capacity for new product development	After designing the modular product family, resource use of designers in the sales-delivery process is reduced.	Duffy & Ferns (1999), Pulkkinen (2007) and Juuti (2008) discuss that design re-use (that the modular product family supports) reduces the needed design effort per product delivery. They discuss about cost, quality and time effects.

R&D investment	Designing of a modular product family needs R&D investment.	Baldwin & Clark (2000) discuss that modular design requires investments because of formulating design rules, experimenting, designing each module and testing.
Design by re-use (solution)	In the design process, there might be pressures for re-using of solution principles in order to reduce design effort.	Erixon (1998) and Juuti (2008) note that re-using of parts, sub-systems or a product is one of the possible drivers for modularisation.
Design by re-use (interface)	In the design process, there might be pressures for re-using of interfaces in order to reduce design effort.	Fujimoto (2007) highlights the role of standardised interfaces in order to facilitate re-using. Standardised interfaces support also planned design changes of which Erixon (1998) discusses.
Design by re-use (component)	In the design process, there might be pressures for re-using of components in order to reduce design effort.	Erixon (1998) and Juuti (2008) note that re-using of parts, sub-systems or a product is one of the possible drivers for modularisation. Sanchez (1999) discusses that re-using of component designs reduces the development costs of new product variations.
New technologies	Modular product family can facilitate replacing of old technologies (tangible assets) with newer. These must be considered when partitioning logic is defined.	Erixon (1998) discusses that technological evolution or technology push can set requirements for the product designing within products whose technology develops fast. Harlou (2006) considers future product elements in defining of architecture.
Encapsulated technologies	Modularisation enables isolating of technologies using well defined interfaces to rest of the system in order to reduce complexity of the overall system.	Baldwin & Clark (2000) discuss that new solution can be incorporated in later rounds relatively simply if design parameters which are isolated (they call these hidden parameters) from other parts of the design are clearly defined. Lehtonen et al. (2003) discuss that

		encapsulating of modules reduces complexity in managing the products.
Facilitating of sales and/or distributing tendering or product instance definition in sales	Configuration knowledge, which is defined in designing of a modular product family, has an effect to sales because the knowledge describes the relations between solutions and variation requirements. Configuration knowledge enables developing of sales configurators and guides towards re-using of product elements.	Victor & Boynton (1999) discusses that human or software driven configurator facilitates defining of individualised products. Soininen (2000) defines that configuration model improves configuration process. Haug (2007) has recognised several benefits of using configurators such as reduced lead time, quality of specifications, preservation of knowledge, need for fewer resources for specifying the product and less time needed for training people.
Product cost	Designing of a modular product family affects to the product cost because the aim is to increase commonality between product configurations without excluding the variation possibilities.	Sanchez (1999) discusses that use of common components in product variations may reduce product costs. Fixson (2006) discusses that part count reduction is commonly seen cost reduction tool.
Component availability / number of supply sources	Component availability describes how easily the component can be acquired. Increased number of possible supply sources facilitates economical procurement.	Baldwin & Clark (2000) discuss that if all items in a product line use common parts, economies in parts sourcing may exceedingly reduce the total cost of production.
Improving controllability of production (transparency, predictability)	Products which have been designed outside the sales-delivery process facilitate improving controllability of the production because impacts of the products to production are more transparent and predictable. This is because products are not completely delivery specific.	Sanchez (1999) discusses that designing of modular components should be done off-line to improve the predictability of product creation process (production). Baldwin & Clark (2000) discuss that modularity can be used to simplify complex processes in production.
Late point differentiation	Maintaining of a product as a base model or as a standard product as long as	Lee & Tang (1997) discuss that delayed product differentiation lowers the

	possible may bring benefits in production because then the processes can be also standardised far. Variation would be done in the later steps of the production or even after the traditional production steps. Modularisation is considered as an enabler of late point differentiation because it separates standard sections of variable sections.	buffer inventories in production thus reducing the complexity of manufacturing process. Erixon (1998) discusses that allocating variations to only one or few parts and keeping the product generic as long as possible can help in reducing inventory and thus the overall costs. Sanchez (1999) discusses that "universal chassis" including all the common components used in different variants enable mass production benefits. Use of universal chassis may reduce variety of parts that must be inventoried and handled in assembly according to Sanchez. Sanchez also explains that late point differentiation may also reduce costs of distributing product variations.
Relocating production (to more favourable area or environment)	Modularisation aspects can facilitate production in the factory (onsite prefabrication) instead in the site of the customer such as in the operating environment of the product. This can be relevant for example when products are large.	Lehtonen (2007) discusses that existing assembly and operating environment reasons of the product can favour production in the factory.
Decreased ramp up time and costs (with distributed module testing)	Modularisation has impacts to the testing of modules because defined interfaces enable distributing and parallelisation of module testing. This is because interfaces should define in which kind of environment the module should be used in. Thus the pressure to test all the product elements together is smaller.	Erixon (1998) discusses that separate testing of modules reduces feedback times about the quality of modules compared to testing done in the main production flow.
Reduction in component quality issues	A reduced number of divergent and unique	Sanchez (1999) discusses that re-use of components

	components increase possibilities for producing of products which meet the specifications better. Learning by repetitions is considered as a main enabler in this mechanism.	may improve the reliability of key components over the time because re-use enables incremental improvements in materials and processes. Juuti (2008) discusses that repetitions in manufacturing and thus resulting learning reduces component quality issues. This reduces warranty costs according to him.
Distributing / decentralising assembly	Possibility to decentralise assembly can be important for instance because of limitations of existing facilities or remoteness of market areas. Requirements set by the assembly environment can be considered when reasoning for the module division is defined.	Lau Antonio et al. (2007) discuss that well-specified interfaces in modularisation enable distributed assembly. They explain also that product modules can be delivered to a location of customer in which the product is assembled.
Reduction in product quality issues	Modularisation affects to the quality of the product because product instances of the family adhere to predefined architecture. In designing of the product family architecture, compatibilities of product element options have to be considered. Using of configuration rules when defining of product instances facilitates producing of functioning solutions.	Tiihonen et al. (1999) discuss that configuration which is enabled by modularisation relates to managing product quality.
Decreased cost of transportation	Cost of transportation can be affected by designing the architecture to match the chosen type of transportation if there are no other rational transportation alternatives that would not affect to the product structuring decisions as much.	Erixon (1998) discusses that standardised modules enable lower administration costs of logistics because of the lower number of assortment. Fixson (2006) discusses that architectural decisions determine the needed packing space and product protection requirements which have relation to logistic costs including

		transportation.
Enabling changes during use life cycle phase	Possibilities for re-configuring the product are affected by modularisation. Locations of product elements and type of their interfaces have strong effect in this principle.	Baldwin & Clark (2000) discuss that modularity in use allows customer to reorganise the elements of the final product to match their taste and needs. They state that reconfiguring can be made by substitutions, augmentations or exclusions.
Reduced down time and maintenance cost (by replaceable modules)	Maintenance cost can be influenced by product architecture and interface decisions by considering the accessibility and easiness of replacing modules likely to need maintenance.	Erixon (1998) discusses that modularisation can be done by focusing on the effectiveness of replacing the possible damageable areas. Umeda et al. (2000) discuss that in maintenance-oriented modularisation, the focus should be in recognising the similar life times of components and designing the product in a way that replacement of working components would be avoided as much as possible if maintenance is needed in other components.
Increased end-of-life value (by reusing modules)	Possibility to reuse some of the modules after the product configuration meets its end in the use environment, increases recycling value of the product.	Erixon (1998) discuss that module division can be made by easiness of recycling. Umeda et al. (2000) discuss that proper designing can help to maintain the profitability of the company in the later stages of product life cycle by providing for example services for reducing the amount of waste by reusing the modules.

4.3 The Brownfield Process: customisation

Is it possible to customise the BfP? In Figure 4.1, the BfP has been presented as a linear process. Customisation of the support depends on the starting point in each case. The need for customisation depends on whether or not the company has valid and sufficient design information related to some area of the modular product family development before any step of the BfP is applied. These areas are, for instance, design information related to the five elements of the Module System and thus the main results of each step of the BfP. How can the validity of the existing design information be analysed prior to the BfP? One approach that could help validation would be to retrace the design path of the information element to be validated using the process description of the BfP. In this retracing, it could be verified as to whether or not the existing design information element considers all the suggestions provided by the BfP. In this thesis, and the resulting design support, more detailed tools or suggestions for validating the existing information related to the designing of modular product families are not considered, other than the BfP step and the Module System element explanations.

An impression of the primary order of progression was presented in Figure 4.1. In the proposed order, as shown in Figure 4.1, preliminary architecture (Step 3) is defined after the generic element model (Step 2). Steps 2 and 3 are closely related to each other, so it may be beneficial to also think of these together. Target setting, based on the customer environment (Step 4), is done before the preliminary product family description (Step 5) is discussed. This early studying of customer context in detail (Step 4) facilitates the estimation of standardisation possibilities in greater detail in Step 5. Steps 4 and 5 could also go hand in hand.

In Step 5, in which preliminary possibilities for standardisation are discussed, it may be recognised that the generic element model (Step 2) and the resulting architecture (Step 3) need modifications in order to improve standardisation opportunities. Hereby using this order of progression, there might be a need to define the architecture using generic elements and their interfaces more than once because of possible iterations resulting from Step 5. In this case the order of progression would be: 1,2,3,4,5,2,3,6,7,8,9,10 (steps 2 and 3 twice). The application of this order is also a possible alternative. There could also also other candidates for orders of progressions. These examples are discussed next.

a) Order of the BfP steps: 1,4,2,3,5,6,7,8,9,10

In this alternative ‘a’, customer environment (Step 4) is studied after business environment (Step 1) and after that the order of other steps is similar to that shown in Figure 4.1. Why is this order not the suggested primary order of the BfP steps? The reason for this is an assumption of the author of this thesis, which states that product-oriented thinking is dominant in design organisations. At the beginning of a product development project, there is high motivation to begin discussions related to the concrete products, after primary goals have been set. The second assumption is that, in some cases, focusing on definition activities deep within customer-related issues at the beginning and only later on product issues might weaken the motivation of product-oriented persons in regard to the design initiative. Technically the BfP does not set any constraints that would prevent applying the process in this step order. Relations of the results of Step 4 do not cause disturbance to the overall process.

b) Order of the BfP steps: 1,2,4,5,3,6,7,8,9,10

In this altenative ‘b’, architecture, including generic elements and their interfaces (Step 3), is not defined until the preliminary product family description (Step 5) is done. Could this be a possible alternative order of progress? The preliminary architecture (Step 3) is most needed in Step 7, where the structure of the product family is defined in more detail. By using this order, the preliminary architecture, including generic elements, would be described after standardisation possibilities for the chosen generic element model are discussed. Thus the possible changes to the generic element model from Step 5 could be explained right in the architecture description but this order would not have a guiding overview about the preliminary architecture when Step 5 is done. Thus this is not considered as a primary order of progression.

c) Order of the BfP steps: 1,2,3,4,5,6,7,8,10,9

In this alternative 'c', business impact analysis (Step 10) is performed before product family documentation (Step 9). This is also a possible alternative to the order shown in Figure 4.1, if separate documentation of the content of the product family (Step 9) is not needed in order to enable business impact analysis. In documenting the product family, new information that could change the structure of the product family is not really defined but the structure of the product family, its design rationale and partitioning logic are documented. This means that the business impact analysis could be done before or also parallel to documentation, although the documentation might facilitate the business impact analysis by summarising the content of the product family. Business impact analysis could also be done parallel to the steps in which decisions related to architecture, modules or interfaces are made. Continuous analysis of business impacts of design decisions of the product family structure related to different life cycle phases requires extensive understanding about the big picture, including the disposition mechanisms. Business impact analysis in the BfP includes a model for facilitating estimation of costs and other effects but the step does not explain how these estimations in each mechanism or guiding principle are done in detail. The analysis step presumes that the case companies have the ability to analyse the most relevant effects.

Based on the above discussed possibilities for customising the progress order, it can be said that the BfP includes flexibility in relation to the possibility of applying the steps in a specific order. Besides these alternative step orders, some of the steps include alternative tool or approach suggestions. These were discussed in the descriptions of each step in more detail.

4.4 Summary of the proposed design support

Figure 4.38 presents a summary of relations between different steps and required and resulting design information elements in the BfP. This figure has been composed by using separate step summaries as presented in Chapters 4.2.1 – 4.2.10. The figure illustrates the steps of the BfP, design information elements defined in the steps and the main elements of the Module System each result is related to. External requirements have been explained in relation to steps 1, 4 and 10. This is because in these steps, this kind of external knowledge is more important than in other steps, due to the fact that, for instance, steps 1 and 4 do not have predecessors in the BfP. Also Step 10 requires abilities which results of the BfP steps do not fully contribute to. Other steps also need other information and knowledge that is not visible in Figure 4.38 but these have not been presented in this figure because of clarity. These issues have been discussed in separate descriptions of each step in Chapter 4.2. The figure does not emphasise tools or approaches of each step but it aims to highlight the needed and resulting design information.

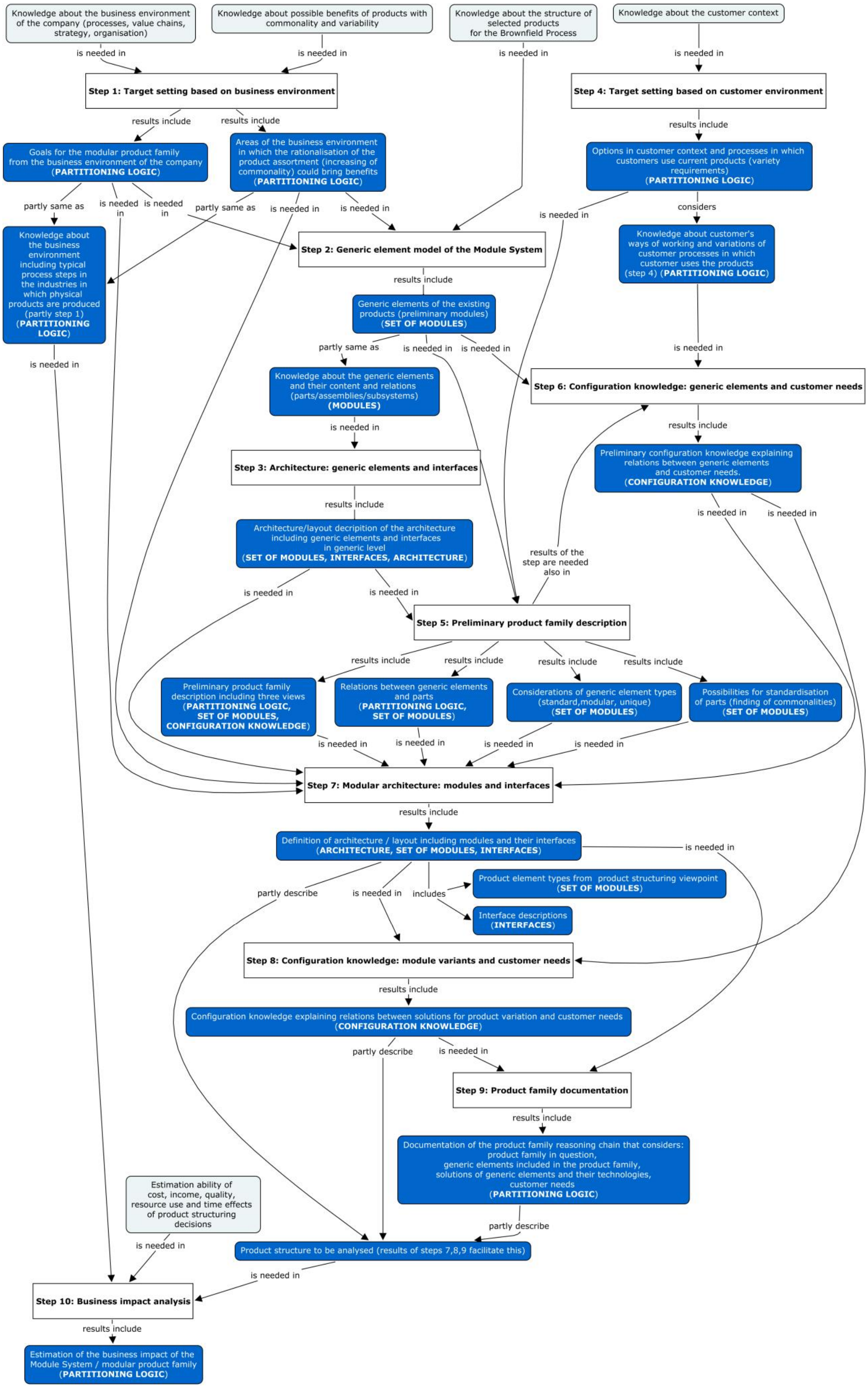


Figure 4.38. *Summary of the BfP.*

5 VALIDATION OF THE DESIGN SUPPORT – CASE STUDIES

As can be seen in the presentation of the BfP in the previous chapter (Chapter 4), validation of the BfP is founded strongly on earlier academic publications in which suggested tools and approaches were presented separately. Thus the application of, for instance, reference and impact model thinking presented in DRM contributes to academic validation, especially from a consistency viewpoint. This chapter discusses how the BfP and sections of it have been applied in industry, using two cases. These cases and their contribution to the validation of the BfP steps from an industrial viewpoint have been explained in Table 5.1.

Table 5.1. *Steps of the BfP and related cases.*

Brownfield Process	Case A	Case B
1. Target setting based on business environment	x	x
2. Generic element model of the Module System	x	x
3. Architecture: generic elements and interfaces	x	
4. Target setting based on customer environment	x	x
5. Preliminary product family description	x	
6. Configuration knowledge: generic elements and customer needs		x
7. Modular architecture: modules and interfaces	x	
8. Configuration knowledge: module variants and customer needs	x	
9. Product family documentation	x	
10. Business impact analysis	x	

In Case A, the BfP has been gone through to almost the same extent as described in the previous chapter (description of the intended support**)**. Case B focuses on the selected process steps, including target setting from business and customer perspectives, defining of generic elements and configuration knowledge aspects. These cases are discussed in the following Chapters 5.1 and 5.2.

5.1 Case **A**

Case company A manufactures sheet metal processing equipment comprised of loading equipment, portal robots, tables, carriages and conveyors. Figure 5.1 shows an example product manufactured by the company. This case was discussed in a conference article by Lehtonen et al. (2011b), an article in which the author of this thesis also participated, but in that article the content of the BfP as well as the results were presented within larger entities. That article also did not present all of the steps, as suggested in this thesis. Business impact analysis (Step 10 of the BfP) was not discussed in that paper.

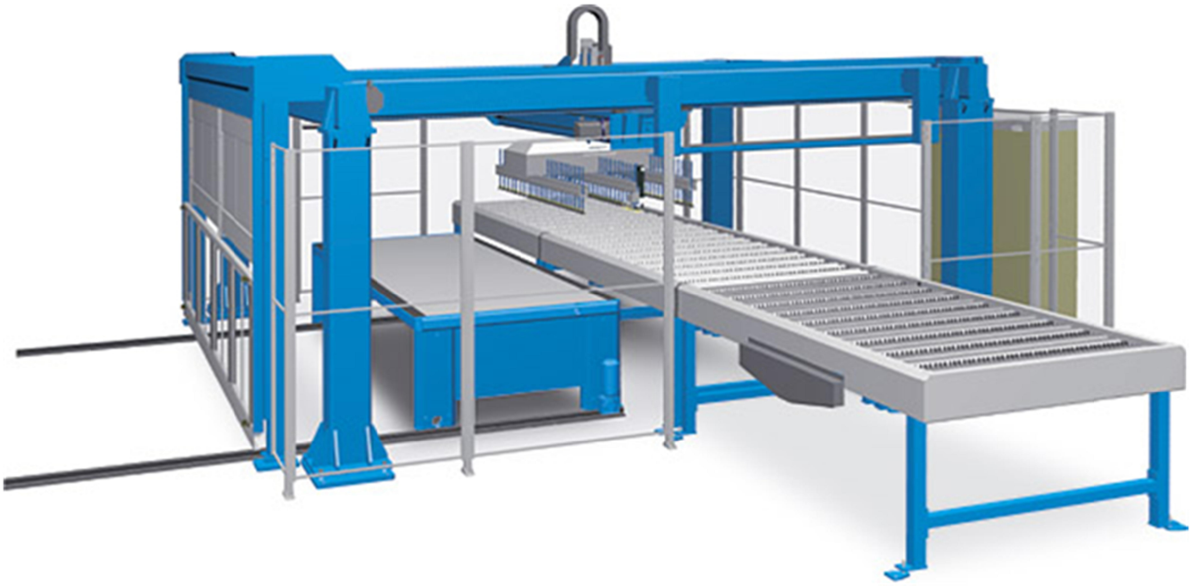


Figure 5.1. *Prima Power portal robot with a material carriage and a conveyor. Picture: Prima Power.*

The case company had an excessive amount of different product solutions which nonetheless fit the delivery process. In this case, the focus was on redesigning product assortment with fewer variants, but still able to fulfil mature customer requirements. Rationalised serial production, good methods of working and good solution principles were all familiar to the company, but the challenge was to define the product family as including technical solutions with commonality and variability. The method for rationalisation work of the existing product assortment was missing within the company, although the company had earlier experiences with modularisation. In the earlier cases, successful modularisation was not completely achieved.

5.1.1 Step 1: Target setting based on business environment

In Case A, target setting from a business viewpoint was done using the cause-effect concept map, as shown in Figure 4.9. Application of the CSL, as suggested in Chapter 4.2.1, was not done in this case because the business environment was already well defined prior to application of the BfP. Thus the process was begun by summarising why variety should be designed with commonality to technical systems. The case company answered this question using Figure 4.9, and the opinion did not change during the application of the BfP. From business viewpoint, the primary target was to reduce operating expenses (bottom left corner in Figure 4.9). To realise this target, further targets were also defined. A target group of products for this project was selected. One example product of the chosen product group of sheet metal processing equipment is shown in Figure 5.1 above.

The defining of a common architecture (product family) with common modules for the selected product assortment was considered as a sub-goal for pursuing the above-mentioned primary goal. The aim was also to enable development of modules as separate streams, as discussed also in dynamic modularisation (see Chapter 3.8.1 and publications by Riitahuhta & Andreasen (1998) and Lehtonen et al. (2003) for further details about Dymo). This product family structure should enable use of the same modules in different product variants for customers. Thus these variants would be based on the product family. In addition to this, reduction of existing variants which do not add customer value and do not support or facilitate long-term development or production were highlighted.

5.1.2 Step 2: Generic element model of the Module System

The generic element model of the Module System was defined in a brainstorming session. Organisational functions of the company such as sales, product development and mechanical, electrical and software engineering participated in this session. The starting point was the position that there existed unnecessary technical solutions for an almost identical purpose. Figure 5.2 presents some of the old material management devices of the product assortment. The objective was to describe ideas of the element groups that could be building blocks for modular product family architecture. Consequently the purpose of the step was to find a comprehensive generic suggestion for a starting point of defining actual modular product solutions.

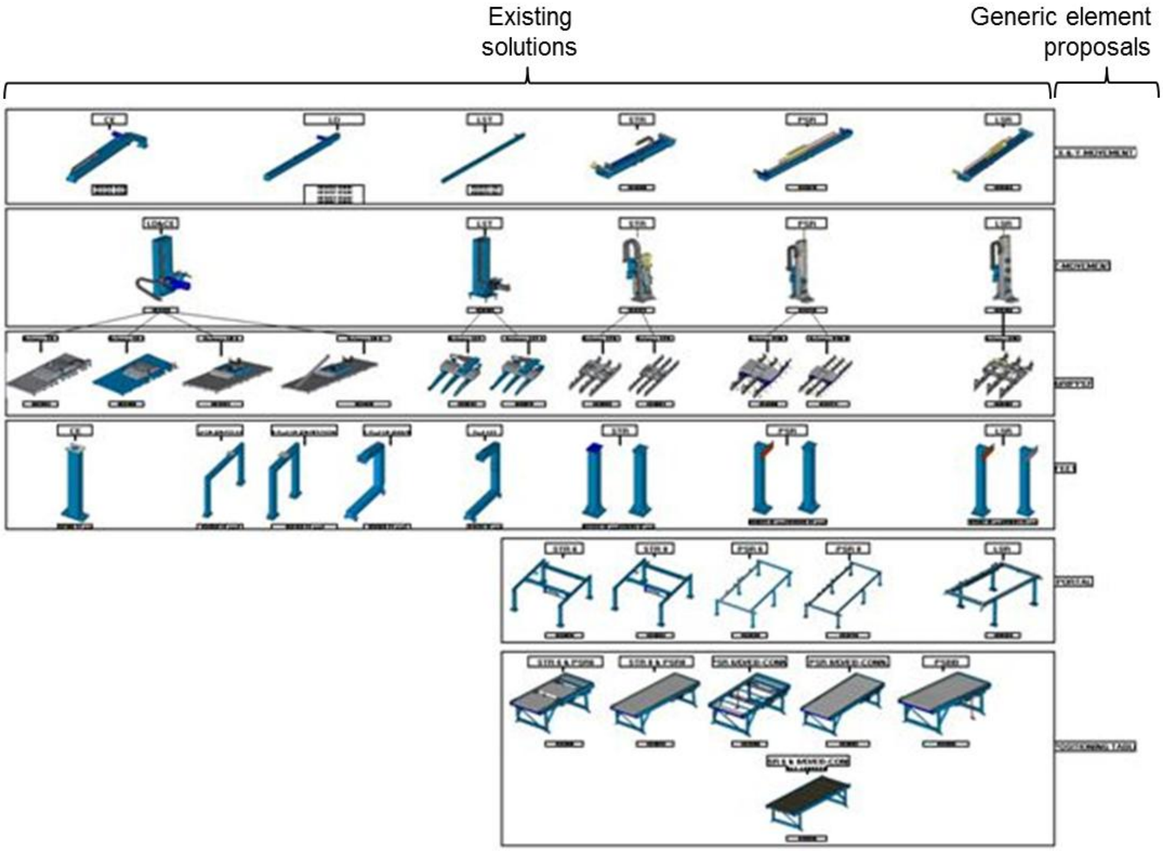


Figure 5.2. *The starting point in the company was the position that there existed several technical solutions for an almost identical purpose. Some of them are presented in this figure.*

At first, participants worked individually in the brainstorming session. A common session was organised after that. In this common session, participants formed pairs and analysed their own suggestions and tried to find a common understanding of terms and relations in their generic element model suggestions. In this case, five proposals for a generic element model were defined. These proposals were analysed in a common session by the same multi-disciplinary group of participants from the company. It was found in the analysis that the proposals for the generic element model differed considerably from each other. In the defining of the generic element model these distinctions were considered highly beneficial because the proposals now included different views of the same primary goal. A model of the generic element proposal, which included all the different elements discussed in the separate proposals, was drawn on the whiteboard. This model included 37 generic elements. When this overall model was done, it was recognized that some of the elements, such as software elements, needed further dividing. In this case, there was a separate generic element suggestion made for software elements, which included 12 different elements.

Finally, the proposal was discussed against the business targets defined in Step 1. It was found that the proposed generic element model could not completely fulfill the objectives. Because of this, there was a need to define another new suggestion for the generic element model. This was also done in a brainstorming session. A preliminary suggestion included fewer than 20 elements, but this was found to be too little. Finally, a combined model accepted by all participants was defined. This final generic element model for the designing of modular architecture included tens of elements. Some examples of the elements can be seen in Figure 5.3. The generic elements included, for example, protection, a loading device, tables, a turning/reversion device and electricity elements.

5.1.3 Step 3: Architecture: generic elements and interfaces

A preliminary architecture was described using a traditional spreadsheet program (Microsoft Excel). A layout figure was drawn of the product assortment in question. This simple two-dimensional layout figure included generic elements and how they are typically located within the products. The purpose of the figure was to clarify the same understanding of the elements for the design group.

5.1.4 Step 4: Target setting based on customer environment

Target setting based on customer environment was done using the suggestions discussed in Chapter 4.2.4. The aim was to analyse the environment and processes in which the customer operates. In this step, the main customer requirement groups were identified, and more detailed optional requirements or ways of working related to each group were defined. These requirements included, for example, options related to sheet size, material type to be handled, automation level, factory layout and production process type.

5.1.5 Step 5: Preliminary product family description

Preliminary product family description was studied using three views, including customer requirement, generic element and part/assembly view, as discussed in Chapter 4.2.5. Figure 5.3 presents a sample from this step. In this case, the actual model was drawn on the white board in a workshop held at the company. Generic elements were written on the middle of the white board at first. Then customer requirements were written on the left hand side and parts and assemblies that relate to each generic element were written on the right hand side of the generic elements as demonstrated in the figure. Only some examples of parts and assemblies were described in this step because the amount of them can multiply quickly in this view. A significant phase in this step is to define relations between these three views. Relations were drawn from customer requirements to generic elements and from generic elements to parts and assemblies. By using these three views, discussions of the preliminary formalisation of the product family were enabled. Solutions and also possible problems and questions related to the product family could be stated by referring to this model, as shown in the Figure 5.3.

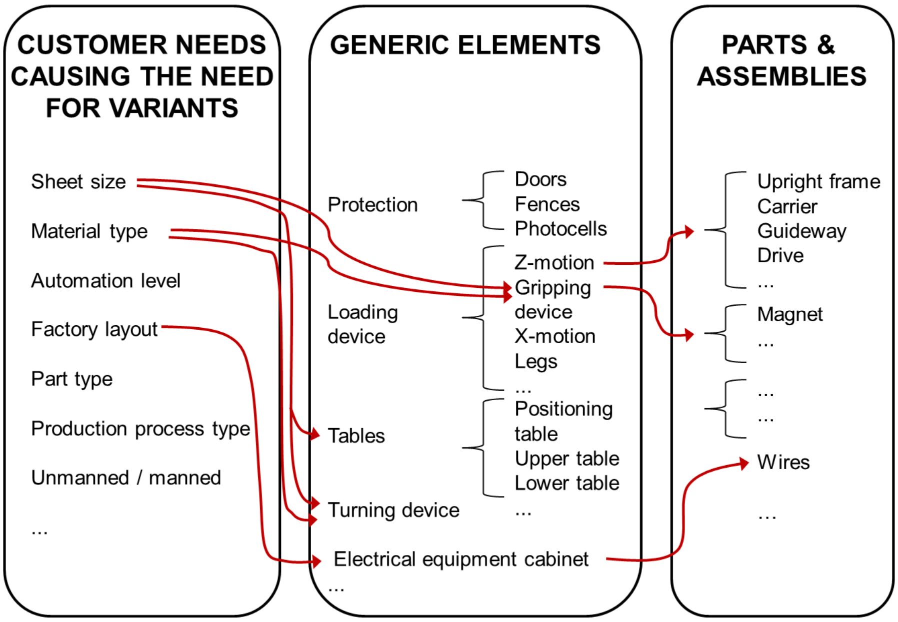


Figure 5.3. *Preliminary product family description was discussed using three views, including customer requirement, generic element and part/assembly view. This sketch follows the ideas discussed in the PFMP by Harlou (2006).*

When the above model was defined within the company, possibilities for standardising were also discussed, based on the descriptions given in Chapter 4.2.5. This step was an initiator for finding ideas for rationalised product assortment. Based on the three views presented in Figure 5.3, the design team mapped out concrete solutions which related to specific generic elements. During this step, an overall picture of the generic elements and related concrete solutions and their 3D drawings was created. This overview facilitated discussion on the necessary variants in the later steps. Thus this step was the initiator for the defining of proposals for solutions in the modular product family.

5.1.6 Step 6: Configuration knowledge: generic elements and customer needs

In this case, preliminary configuration knowledge that included the highest abstraction level of generic elements and their relations to customer needs creating the variety need was not defined using the matrix suggested in Chapter 4.2.6. These definitions were arrived at in the earlier phase, where relationships of customer requirements and generic elements (and also part and assembly view) were discussed using the PFMP-like approach. Thus a more detailed considering of configuration knowledge was done later in Step 8, specifically in Case A, after more concrete solutions to high level generic elements were defined.

5.1.7 Step 7: Modular architecture: modules and interfaces

The aim of this step was to define technical solutions for the modular product family. The goal was also to define a minimum number of modules that could fulfil the customer needs that create the need for variety. In designing the structure of the product family, the significance of solutions at a company level had a major role in decision making. The design of one common solution for all the variants of each generic element was emphasised in this step as a main goal.

This step included a brainstorming sessions in which multidisciplinary participants from, for example, organisational functions such as product design, procurement and production were participating. In these sessions, ideas regarding how to realise solutions for generic elements were considered. Researchers participated in these sessions, but the role of the company's personnel was more significant because of the detailed knowledge needed of the products in this step. During these sessions, issues that needed special consideration were also recognised. For these needs, meetings with smaller groups of participants were organised in the company. In these meetings, areas such as cost effects and economies of scale issues of solution alternatives and suitable part structures and preliminary solutions were discussed and designed on a more detailed level than in the more common sessions.

In this step, different product structuring tactics were also recognised. It was found that at least five different options for solutions regarding generic elements could be defined in this case:

- Standard parts that can be used in all deliveries
- Interchangeable modular solutions with standardised layout (no changes for dimensioning/design)
- Interchangeable modular solutions with layout alternatives (options for the layout)
- Parametric solutions including delivery-specific defining
- Solutions that require free layout designing (needs delivery-specific designing)

Basically these tactics follow the element types of product structure discussed by Juuti (2008). At first solutions related to each generic element were analysed using the above product- structuring alternatives. Product-structuring types and solution principles for each generic element were suggested. In analysing the types of solution principles, history data from the earlier product deliveries was used. In this step, a reasonable size for the product sections to be standardised was also considered. Decision making was guided by the variants with the most considerable volumes.

The new product assortment defined in this step included product elements which had been earlier considered as different elements, although they included similar features. Now the emphasis was also on designing more commonality for the products, as discussed earlier. Possibilities for using only one solution for different variants were recognised for certain elements which had earlier been considered as two or more product elements. Analysis of existing solutions and the combining of solution models facilitated this work. Alternative realisation techniques and manufacturing methods were also considered in the brainstorming sessions. In this step of the BfP, it was furthermore recognised that there is a need for one new generic element that was not considered in Step 2. The solution for this element was also defined in this step.

All of the generic elements and their solution principles could not be standardised as large elements, but there was a need to divide these generic elements into smaller elements and to define configurable structures. Thus architectural principles as suggested in Chapter 4.2.7 were considered in the case. Most of the solution principles were based on standard solutions, but the product family also includes variable sections, for which case specific solutions are required. When defining the content of some of the elements, questions related to the possible number of modules to be offered were asked. Thus in defining the structure of the product family, “cut-to-fit” (see Figure 3.25 of different modularity types) issues had to also be enabled for certain solutions.

In this case also, interfaces related to how elements are attached to each other. Generic fastening solutions were defined. In this case, separate interface documentation was not discussed during the time researchers participated in the case.

Solution principles for the generic elements, their backgrounds and possible needs for further consideration were documented during the brainstorming sessions. Background information included reasoning for a suggested solution.

5.1.8 Step 8: Configuration knowledge: module variants and customer needs

Configuration knowledge was modelled using the matrix approach, as suggested in Chapter 4.2.8. This modelling was already begun when solution principles for generic elements were brainstormed in the previous step. In that step, requirements that were directed to a specific product element were considered. Results of the ideation were summarised in the configuration matrix shown in Figure 5.4. Besides typical configuration knowledge (product elements vs. customer requirements), the configuration matrix described what kinds of solution principles and product structuring tactics are used in the realisation of generic elements. Relations between product elements and customer requirements were described using the same kind of notation, as discussed in Chapter 4.2.8. The exception was that colour coding was used to mark relations instead of numbers. The driver of this step was that, in particular, sales personnel's level of awareness is highly important for the success of a modularisation project aimed at product configuration, and that this kind of modelling of configuration knowledge could facilitate it.

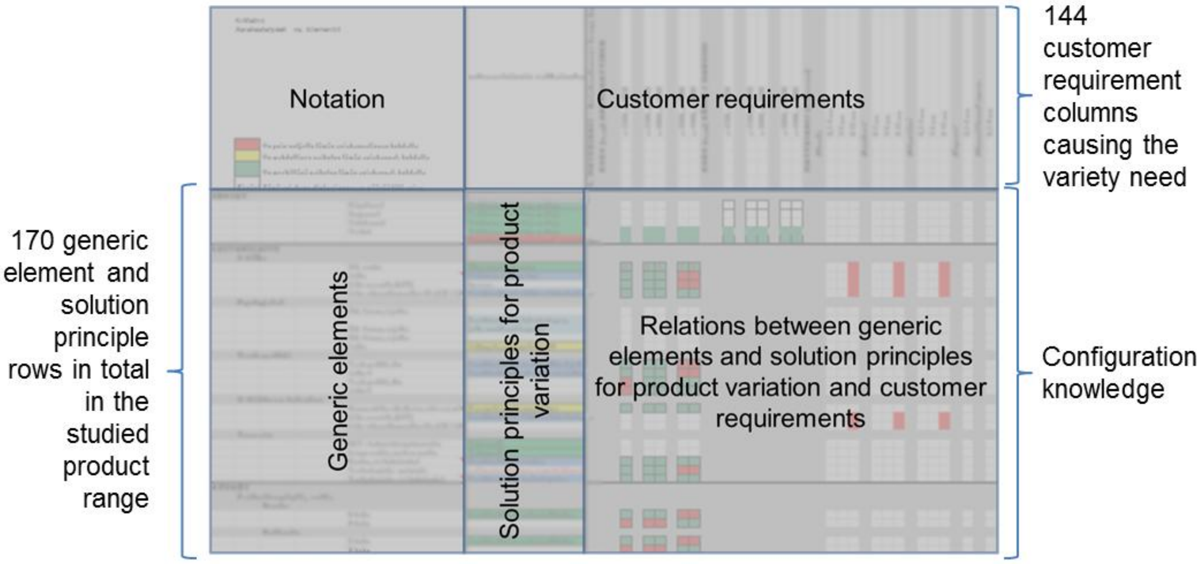


Figure 5.4. *A snapshot of the early phase of defining a configuration matrix. Because of company confidential reasons, configuration knowledge is not discussed in more detail in this thesis. Colour coding was used in this case instead of numbers, as suggested in Figure 4.24, but the principle idea was the same.*

5.1.9 Step 9: Product family documentation

For documenting the reasoning path of the developed solutions, PSBP as discussed in Chapter 4.2.9 was suggested. These kinds of drawings were made up of generic elements in order to emphasise the purpose of these documents. Figure 5.5 presents on an abstract level what these PSBPs can look like in a real situation.

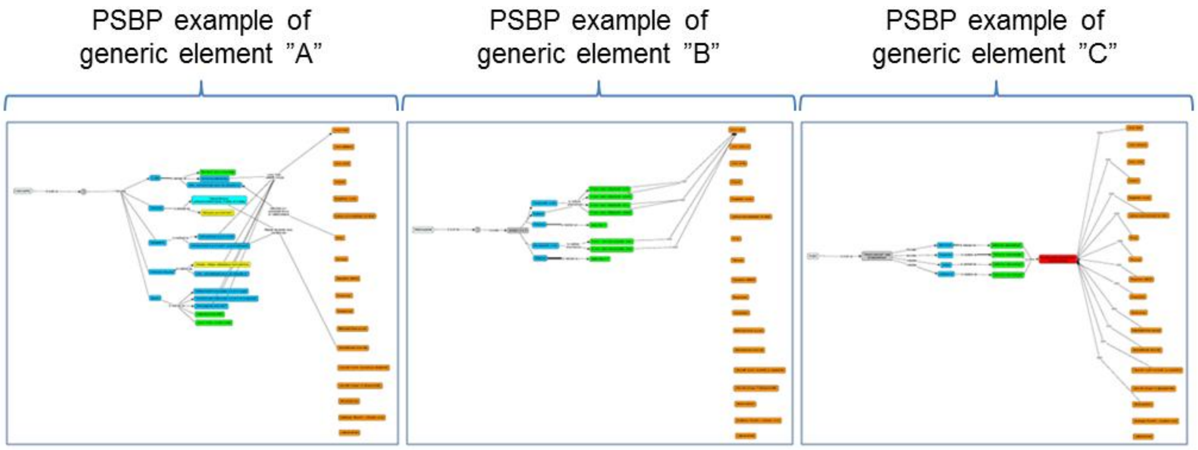


Figure 5.5. *Three examples of PSBP documenting done in Case A. See Chapter 4.2.9 for an explanation of content on the generic level. The PSBP drawings created in Case A cannot be explained in detail due to company confidential reasons, but this figure shows an example of what these PSBP documents can look like.*

In this case, the reasoning of PSBP from left to right included generic elements, first at a high abstraction level and then in more detail. After that, solution principles for product variation were described. In this case, there were five different product structuring tactics recognised, as discussed in Chapter 5.1.7. These included standard parts, interchangeable modular solutions with standardised layout, interchangeable modular solutions with layout alternatives, parametric solutions and solutions which require free layout design. On the far right-hand side, the main groups of customer requirements were described.

5.1.10 Step 10: Business Impact Analysis

In the last step of application of the BfP, the business impacts of the designed product family structure were estimated. The business impact analysis model presented in Chapter 4.2.10 was used as a supporting tool in the analysis of effects. Management personnel of the company participated in this step. Guiding principles and mechanisms, as shown in the model in Figure 4.31, were gone through and estimations in "decades" of money were made for each suggested relation to life cycle phases. During the analysis it was found out that not all of the topics could be answered or else they were not seen as being relevant in the case. Thus this step of the BfP has a clear link to the target setting done in the first step of the BfP. As a result, the number of times different decade classes of money exist was able to be seen in the analysis, as well as to which guiding principles or mechanisms and cost topics (income, cost, quality, resource use or time) they were related. Profit effects differed greatly between guiding principles and mechanisms. Because a completely new product family was not designed, savings on materials and components were moderate. Impacts were higher in terms of operational costs for the company. In certain cost topics, it was evaluated that costs could even be reduced by 40 %. Based on the analysis, the repayment time for the product family development project was also estimated. This estimation for the design project was seen as rational and thus the project was moved forward towards the concretising of the product family.

5.1.11 Conclusions of Case **A**

In Case A, the description of the desired result – the content of the modular product family – was begun immediately at the beginning of the project because there was no need for a detailed analysis of the business environment from scratch. This eventually led to a more detailed defining of customer requirements which were not product or specific delivery project related but rather were defined on a more generic and solution-free level. The formation of a generic element model based on the existing product assortment enabled direct ideation of the final modules. Effectiveness of the modularisation was based mainly on an increasing of commonality, which resulted in an increase in operative benefits and efficiency in this case. The core of the BfP gained acceptance within the company. Based on this product family design project, the case company began another rationalisation project for the existing product assortment, in which the researchers were not needed as facilitators. Thus it can be stated that by going through these method-like steps of the BfP there was facilitated a common understanding of the issues that must be considered when designing a modular product family. It also enabled the achievement of the objectives set out at the beginning of the process.

5.2 Case **B**

Case company B manufactures material-handling systems, including belt feeders and larger conveyor solutions. Figure 5.6 shows an example product that is manufactured by the company. In Case B, selected steps of the BfP were performed. The emphasis was on the front end steps of the process. The case included Step 1 (target setting based on business environment), Step 2 (generic element model of the Module System), Step 4 (target setting based on customer environment) and Step 6 (configuration knowledge: generic elements and customer needs) of the BfP.

Figure 5.6. *A crawler-mounted bridge stacker conveyor is an example product manufactured by Paakkola Conveyors (Picture: Paakkola Conveyors Ltd).*

Application of the steps of the BfP was part of a larger project in which the aim was to increase competitiveness by reducing delivery-specific work and quality problems related to designing and production. The aim was to define a technical structure for a modular product family that would enable systematic configuration against the defined needs of different customer segments. Product family structure should include commonality as much as possible from the viewpoint of designing, production, assembly and other steps of the product life cycle. The objective was also the realization of the benefits of commonality within material procurement, warehousing and production, with the help of standardisation at several levels: interfaces (fixing points), sub-assemblies, components and solution principles. Thus the focus of rationalisation was to seek out effectiveness. Compared to Case A, there was a need for more discussion of internal requirements in Case B, as opposed to discussion of customer requirements. Thus the application of the BfP was initiated with the CSL workshop.

5.2.1 Step 1: Target setting based on business environment

In Case B, target setting based on the business environment was facilitated by the CSL framework (see Chapters 3.5.3 and 4.1.1.). The aim of this workshop was to define requirements for the products from a company business environment point of view. Figure 5.7 presents an overview of the results of the CSL workshop. These are discussed in the following.

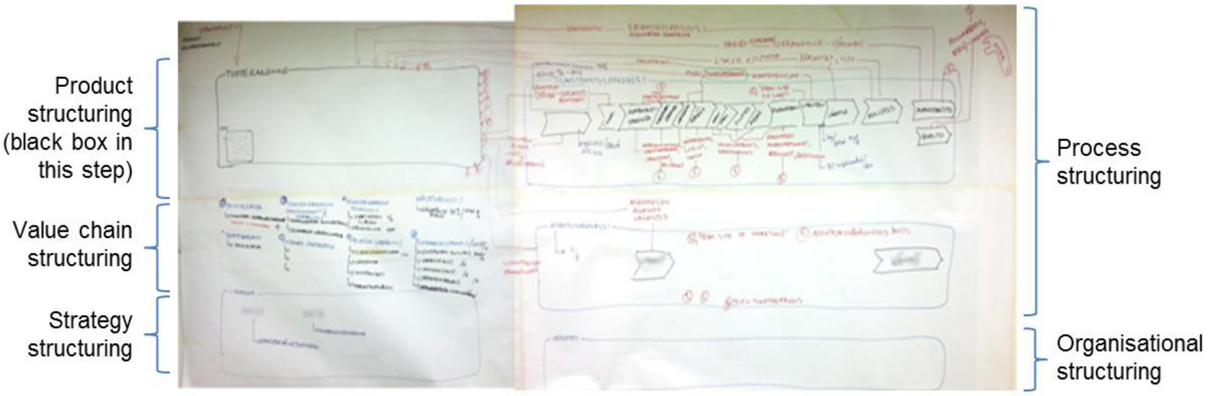


Figure 5.7. *The figure presents the CSL model drawn up in the workshop. The result of the CSL workshop described the business objectives from a product structuring viewpoint. Product structure was kept as a black box in this workshop. The main emphasis was on the process and value chain aspects. Organisational aspects (bottom right corner in figure) were included in the analysis of processes (top and middle sections in the right hand side in figure).*

In this case, the first step was to model the **sales/order-delivery process** of the company. As a starting point in this step, the earlier results of another research project done in the company were used, and with the help of which the sales-delivery process was studied. In the CSL workshop, this sales-delivery process model was gone through and it was found that some phases of the sales-delivery process were missing and some phases needed to be defined in more detail in order to define requirements from a product structuring viewpoint. Process steps of the sales-delivery process included phases from tendering and designing all the way to service and maintenance.

After completing the sales-delivery process model, relations between the product structuring view and the **process structuring view** (phases of sales-delivery process) were defined. The idea was that these relations would describe the requirements that the sales/order-delivery process phases would bring to products (product structuring). The product structuring view was considered as a "black box" in this phase because the aim was to analyse requirements from the business environment in terms of products without thinking of a specific product variant. Requirements from every sales/order-delivery process phase could be recognised.

The third task in the CSL workshop was to define other critical objectives and issues related to the product structuring. These were more common requirements that could not, for example, be linked directly to any phases of the sales-delivery process. These requirements were collected under the **value chain structuring** view. During the CSL session, more high level strategic issues were also discussed. These were defined according to the **strategy structuring** view in the CSL template (see Figure 3.17).

The primary objective in company B was to reduce delivery-specific workloads by defining a technical structure for a product family that would be systematically variable in terms of the requirements of relevant customer segments. In practice, the results for this goal would be seen in, for example, areas such as procurement of materials, warehousing and production because of standardised interfaces, subassemblies, components, attachments and solution principles. It was noted that the design organisation or the designer can be different in each delivery project. This is one reason why the product and the whole product assortment have not formed in a standardised manner, especially from a production point of view. These issues reflected, for example, the **organisational structuring** view within the CSL. Thus, there was emphasis on finding effective solutions by considering the requirements set by the company's business environment.

5.2.2 Step 2: Generic element model of the Module System

The generic element model was defined based on the existing item hierarchy documents. This step had similarities to the kind-of and part-of structures discussed by Harlou (2006) and Pulkkinen (2007). Existing solutions were considered at the lowest level of item hierarchy (part-of).

The aim was that this kind of model for generic product elements would facilitate the finding of commonality within the product elements. Increased commonality was pursued in the later steps by considering which of the generic elements could be (or are) similar and could the number of common elements be increased by changing the structure of the generic element model. Later on, when relations between generic elements and customer requirements were analysed, changes to the generic element model defined in this step were made.

5.2.3 Step 4: Target setting based on customer environment

Target setting based on customer environment was done using the same principles as in Case A. Main customer requirement topics were first identified. Case A was dealt with prior to Case B. Although the products that these two companies produce are different, the purpose of those products at a high level had similarities. Consequently, customer requirement topics for Case A, which included options that created a need for variants, could be used as a starting point for discussions of Case B. The content of these topics was then defined in more detail, including the most important alternatives from a customer environment perspective, where the products are used. The participation of sales personnel was important in this step. These needs for variety were later defined in more detail when preliminary configuration knowledge was discussed in Step 6 of the BfP.

5.2.4 Step 6: Configuration knowledge: generic elements and customer needs

Case B included the defining of preliminary configuration knowledge after the customer environment was studied. Configuration knowledge was defined using the matrix approach, as discussed in Chapter 4.2.6. Each generic element and customer need (variety need) pair was analysed, and relations were defined. Figure 5.7 presents an overview of the configuration matrix. Due to company confidential reasons, a detailed view of the matrix is not presented.

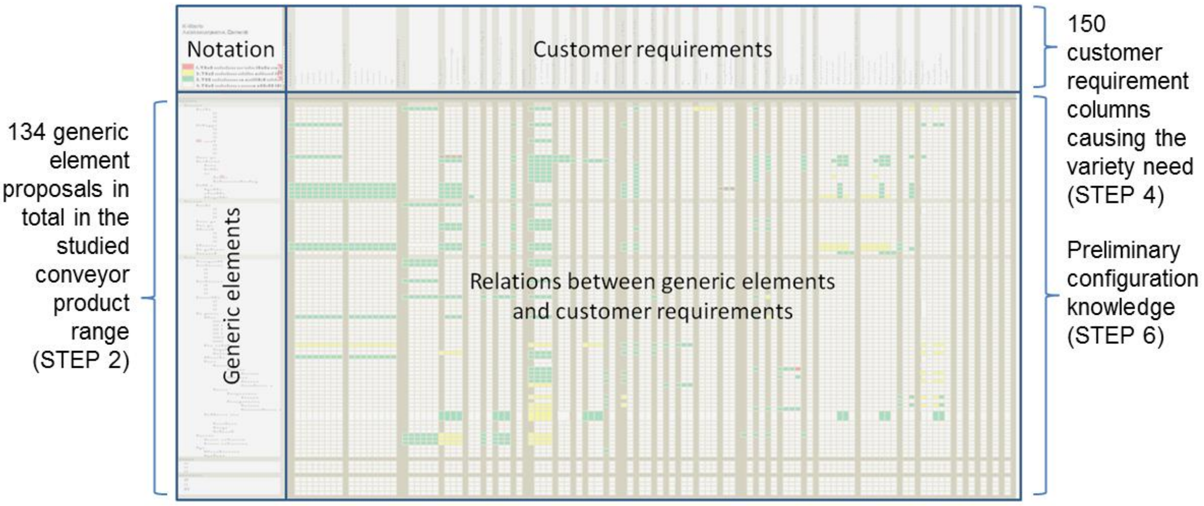


Figure 5.8. *Preliminary configuration knowledge matrix in which relations between generic elements and customer needs are analysed. The matrix included 134 rows of generic element proposals and 150 columns of customer requirements creating the need for variants.*

During the step a separate description, in which the reasoning behind each marked relation was described, was also done.

The aim here was for this kind of analysis to support actual rationalisation and definitions of modules, as the description of the BfP also suggests.

The result of the step is a base for the defining of actual product family solutions, including product structuring tactics such as standard, configurable and unique product elements. The aim was that when product solutions are defined, this matrix could be completed with knowledge of solution principles for a certain element.

Application of the later steps of the BfP was not carried out in the case because the focus of research and activities in the company moved in another direction. One of the other projects included the defining of a sequence of design activities along with the defining of milestones from a customer need perspective. These milestones included the latest points in which a specific customer need is needed in order to enable a good and proper flow of design activities. The preliminary configuration matrix supported this task because it presented which customer needs should be considered in the designing of a specific element. Of course these relations are not sufficient alone but the defining of relations between design sequence and design parameters of parts was also considered essential. This is, however, another story and is not discussed further in this thesis.

5.2.5 Conclusions of Case B

Case B included the application of Step 1 (target setting based on business environment), Step 2 (generic element model of the Module System), Step 4 (target setting based on customer environment) and Step 6 (configuration knowledge: generic elements and customer needs). Thus this case ended with final rationalisation of the existing product assortment with a result that described preliminary configuration knowledge, including generic product family elements and customer requirements creating pressure for variety. Nevertheless, Case B was valuable for this thesis because it included the application of alternative tools for the BfP, compared to Case A, where CSL was utilised in the first step and a modified K-Matrix in the sixth step.

To summarise, Case B does not validate the whole BfP as it is presented in Chapter 4, but the case focused more on the early phases of the BfP, concentrating specifically on the defining of partitioning logic, preliminary modules and preliminary configuration knowledge. Application of the BfP indicated the distance and increased understanding of getting into an operational mode of product configuration based on modular product families for the company. The outcome was that the company did not select this path but continued with projecting business in a way which the core of the BfP is not designed for.

5.3 Conclusions of validation of the design support

Figure 4.31 presented the overall flow of the BfP. If compared to this flow description, it can be stated that Case A considered the intended design support described in Chapter 4 almost to the letter, but that there were also shortages. Case A did not consider the defining of preliminary configuration knowledge, as Step 6 presents. According to Figure 4.31, this means that relational information between customer needs and product was based on the results of Step 5. The tool suggestion in Step 5 is not as systematic when compared to the intended matrix tool as presented in Step 6. Step 5 suggests the considering of standardisation options and the potential for existing parts and assemblies whereas Step 6 has a different focus on more detailed relation mapping between customer needs and product. In Case A, configuration knowledge was later defined using the matrix, after solutions for generic elements were defined. Separate interface documentation was not done in both cases. In spite of this, Case A showed that it is also possible to obtain good results compared to starting point without strict application of the suggestions given in the BfP.

According to the flow description of tasks and information presented in Figure 4.31, it can be seen clearly that Case B focused on the application of the early phases of the BfP in a real-life situation. This case supported the descriptions given in Chapter 4 of these steps because Case B included application of suggestions that were not made in Case A.

At the beginning of Chapter 2, the objectives of this research were discussed from academic, authorial and industrial perspectives. In particular, this Chapter 5 considers contributions to manufacturing industry. In this chapter, it is presented how the steps of the BfP are applicable, and how a considerable amount of training is not needed, as well as facilitating the defining of design information (results).

6 CONCLUSIONS AND VALUE OF THE RESULTS

The main contribution of this research is the Brownfield Process (BfP) for the designing of modular product families, which includes ten steps that aim to facilitate the defining of design information related to partitioning logic, set of modules, interfaces, architecture and configuration knowledge. This was presented in Chapters 4 and 5. This chapter presents conclusions about the research contributions and includes an evaluation of the results.

6.1 Research questions and research contributions

In this section, core contributions which are also answers to research questions are summarised and their theoretical and practical implications are discussed. Research questions posed by this thesis were:

RQ1. How to structure the design information needed in the designing of modular product families?

RQ2. How to create the design information needed in the rationalisation of existing product variety towards a modular product family?

The main contribution of this thesis is a definition of a framework for the designing of a modular product family based on existing product assortment. This framework includes a design process model known as **the Brownfield Process (BfP), which includes ten steps:**

- Step 1: **Target setting based on business environment**
- Step 2: **Generic element model of the Module System**
- Step 3: **Architecture: generic elements and interfaces**
- Step 4: **Target setting based on customer environment**
- Step 5: **Preliminary product family description**
- Step 6: **Configuration knowledge: generic elements and customer needs**
- Step 7: **Modular architecture: modules and interfaces**
- Step 8: **Configuration knowledge: module variants and customer needs**
- Step 9: **Product family documentation**
- Step 10: **Business impact analysis**

These steps facilitate the defining of the **design information elements of the Module System including partitioning logic, set of modules, interfaces, architecture and configuration knowledge.** This thesis suggests that the BfP answers **RQ2** and these five design information elements are also the answer to **RQ1**. This design support presented by the author contains the premise that the five elements of the Module System facilitate the design team in the designing of a modular product family by highlighting important design information issues to focus on in order to enable benefits with products with commonality and variability. Thus it can be stated that defining the Module System defines the content of the modular product family.

The content of the different steps in the BfP is not completely designed by the author but the role of the author has been in synthesising an overall process model based on several separate approaches discussed in the literature, and to modify these or to define new approaches in the areas in which the existing literature provides limited suggestions.

This kind of comprehensive process model has not been presented earlier. Various earlier design supports focus, for example, on function-oriented thinking and those design support models do not take a case-company-specific view of their products as a starting point for the modular structure, as in the BfP (generic element model). The generic element model does not prevent function-oriented structuring of the product family content if it is seen as beneficial for the company. The point has been presented in earlier publications (Lehtonen 2007) that modularisation based on function structure is often possible, but that it does not necessarily lead to good solutions from a business perspective if module division is made purely using the "one function - one module" principle. Pahl & Beitz (1996), in their book, also discussed that working with functions and function structures with adaptive and variant designs has been rare and not the most preferred action in practice (this was also discussed in Chapter 3.6.1 in this thesis).

As discussed earlier, various design supports highlight the design of new products, but in **industry** the situation is different and most designing is based on incremental development of existing products. This has been discussed by, for instance, Oja (2010). Because of this, design support, including the BfP that considers existing products of the company as a starting point in product development can be considered as useful.

As the literature review reveals, many of the existing design supports in this field focus only on one or a few elements of the Module System. In order to enable the benefits of modularisation and product configuration, the premise is that all of these elements (partitioning logic, set of modules, interfaces, architecture and configuration knowledge) need to be considered. Defining modules without standardised interfaces does not enable effective operation in the sales-delivery process and in the later life cycle phases. Thus, from an **academic** perspective the contribution is worthwhile because it synthesises different areas related to modularisation for one design support. The design support discussed in this thesis is not "yet-another-new-tool" because separate existing design supports have been used in defining this support. Hereby it can be stated that design support has its own academic background and publications can be found with more details regarding suggestions and approaches that are included in this support (the BfP).

From a practical viewpoint, the design support — the BfP — is useful because tools and also many of the suggestions given are concrete. The BfP provides a process-like approach to product development for a modular product family in which existing products have to be used in redesigning. The process suggestions have been kept at a generic level so the support could be applied in different cases. Thus it is stated that the support fulfils requirements for a method, although only one case in which the entire BfP has been tested has been presented in this thesis.

6.2 Evaluation of the results

Different perspectives on product development have been presented in this thesis. These aspects included artificial objects, production paradigms, competitiveness viewpoints, Design Science framework, product structuring tactics, generic design processes, novelty aspects of the design object and approaches, tools and methods for rationalisation of product assortment. In this chapter, relations of these perspectives to proposed design support, the BfP, are discussed.

6.2.1 The Brownfield Process and artificial objects

Chapter 3.1 included a discussion of artificial and natural objects and design. The BfP takes artificial objects into consideration. The starting point is an analysis of physical product variety and its improvement by considering requirements within a business and customer context. The BfP is a design process that considers sequence and priority of design tasks and resulting information. Thus the basic concepts discussed by Simon (1996) are included in the BfP.

6.2.2 The Brownfield Process and production paradigms

Production paradigms were discussed in Chapter 3.2. Different questions can be asked in order to facilitate discussion: How is the BfP located in the framework of different paradigms? Is the BfP suitable only for a specific production paradigm? How do production paradigms relate to the application of results of the BfP?

The BfP follows the suggestion by Juuti (2008) that product structure can be partly configurable. This is an important basic principle of the process. Thus it cannot be said that the BfP is automatically a method of pure **mass customisation,** although modularisation is often related to this paradigm. It can be stated that in applying the field of the BfP, aspects which are specific to other paradigms must be considered also. The connection between paradigms presented in the literature and the application and successful result of the BfP — a modular product family — is case specific. The starting point and development possibilities from a business and product perspective affect what kind of issues related to a specific production paradigm need to be considered.

In applying the BfP in a situation in which all of the sections cannot be designed as a standard of configurable with company-level standardised module alternatives, aspects such as the need for delivery-specific designing, testing and uncertainties and risks which are typically related to a **craft** paradigm can exist.

It is also possible that the principles of **mass production** can be seen in application of the BfP. One aim of the BfP is to standardise sections of the products where the need for customer-driven variety is not focused upon. In these sections of product structure, benefits of mass production based on economies of scale could be achieved if volume of the product sales and structure solutions of the product supports these benefits. For example, does standardisation enable repetitive operations that could enable structuring of work to more efficient sections, or does the standardisation enable more inexpensive procurement of materials and parts?

In the designing of a modular product family, inherent issues related to a **process enhancement** paradigm could come up as well. Process enhancement is considered as a paradigm between mass production and mass customisation (Victor & Boynton 1998). When moving towards mass customisation from mass production, functions of a company differ. Differences relate to almost all of the functions of the company. An essential part of process enhancement is to collect knowledge related to processes and best practices with the help of experience and repetition. Victor & Boynton consider this important in enabling the offering of more flexible products in a business environment in which one standard product is not enough. Thus it can be stated that process enhancement focuses between the producing of standard products and variable products. How can a standard element be designed in a way that it can serve as a variable element, including, for example, a couple of interchangeable and standardised modules? The BfP presented principles for this question especially from a product architecture viewpoint highlighting the role of interfaces in regard to other product elements and the role of other spatial requirements.

The **flexible production** paradigm highlights adaptation to environment, emphasising better customer responsiveness and quality compared to products of mass production, as was found in Chapter 3.2.6. From the BfP perspective, the techniques and values which this paradigm suggests are important if results include standardised elements which were one-of-a-kind elements before rationalisation. In the production of these standardised elements, suggestions made in this paradigm can be beneficial.

Solutions and approaches given in a **mass customisation** paradigm can be clearly seen in the BfP. The BfP underlines the designing of modular solutions to variety needs and highlights modelling configuration knowledge during the product family development because this kind of knowledge is useful in, for example, supporting sales in the sales-delivery process.

Consideration of solution models presented in the **co-configuration** paradigm is low in the BfP. Application of the BfP successfully results in a modular product family that responds to commonality and variety needs, analysed from a business and customer context during the designing. The BfP does not support the principle of continuously adapting products without the involvement of the customer or company, which the co-configuration paradigm stresses. Thus in applying the BfP, it is thought that if requirements that cause the need for variants change in a way that a once-designed modular product family no longer matches existing customer requirements, there is a need to consider applying the BfP design method again.

The **post-mass production paradigm** highlights considerations of product life cycle in designing, especially highlighting phases after use such as maintenance, remanufacturing, reuse and recycling issues. The BfP cannot be considered unambiguously as a design method of the post-mass production paradigm but the BfP includes consideration of life cycle phases and the recognition of requirements for product family structure out of these phases. The highlighting of certain life cycle phase is case specific in the BfP.

In addition, issues related to a **sustainable production** paradigm are case specifically considered (or not) in applying the BfP. These issues can be particularly visible in the first step (target setting based on business environment) and in the fourth step (target setting based on customer environment).

Movement from one paradigm to another was also briefly discussed in Chapter 3. In that case, the following questions can be relevant: What changes? What remains the same? How is the change implemented? Consideration of these questions in the BfP context was left outside the thesis’s scope.

6.2.3 The Brownfield Process and product competitiveness and competitive company

Chapter 3.3 presented aspects of product competitiveness and competitive company. In the BfP, these topics are covered in the first and last step. In target setting, the aim is to define possible benefits that rationalisation of the selected product assortment towards a modular product family could enable. The last step of the BfP presents a model for estimating the business impacts of the designed solution. This model highlights consideration of income, cost, quality, resource use and time aspects from a financial perspective. The result of the last step of the BfP should provide an estimation concerning the business effects of the modular product family. This result can be used for estimating the reasonability of the product family and for identifying aspects that might need further consideration. Thus it can be stated that the BfP considers competitiveness aspects.

6.2.4 The Brownfield Process and Design Science

Design Science by Hubka & Eder (1996) (see Chapter 3.4) is considered as a major publication in the field of engineering design and it is often cited in theses. Design Science includes four areas: 1) Theory of Technical Systems, 2) Theory of Design Processes, 3) Design object knowledge and 4) Design process knowledge. As summarised in Chapter 3.4, Design Science includes several kinds of classifications and categorisations related to areas of designing in particular.

The transformational model of the **Theory of Technical Systems (TTS)** relates to the BfP. Main **operand in state 1** (Od1) is existing product assortment and **operand in state 2** (Od2) is modular product family. Existing product assortment includes a group of similar kinds of products which do not include clearly defined common architecture but the group has redesign potential from, for example, a commonality perspective. Product assortment in state 2 is a modular product family which includes defined architecture considering the content of product family and its element types and interfaces. Thus the BfP could be understood as a **transformation process** in this case. **Operators** have been also considered in the BfP. **Living things** (humans) can be understood as users of the BfP (transformation process). **Technical means** could be regarded as tools and approaches that the BfP suggests. An **information system** could also be understood as an example of tools and related suggestions that the BfP includes. The aim of these tools and suggestions is to facilitate the documentation of the results of designing and its reasoning for instance. The **management & goals system** is especially relevant in the first and last steps of the BfP, in which business objectives were discussed.

BfP also considers aspects of the **Theory of Design Processes**. The product development that the BfP suggests is not new product development if originality of the operand is analysed. The Theory of Design Process also suggests a broader categorisation of the design processes to traditional, methodical and mixed processes. The BfP includes methodical characteristics, but these characteristics do not eliminate the need for trial and error (traditional processes) when, for example, defining the concrete solutions for the generic elements of the modular product family. Thus the BfP could be described as a **mixed design process**. Hubka & Eder have also described properties of methods. The BfP cannot be considered as a strictly algorithmic procedure but more as a combination of **heuristic instructions** and **relatively fuzzy guidance**.

Another kind of definition regarding method also exists. By applying **the method definition by Newell** (1983) (this was presented in Chapter 3.4.2), the BfP was characterised in the following way:

1. The BfP aims to present a specific way to proceed in the designing of a modular product family including different steps. The goal of these steps is to define needed design information from a Module System viewpoint.
2. The aim of the BfP is that by following the steps, the possibility for defining a rationalised product assortment (a modular product family) increases.
3. The BfP includes generic sub-goals and sub-plans. The name of each step tries to describe the result of the step. In addition to this, the steps contribute to suggested

elements of the Module System. The BfP does not define exactly how these sub-goals can be achieved in every different case but the process aims to offer generic suggestions that may help in the realisation of these sub-goals.

4. Use of the BfP (whether the method is used or not) can be estimated by comparing the existing results or design information related to product family development and the suggested main results of each step in the BfP. The aim in the BfP description has been to define the results of each step, including what these results look like and to which other steps results of a specific step relate.

Based on the above statements, the BfP can be considered as “more than a tool”. Hubka & Eder additionally present **a checklist for describing properties of a method** (see Chapter 3.4.2). In the **background and origin** of the BfP, a clear connection to earlier research in standardisation, modularisation, product platforms, product families and product configuration can be seen. These are discussed in more detail in the next section. The **purpose** of the BfP is to help a company in the rationalisation of existing product assortment that does not include a well-defined common structure and which does not facilitate reaching the benefits of design reuse. The BfP is **intended to be used in a company** in which product assortment has increased over time because of, for example, projecting business and a common structure or architecture for similar kinds of products that would enable benefits of reuse has not been designed but the company wants to invest in order to achieve these benefits. Consequently the BfP aims to **facilitate the redesigning of a physical product assortment**. **Different knowledge and background data** is needed in the steps of the BfP in order to reach the aimed-at results. These issues were discussed in the presentation of each step.

Each step of the BfP has a different objective. Thus **design object knowledge** issues such as the different sources of branch knowledge discussed by Hubka & Eder are also relevant in the BfP because a different kind of knowledge is needed in the steps, as discussed in an earlier paragraph.

Design process knowledge highlights selection of method, description of relations of design process, the describing and defining of tasks, needed information, management, evaluating of product and development of designer’s work. The literature review of this thesis focused on modularisation, product platforms, product families and product configuration methods. Typical design methods were recognised and their contribution to the research problem of the thesis was discussed (see Chapter 3.8.10). The conclusion was that **existing design methods** cannot solve the research problem. The BfP was suggested as a solution to the research problem. The content of the method was described. The BfP includes ten steps. The steps are introduced in Chapter 4.2. **Relations of the BfP** were described in the design information flow model in Figure 4.25. In addition to this, information that facilitates application of **each step of the BfP** was suggested in the process description. The BfP does not highlight **management** tasks in designing but the contribution of the thesis focuses more on suggesting essential design information elements in the designing of modular product families and steps and tools and approaches that could help to define these elements. **Evaluating of the product (family)** is considered in the last step of the BfP. The BfP considers also the **development of designer’s work** because there can exist a possibility for reducing, for example, the amount of one-of-a-kind designing in order-delivery processes if product family architecture can be designed in a way that the number of standardised product elements increases if compared to the starting point. In that case, design resources can be used in different activities such as in platform development or even in new product development if considered relevant.

Based on these statements, it can be concluded that the BfP considers issues presented in Design Science and it can be stated that Design Science facilitates research work in this field of design methods by offering a reminder of important issues and helping in defining and categorising the contribution of the research.

6.2.5 The Brownfield Process and product structuring approaches

The result of the research is based on the product structuring approaches presented in Chapter 3.5. When referring to Figure 3.11 of a **total view on product structuring** by Andreasen et al. (1996), it can be stated that the BfP focuses especially on the product assortment view (focus of the whole BfP) and product life view (the aim of the target setting in the BfP is to consider the whole life cycle). The functional view of structures is considered limited in the BfP. These are more detailed aspects and are not highlighted in this method.

Relative **to the Domain theory** (see Chapter 3.5.1), the focus of the BfP could be linked especially to organ domain. The definition of organ in this case is close to the definition of function carriers. In the description of the BfP, it was stated that generic elements can be sub-systems, function carriers, assemblies or single parts. Thus a definition of organ is narrower than a definition of a generic element. In activity domain, activity can be singular or a sequence of activities or transformations. Activity domain highlights phases that the product will meet during its life cycle. Thus it can be stated that this domain is especially visible in target setting (steps 1 and 4) in the BfP.

Chapter 3.5.2 on product life included a discussion of **dispositions**. In the last step of the BfP, the business impact analysis model was presented (Figure 4.24). This model can also be considered as a disposition model. Mechanisms shown in the model are based on literature findings regarding empirical observation of the effects of modularisation and related strategies (see Table 4.1 for more details). In the BfP, it is explained that important life cycle phases and related requirements should be defined case specifically. Thus this kind of model can also help in setting targets for product development and it is stated that this kind of model, shown in the last step, can facilitate in the defining of business impacts of the modular product family. Similar, but not the exact same kinds of models, have also been presented in the context of other research, such as that by Fixson (2006).

The company strategic landscape (CSL) model (Chapter 3.5.3) is suggested as a tool for the first step of the BfP, in which the aim is to draw a map of the business environment focusing on the requirements from a product-structuring perspective. Based on Case B, as presented in Chapter 5.2, it can also be considered relevant and suitable for purposes of the BfP.

In Chapter 3.5.4 of **product variety, commonality and design reuse**, the commonality-variety trade-off was discussed. Benefits and possibilities related to standardisation and modularisation have been found. Systematic design re-use is suggested as a means for facilitating the enabling of these benefits. Thus these aspects worked as an important motive for this research.

Standardisation is an important area of the BfP. The aim in the BfP is to define product sections which could be standardised and sections which involve the need for variety. Standardisation is also an important aspect in the designing of module interfaces.

Several definitions have been presented for **modularisation**. The BfP is aimed at **M-modularity** (Lehtonen 2007), including the enabling of product configuration and product variants. How would **life cycle modularity** (Lehtonen 2007) be seen within the context of the BfP? With a life cycle modular product, the main focus is on a definition of interfaces from the perspective of some important life cycle phase such as assembly. Lehtonen (2007) states that consideration of module variants to a specific location is not needed in this kind of modularisation. This means that, for example, step 4 of the BfP, in which variety needs are defined, would be unnecessary in life-cycle modularisation. In the life-cycle modularity case, suggestions made by Umeda et al. (2000; 2008) could be useful for studying the product-structuring decisions from different viewpoints. Other kinds of modularity types are also presented (see Figure 3.25 by Pine (1993)). Modularity types can be important from both an architecture and interface viewpoint because they also include different interface principles. The defining of these types is always case specific and thus in the description of the BfP unambiguous guidance regarding what kind of interfaces a modular product family always includes cannot be given.

How does the BfP consider **integral/modular** and **open/closed architecture** types? There can be different starting points in applying the BfP. When architecture includes clearly separated standard and variable sections, standard sections can be designed more integrally. By using integral structures, it is possible to, for example, decrease weight and parts. It can be speculated that architectures of product individuals without common product family architecture can be scattered. These kinds of architectures can include interfaces, but they are model-specific standards and not company-specific standards (categorisation presented by Fujimoto (2007)). Some of these kinds of individual products can include more integral solutions than others, although product individuals would include nearly similar solutions. Consideration of open or closed architecture is a strategic business issue because it especially affects things like whether or not the product can be upgraded with technical solutions produced by competitors. These aspects should also be discussed in setting objectives for product development projects and in defining interfaces for the modular product family. Thus it should be taken into consideration whether or not spatial reservations or interface options for the future are needed or if current solutions are in a position of dominant design, meaning that consideration of current solutions (and to which variety needs they relate to) is sufficient. Thus defining of open or closed architecture is a strategic issue.

In several cases, **function structure** as a starting point of modularisation is not automatically relevant (Lehtonen 2007). Thus methods such as the BfP, in which reasoning for the modular structuring is analysed from the business and customer context and existing product assortment is taken into account, can be regarded as a welcome approach.

In the BfP, **partitioning logic, set of modules, interfaces, architecture and configuration knowledge** are suggested as main design information elements that guide the formation of a modular product family. Existing research supports the fact that these kinds of elements can be defined and knowledge related to these elements is important in modular product family development aiming at product configuration, but as discussed earlier, methods that would clearly highlight these five elements have not been presented earlier.

Definitions of **product platform** and **product family** are relevant for the BfP. Relative to the result of the BfP when applied successfully, standardised product elements that are reused in different variants of the product family can be regarded as a product platform.

The main elements of **product configuration** are activities of configuring, product structures for configuring and IT support for configuring (Pulkkinen 2007). Consideration of these three elements can be partly seen in the BfP. The BfP aims to define the configuration model of the product family. This is considered by suggesting an approach for defining configuration knowledge (configuration rules) that would facilitate the defining of product configurations. If content of the product family is changed, the configuration model needs to be updated. Harlou (2006) and Pulkkinen (2007) discuss part-of and kind-of structures. In the BfP, this is seen in generic elements and their solutions. Hierarchy of generic elements presents part-of structure. Kind-of structure relates to specific solutions, or what types of generic elements are in question and with what kind of solution principles those can be realised. Part-of structure is defined mainly in the second step of the BfP. Kind-of structure is defined mainly in the seventh step. When considering IT support for configuring, the BfP suggests defining of configuration knowledge using matrix tools. Detailed aspects related to the realisation of an actual configurator are not suggested in the BfP. There can be standard, configurable, partly configurable and one-of-a-kind product structures (Juuti 2008). These product structure types are considered when solutions for generic elements are defined. Thus it can be said that these types present kind-of structure in the BfP.

6.2.6 The Brownfield Process and generic design processes

Multiple problems related to generic design processes are recognised by other researchers (see Chapter 3.6). These problems are discussed below from the BfP perspective, although the BfP is not a generic design process.

"Design processes focus on original design although the most of design tasks are based on existing designs." (Gericke & Blessing 2011; 2012)

The BfP does not focus on the designing of a new product family from scratch. The BfP is meant for rationalisation of existing product variety towards a modular product family. In other words, it can be said that the BfP is based on existing products, on which the generic element model is defined. This model is the starting point for the defining of modular architecture.

"Design processes focus on market pull situations. Technology push is not appropriately considered." (Gericke & Blessing 2011; 2012)

Ulrich & Eppinger (2008) discuss the fact that with technology-push products companies try to find a market for products with new technology. In a modularisation context, technology push can be one driver for modularisation, as discussed in, for example, Erixon (1998). The BfP does not directly suggest in the early steps that modularisation should consider technology-push, but the target setting done in the first step of the process using the CSL approach may reveal that this should be considered in defining the modular architecture in a specific case. Thus the purpose of the target setting steps (Steps 1 and 4 of the BfP) is to clarify module drivers in each case.

"Design processes focus usually either on design or on management. Both viewpoints have to be considered in order to provide an improved support." (Gericke & Blessing 2011; 2012)

The BfP considers both design and management issues. A management view is needed, especially in setting the objectives and analysing the business impacts of the result of designing. The design viewpoint, in addition to other views and functions related to the product life cycle, is essential when the modular architecture and product configuration knowledge is defined. Detailed management suggestions in each step are not provided in the BfP but the method aims to provide generic suggestions for each step.

“Design processes do not explain how to perform design activities, only what to do.” (Gericke & Blessing 2011; 2012)

The BfP explains on a generic level what to do in each step. Besides this, there are suggestions given that aim to facilitate the defining of the needed design information in each step. Thus the design support has method-like properties and is aimed at a group of similar basic problems.

“Design processes do not explain the rationale of the proposed processes.” (Gericke & Blessing 2011; 2012)

The rationale of the BfP is based on the earlier work done in the product structuring field. Five elements of the Module System aim at facilitating the designing of a modular product family by reminding designers about what needs to be considered in designing in order to enable the benefits of modularisation, product platforms, product families and product configuration in the sales-delivery process and in later life cycle phases. These elements have been discussed separately in several earlier publications and thus can be considered as relevant elements in the designing of a modular product family, although this kind of approach, in which all the suggested elements are combined under the roof of one design process, has not been presented earlier.

“Design processes do not represent the creative process sufficiently.” (Gericke & Blessing 2011; 2012)

The BfP does not consider the creative process in great detail. This is one potential weakness of the support. Earlier in this thesis, design process categorisation (traditional, methodical, mixed) by Hubka & Eder was presented and discussed. The BfP does not completely remove the need for trial and error, which is a typical property of traditional design processes. The integration of creative tools and methods such as TRIZ with BfP has not been considered widely in this thesis, although for instance the double team ideation method was applied in the case where the generic element model was defined.

“Design processes do not support transdisciplinary team-work sufficiently.” (Gericke & Blessing 2011; 2012)

In each step of the BfP, suggestions related to needed knowledge were explained. Workshop-like meetings were suggested in several steps as a starting point for defining the desired result of the step and to enable common understanding of design goals and ways to proceed. Detailed team-work guidance was not included in the method. Thus this is another weakness of the design support.

“Design processes do not consider goal iteration sufficiently.” (Gericke & Blessing 2011; 2012)

It can be understood from Figure 4.1 that business and customer target setting (and other steps also) are performed once in the BfP design project. If goals change during the designing either from a customer or wider business perspective, iterations to the steps after the target setting are needed. Thus there are no limitations to iterative use of the process, although the process has been described in Figure 4.1 as an idealised linear process.

"Design processes assume that design goals are clear and a valid requirement list can be made at the beginning of the process." (Lehtonen et al. 2011a)

The requirement list, as defined in Pahl & Beitz (1996), is not done in the BfP. The requirements for the product family are considered using different kinds of approaches. As discussed in the previous problem, iterations of design goals are possible, but it must be borne in mind that iteration or updates related to results of earlier steps may cause a need for revision of later steps. Thus changes in partitioning logic, for example, can lead to changes in the architecture, including modules and their interfaces.

"Design processes consider poorly the sequence of the emergence of new knowledge and design processes do not address the learning aspects during the designing." (Lehtonen et al. 2011a)

This sequence relates to what is known about the product in each step (Lehtonen et al. 2011a). Thus the statement considers idealisation of the design processes. Lehtonen et al. (2011a) state that several of the design processes are presented as a linear process, although not all is known in the early steps of designing and it is believed that the amount of knowledge increases as the designing proceeds. This might cause a need for iteration. Although the BfP is presented as a linear process in Figure 4.1, it is explained that there can be iterations between steps. The BfP suggests different steps that can facilitate the designing of important information from a modular product family perspective. The BfP includes a built-in "double loop" in some of its steps, meaning that at first a specific issue is defined preliminarily and later on in more detail when more is known about the design objective. Thus from this perspective, it can be stated that the BfP considers iteration.

"Design processes discard the role of existing knowledge, ability and skill level of the actual design team." (Lehtonen et al. 2011a)

Existing knowledge related to design solutions, products, their parts and also to the business and customer environment is necessary in applying the BfP. This is highlighted within several steps of the process. Designing of a modular product family requires expertise related to product development and an understanding of the business and customer environment. A method such as the BfP is not sufficient alone.

How does the BfP relate to different design process categories? Categories of design process models are presented (see Table 3.9. in Chapter 3.6 by Gericke & Blessing (2011; 2012)). Of these categories, the BfP could be described as a **process model** and a **design method**. The BfP cannot be considered purely as a management method because it does not consider traditional project management techniques such as project planning with schedules, although tasks, results and their relations have been suggested. By using the definitions by Gericke & Blessing, it is difficult to estimate whether the BfP is a stage-based (every stage covers a considerable period of time) or activity-based model (design activities relate to the more detailed problem-solving process of individuals, thus activity is a finer division than stage). According to these definitions, the BfP includes elements of both models (**combined model**) because the steps present a higher level of stages, but activities are also suggested in each step. Is the BfP more of a solution-oriented model than a problem-oriented model? Based on definitions by Gericke & Blessing, the BfP cannot be considered as a problem-oriented model (problem→abstraction→concept→product), because the BfP does not include abstraction of the requirement list. Thus the result of this thesis is closer to the description of a **solution-oriented model** (problem→concept→product). Table 3.9 also includes a comparison of design- and project-focused models. The BfP is a combination of both: the **design-focused model** because it focuses on product family design activities and the **project-focused model** because it suggests also tasks and their order of execution. The defining of the BfP as an **abstract** or **procedural** model is challenging because it includes both elements. It is difficult to present all of the steps with clear instructions that would automatically lead to good results because then the suitability of the BfP to more than one case would be speculatively compromised.

In some theses (e.g. in Erixon (1998)), the relationship of the suggested method and generic design process stages have been discussed in order to highlight the role and location of the results at a higher level and in a commonly known framework within the research community. Is it possible to link generic design process stages with the BfP? Different suggestions exist for generic design process stages, as was discussed in Chapter 3.6. Howard et al. (2008) present there there are stages: 1) establishing a need, 2) analysis of task, 3) conceptual design, 4) embodiment design, 5) detailed design and 6) implementation. Of these generic stages presented by Howard et al. (2008), BfP Step 1 (target setting based on business environment) and Step 4 (target setting based on customer environment) could contribute to the **establishing of need** and an **analysis of task**. Step 2 (Generic element model of the Module System), Step 3 (Architecture: generic elements and interfaces), Step 5 (Preliminary product family description), Step 6 (Configuration knowledge: generic elements and customer needs) and Step 7 (Modular architecture: modules and interfaces) could relate to **conceptual design**. In this case, the concept describes the structure of the modular product family. **Embodiment design** could relate to Step 2 (Generic element model of the Module System) and to Step 7 (Modular architecture: modules and interfaces). This is because generic elements (Step 2) are based on existing designs and in Step 7 the solutions for a modular product family are discussed. **Detailed design** could relate to the defining of configuration knowledge using actual solutions and customer needs (Step 8) and product family documentation (Step 9). Step 10 (Business impact analysis) can be done parallel to several steps, as discussed in Chapter 4.3. Thus it it is difficult to relate to a specific stage. Step 8 (Configuration knowledge: module variants and customer needs) could also be related to **implementation**, because configuration knowledge supports the sales-delivery process.

6.2.7 The Brownfield Process, incremental designing and new product development

The BfP is directed more at **incremental design** than new product development because incremental design and static concepts are more common in the industry, according to Pugh (1996) and Oja (2010).

How can it be observed that the BfP focuses more on incremental design than new product development? The starting point in application of the BfP is the existing products of the company. Consideration of these products is important, especially in the second step of the BfP, in which the aim is to define the generic element model that would describe the part-of structure (Harlou 2006; Pulkkinen 2007) of the modular product family. Thus this kind of model describes the content of the product assortment on a generic level. Basic requirements for the products are not considered in steps 1 and 4 of the BfP. In new product development, the defining of these kinds of requirements is more important. In the BfP, the assumption is that these kinds of requirements are already well defined and understood.

Hubka & Eder (1988; 1996) categorise technical systems according to their novelty in regard to re-used, adapted, re-designed and original technical systems. How do these categories relate to the BfP? Suitable input for the BfP can be defined as an **adapted technical system** because this definition highlights a possible modification need without changing the core concept. Output of the BfP can be defined as a **redesigned technical system** because when compared to the starting point in designing, the aim is not to change everything in the products but to only do changes to areas of products in which changes are necessary. The successful result of applying the BfP includes also properties of **re-used technical systems** because the aim is to define architecture that includes categorisation of its elements, for example, into standard, configurable (with module alternatives) and unique sections. This kind of product structuring would facilitate the re-use of standard structures. The BfP is not directed at the defining of an **original technical system** as its main result. The presumption is that existing products that are used as an input in the BfP have related customer needs against which they have been designed. This means that technical systems (products) for the most important requirements exist in the company, but do not adequately enable benefits with re-use. For this reason other definitions besides original technical system are more reasonable when describing the result of the BfP when the method is applied successfully.

6.2.8 The Brownfield Process and existing design supports for the rationalisation of product variety

Chapter 3.8 presented design support suggestions for rationalisation of product assortment. Presented approaches, tools and methods focused mainly on modularisation, product platforms, product families, configuration knowledge and business impacts in applying these product development strategies.

The contribution of **Dynamic Modularisation** to BfP is in providing principles of product platforms. It also emphasised the role of common architecture in providing customer variants. This is also one premise in the BfP.

Lehtonen (2007) presents a **process for new modular product architecture**. How does the BfP relate to this process? The BfP does not follow this process accurately, but it includes similar thinking. The CSL is a common tool both in the process by Lehtonen and in the BfP for clarifying objectives. The second step of the process for new modular product architecture includes the defining of target architecture for the module system. It can be stated that this result has a considerable effect on the result of the designing. In the process by Lehtonen, target architecture is defined prior to definition of modules. The BfP can be considered more as a “bottom-up” approach because existing product solutions are considered in the formation of a common architecture. The BfP also provides more suggestions and guidance for the defining of modular architecture. Because the BfP relies on existing products, these products already have architecture, thus the modular architecture is not defined from scratch. The process for new modular product architecture does not separate modules and their interfaces, which is emphasised in the BfP. This is another big difference between these approaches. In addition, the process by Lehtonen does not consider suggestions for the defining of configuration knowledge, which is important in the defining of product variants in the ordering/sales-delivery process. Although testing tasks presented in the process for new modular product architecture (Lehtonen 2007) are not described similarly in the BfP, it can be speculated as to whether or not these testing aspects are built in to the BfP. In the BfP, interface aspects between generic elements and actual solution principles were highlighted. Thus the ability to integrate the modules relies on a definition of interfaces. Modules have to fit the modular architecture and their interfaces have to be standardised (at least product family specific) in order to enable interchangeability. Efficient defining of product variants cannot be done without this. Checking the module system's ability to produce the required variants (a task in the process by Lehtonen) could be understood to be included in, for example, the application of product family master-plan thinking in Step 5 (preliminary product family description), in which the relation between customer requirements and generic elements and parts are considered. Moreover, the defining of configuration knowledge considers abilities to produce the required variants because the relation between customer requirements and product elements are also discussed in those steps (6 and 8) of the BfP. Validation of module system against business goals (Lehtonen 2007) is considered in the last step of the BfP. Thus it can be stated that the BfP and the method presented by Lehtonen (2007) are not completely different.

Do **engineering design processes,** such as the process presented by Pahl & Beitz (1996) and the BfP, have anything in common? Some of these aspects of generic design processes were already discussed in Chapter 6.2.6. **Systematic design process** (Pahl & Beitz 1996) can be applied in the designing of single modules, but not in the designing of a new modular architecture (Lehtonen 2007). Based on this argument, one could argue that if modular architecture has been defined well, the steps of the systematic design process could be utilised when single modules are designed. The BfP does not consider formation of the modular architecture from scratch. The BfP presumes that basic requirements that are not related to variety or commonality needs are explicit and that concrete solutions and products also exist. This is why the **requirement list,** as suggested by Pahl & Beitz, is not defined in the BfP. The setting of requirements is done from the perspective of the business and customer environment in the early steps. The objective is that Step 1 of the BfP would clarify what kind of commonality and variety needs can be recognised from the business environment of each case. The aim of analysing the customer environment (Step 4 of the BfP) focuses more on variety perspectives. The BfP does not suggest **abstraction** of the design problem in defining the structure of the modular product family because selected products for the BfP initiative do not solve new problems of the customer but rather the aim of the suggested method is to rationalise the existing product assortment from a business perspective, not just from a customer perspective. Thus the main problem that the products provided by the company are aimed at is known. Can a **function-oriented approach** be linked with the BfP? It can be speculated that every module or generic element defined using the BfP could also be defined from a function perspective, describing the most important function to which it corresponds. One possible problem is that defining a single function per module can be difficult. Functions of each module would be affected by business and customer needs related to each generic element in the BfP. Thus function-oriented designing does not necessarily bring any extra value to modularisation, as Lehtonen (2007) also states. Consequently, architectural solutions are defined based on generic elements and not sub-functions of function structure in the BfP. Interfaces are highlighted in modularisation. Systematic design process presents material, energy and information/signal flows for defining relations between functions. According to several publications, (Pimmler & Eppinger (1994), Stone et al. (1994), Avak (2006), Fixson (2006), Sosa et al. (2007), Rahmani & Thomson (2009), Helmer et al. (2010)), these can also be considered as in interface description. Spatial

(Pimmler & Eppinger (1994), Erixon (1998), Fixson (2006), Sosa et al. (2007), Rahmani & Thomson (2009), Helmer et al. (2010)) and structural (Sosa et al. (2007)) considerations are also suggested. How are the defining and evaluation of **alternative concepts** and **solution principles** considered in the BfP? The BfP does not highlight any specific **ideation method** in designing, as also discussed in Chapter 6.2.6. In Case A (Chapter 5.1), solutions were defined using brainstorming-like sessions in which each generic element and its alternative solutions were discussed. Thus the BfP does not prevent the use of ideation methods, as discussed, for example, in the publication by Pahl & Beitz (1996). Because of the nature of the BfP method (see e.g. Chapter 6.2.4), it is difficult to present exact steps or one specific ideation method that would provide sufficiently good solutions in different cases. The main focus of this research is not the comparison of different ideation methods and their application in the designing of modular architecture, modules and other elements of product structures. Issues of **embodiment design,** as presented in Pahl & Beitz (1996), are not discussed in the BfP. Those suggestions are important for designers of mechanical objects, but the aim of the BfP method is not to discuss mechanical engineering at an extremely detailed level. **Detailing** aspects could be recognised with the BfP. The BfP suggests a documentation approach called the Product Structuring Blue Print (see Chapter 4.2.9) for presenting the design rationale from a customer perspective. The defining of configuration knowledge using matrices can also be considered as documentation in the BfP.

The approach for **architecture definition by Ulrich** is function oriented and thus has not been considered within the framework of the BfP. Interface suggestions by Ulrich are compatible with the BfP.

The **MFD method by Erixon** (1998) and the BfP have the same high-level goal — to develop modular products by utilising existing non-modular products. The MFD includes good principles for the reasoning of modularisation by suggesting a set of **module drivers** to be analysed in each development case. Steps 1 and 4 of the BfP contribute to the defining of reasoning for modularity; these steps basically aim to define “module drivers”. The MFD method includes function orientation in the defining of modular architecture; thus this property leads to a rejection of the method as inappropriate in the paradigm of our research and application environment.

As with the BfP, **the Integrated PKT approach discussed by, for example, Krause & Eilmus (2011),** focuses also on the rationalisation of an existing product assortment (reduction of company internal variety) and on enabling the offering of external variety (product variants for customers). The integrated PKT approach highlights function structure in the defining of modular product architecture; thus this method also represents function-oriented approaches. In the method by Krause et al., product family development issues are considered at different levels (see e.g. the Variety Allocation Model in Figure 3.71). The suggestion regarding architecture descriptions in the BfP has similarities to the **Module Interface Graph** presented in the integrated PKT approach. Both approaches suggest the defining of product element types, but by using different categories. The integrated PKT approach discusses standard, variant and optional product elements, whereas in the BfP standard, configurable (with alternative modules) and unique elements are suggested. Optional product elements are not highlighted in the BfP, but these kinds of elements are related to configurable and unique elements. In principle, the Module Interface Graph could be an alternative tool for describing the designed architecture and its elements and interfaces. The problem is that this tool does not explain the type of variable section of the product as clearly as the BfP does (whether or not a specific variable section is based on predesigned modules or completely unique solutions).

PFMP and Generic Organ Diagram by Harlou (2006) have a clear contribution to be made to the BfP. PFMP highlights customer, engineering and part view. This kind of mapping is used in the defining of preliminary product family structure in the BfP. PFMP-like thinking is also visible in the defining of solutions for generic elements. The product family and its generic elements were presented in these steps using a hierarchic structure, which PFMP also suggests. Both models suggest presenting the building blocks of architecture and interfaces between the blocks. Architecture description as it occurs in the BfP has also taken its influence from Generic Organ Diagram. The most important difference between Generic Organ Diagram and the architecture description presented in the BfP is that Generic Organ Diagram does not separate standard, configurable (with module alternatives) or one-of-a-kind elements, which are essential from a product configuration point of view, as Juuti (2008) also suggests. Generic Organ Diagram considers organs, varieties of organs and optional organs; thus Generic Organ Diagram also has similarities with the Module Interface Graph presented in the Integrated PKT Approach.

The BfP highlights integration between the modular product family and product configuration viewpoints. Thus the method deals with configuration knowledge. **Bongulielmi (2003)** presents a clear and easy-to-understand approach for the defining of **configuration knowledge and compatibilities among product elements using matrices**. These are suggested also in the BfP. The main difference is that Bongulielmi uses a notation of ‘x’ to demarcate a relation between two elements and ‘empty’ if there is no relation between two elements. The BfP suggests a more detailed notation because in the early phase of designing all relations might not yet be known with the degree of precision suggested by Bongulielmi. The **configuration matrix by Nummela (2006)** could be an alternative tool for presenting configuration knowledge. The main difference between the approaches by Bongulielmi and Nummela is that Nummela presents one type of matrix for configuration and the defining of compatibilities. This matrix includes sales perspective, variant modules and base machine, including basic modules. Thus this approach also considers the standard and variable sections of the product family. In the BfP language, saleable options would refer to a definition from the customer process that causes needs for variety. Variant modules could be understood as generic elements which are either configurable (with module alternatives) or one-of-a-kind solutions. A base machine would be defined using generic elements with standard solution principles describing a product platform. **UML or other class diagram approaches (Felfernig et al. 2002)** can also be used in describing configuration knowledge, but in the BfP they are not suggested because the application of those approaches is more difficult than with matrices because of specific notations. Despite this issue, the BfP does not prevent the use of class diagrams for describing configuration knowledge.

The approach by **Fixson (2006)** to **product architecture costing** is a clear example of how product architecture elements and business impacts can be considered. At a high level, the same kind of principle is included in the last step of BfP. From a product perspective, Fixson highlights the function-component allocation scheme and interface characteristics in his model. In the BfP, the product viewpoint includes five elements, including partitioning logic, set of modules, interfaces, architecture and configuration knowledge. Fixson presents mechanisms that have some effect on measures, such as cost and time. In the business impact model of BfP, this same idea was used. Different mechanisms, or in other words guiding principles or dispositions (Olesen 1992) or module drivers (Erixon 1998), were recognised. In the BfP’s model, measures included income, cost, quality, resource use and time effects. BfP’s business impact model also included a suggestion of a life cycle view to which these dispositions were linked.

The literature review regarding **other approaches and methods for the designing of modular product families** revealed that the number of other approaches and methods published in this research field is very large. Some of the typical and often-cited approaches were discussed in Chapter 3.8.10. Based on the literature review, categorisation into **scale-based methods**, **mathematical models and optimisation methods and algorithms**, **matrix-based methods**, **function structure-based methods** and **index-based methods** was suggested (see the end of Chapter 3.8.10). The main issue is that all of the five design information elements (partitioning logic, set of modules, interfaces, architecture and configuration knowledge) that the BfP suggests focusing on are seldom considered in the studied approaches and methods. For example, the approaches studied in Chapter 3.8.10 do not solve the research problem because product configuration aspects are seldom considered in those. It was discovered, however, that these existing methods include very well defined and relevant aspects related to, for instance, interface management, but as discussed, a complete method that includes analysis of reasoning and objectives for the modular product family, consideration of architecture, module and interface in the defining of modular product architecture, or in other words, product family architecture, and consideration of product configuration knowledge is missing for the rationalisation of existing product variety. Thus the result of this thesis — the Brownfield Process — can now be considered as a relevant addition to existing approaches and methods.

6.2.9 The Brownfield Process and the selected research approach

The main elements of the DRM research method (Blessing & Chakrabarti 2009) were applied in this thesis. This method provided a clear structure for the thesis, highlighting the presentation of the **current** and **desired state** by considering **influencing factors** and **impacts** related to modular product family development. From a research problem viewpoint, product structuring was considered as the most important topic and it enabled recognition of the main **influencing factors** and **impacts**.

The structure of the work follows the DRM suggestion, including the main stages of Research Clarification, Descriptive Study I, Prescriptive Study and Descriptive Study II. This kind of high-level structure, as presented in this thesis, is also visible in other research approaches (defining of problem, literature review, contribution and evaluation of the results) as discussed later in this section.

Research Clarification created a focus for the more extensive literature review done in **Descriptive Study I.** In Chapters 1-3, which contribute mainly to Research Clarification and Descriptive Study I, it was discovered that **success** in rationalisation of product variety depends on beliefs and objectives. In this context, viewpoints such as production paradigms, which present different goals in different situations, were discussed. By taking these paradigms into account, it can be stated that the contribution of this thesis, the BfP, also considers aspects of other paradigms, in addition to mass customisation in which modularisation, product platform and product family aspects are typically discussed. Relating to success, competitiveness issues are essential. Publications related to this topic were useful in clarifying typical **impacts** which should be considered in product development and in evaluating its results. Because many publications already exist in this field, **initial impact**

models could be also found from the literature. For example, Figure 3.20 by Juuti (2008) was considered valid for this thesis. The **influence factor** and **impact models** were made from the main aspects discussed in the product structuring section of the thesis. In defining these models, the following technique was used: Literature was studied first. After that, the main aspects were summarised into text format. Then separate factors and impact elements were recognised and defined separately by using a concept map tool. Finally, separate factors and impacts were connected to a model of each viewpoint in which relations were described, based on the literature. The creation of these kinds of models is laborious and the models can easily become quite large. For this reason, separate models were created of each main section of the product structuring chapter. Although several models were created, these models helped in recognising the main characteristics that should be considered in successful rationalisation of product variety. Thus these characteristics helped in defining actual **design support**, the BfP. These models supported the defining of **key factors** later on. In this research, five elements of the Module System, including partitioning logic, set of modules, interfaces, architecture and configuration knowledge were considered as key factors. In the design support (the BfP), these five design information elements (key factors) related to steps in which the design information related to each was defined. The **Business Impact Analysis** (BIA) model, which is presented in the last step of BfP, also takes these key factors into consideration. In this model, the aim has been to present a cause-and-effect chain based on the literature and empirical findings. It can be seen that several impact models are presented in this thesis. The BIA model presents product-structuring issues on a more detailed level, considering not only standardisation and modularisation aspects.

Prescriptive Study includes **documentation** and **description of the intended support**, the BfP. Prescriptive Study is considered mainly in Chapter 4 in which the author suggested how influence factors relate to key factors. The BfP aims at considering key factors in a systemic way, as the DRM also suggests. The DRM also suggested checklists for defining characteristics of design support. These checklists helped in holistic documentation of the BfP. The DRM presents the issue that key factors are the most useful factors to address in order to improve the existing situation and key factors have the strongest influence on success. Consequently, the steps of the BfP aimed at suggesting approaches and guidance that help in defining the desired design information related to each key factor. Chapter 4 also considered viewpoints of introducing the design support. In the description of the BfP, customisation, use and maintenance issues were also discussed.

In the DRM, the difference between **intended** and **actual support** is also discussed. In terms of this thesis, this can be thought of in the way that intended support description is presented in Chapter 4. Actual support description could be understood as a support that has been tested in industrial cases (Chapter 5). Thus **intended** and **actual impact models** could also be separated. Figure 4.31 could be defined as an intended impact model. An actual impact model could be understood as a model that includes only relevant factors and impacts in each case. Because the literature supports the existence of suggested mechanisms and drivers presented in the BIA model, separation of intended and actual impact models was not done in descriptions of the BfP. **Results of the support evaluation** were presented mainly in Chapters 5 and 6 (this chapter), but Chapter 4 also included evaluation aspects, such as discussions concerned with modifying the design support. A separate **evaluation plan** was not described in this thesis. Case validation and sections of this discussion chapter considering the main aspects presented in the thesis are aimed at facilitating evaluation and suggest a structure for evaluation.

DRM suggests that **Descriptive Study II** aims at understanding the **impact of the suggested design support** and considers actual introduction and maintenance of the support in the use environment. This suggestion also means that Chapter 4 is related to this phase of the research method because the BIA model presented in Step 10 of the BfP included suggested key factors and how they related to mechanisms and drivers for modular product family development and, further on, how these mechanisms and drivers related to stages of the product life cycle. Reference and impact models also helped in evaluating the research results. It is possible to refer to issues that are considered in the suggested design support and to issues which are not. For example, the role of IT support is considered important in modularisation and product configuration, but suggesting these kinds of solutions in detail was left outside boundaries of this thesis. Consequently, it can be stated that the application of DRM can be seen in this thesis, mostly because of the reference and impact models that are presented. It can be seen, however, that these kinds of models were not made in respect to every topic presented in the thesis. Thus this research **cannot be considered as "strict" DRM research**. Summaries of each topic in the literature review aimed, however, at highlighting the importance of each viewpoint for the research problem. The main results of the **application evaluation** are discussed in the following. The DRM suggests that the design support has to be applied without knowing the outcome in order to see the real effect of the support. The situation regarding application was similar in our case. Results were not known when the application of the BfP was begun. The DRM also suggests consideration of suitability of the design support for the task for which it is intended. Application of the BfP in an industry setting proved that the main aspects of the BfP were usable, although all of the suggestions given in Chapter 4 (intended support description) were not made during the time when researchers participated in cases. The introduction of the BfP in the use environment was successful in Case A because the company considered that it had learnt essential steps of the method and continued with the second case without need for facilitating by the researchers. Thus user understanding about the main aspects of the BfP was achieved in this case. DRM also emphasises consideration of how the key factors were addressed. Does the BfP address key factors (partitioning logic, set of modules, interfaces, architecture and configuration knowledge) in the way they are supposed to be addressed? This is a somewhat difficult question to be answered because a single correct way does not exist. Descriptive Study II additionally emphasises consideration of **success evaluation**. To summarise, it can be stated that, based on Case A, the BfP did not at least prevent the achievement of results which were considered better than the starting point in the company. Thus also from the DRM research method perspective the impact of the BfP can be considered **useful**. Case B, in which the BfP was not applied completely, presented challenges of moving into this kind of paradigm to the company and thus the original objectives were not achieved.

Although the principles of DRM were applied in this thesis, this research can also be discussed from the viewpoint of other research approaches. These are discussed in the following paragraphs.

Olkkonen (1994) discusses the fact that concepts of science consider logic for progress differently. He points out that **design sciences** can be applied to research topics in which there is no possibility for complete positivism because possibilities for observation are limited. According to Olkkonen, design sciences have typically followed a kind of logic for progress:

1. defining of the concept of designing in question (objectives for designing),
2. deriving of quality criteria for designing (literature, common sense),

3. evaluation of other designs
4. development of forms of good design
5. comparison of developed solution to practice (indicating beneficial characteristics)

This kind of progress can also be recognised in this thesis. The first step is performed mostly in Chapters 1-3. The second and the third step are considered in Chapter 3. The fourth step is considered in Chapter 4, in which the BfP is suggested. The fifth step is performed in Chapter 5, which considers case study.

Olkkonen (1994) also discusses progress of **empirical studies** and presents a positivistic formula for progress:

Observations, intuition → inspiration → hypotheses → experiment or observation plan → results → falsification or verification → trueness of hypotheses according to the results

As Olkkonen states, this kind of formula is challenging in anti-positivistic research approaches such as hermeneutics. This was also discussed in the second chapter of this thesis, in which the lack of hypotheses in this research was justified, based on suggestions by Eskola & Suoranta (2001). They noted the possibility for learning and also for surprise in research approaches in which hypotheses are not suggested. Thus this kind of research on the empirical studies approach was not considered in this thesis.

Olkkonen (1994) explains that in the **hermeneutic research** approach, the aim is to understand the internal relations of studied phenomena. He also explains that in this research approach, new knowledge is created from empirical material (experience-based) by **induction**. Olkkonen states that inductive reasoning aims to derive a generic proposition out of specific and known facts. Hermeneutical approaches are suitable in research areas in which material for extensive statistical processing is not available and the research problem is difficult to be structured, according to Olkkonen. He presents the following path for this kind of research:

Definition of phenomena deeply and accurately (development stages, reasoning, issues related to decision making, environment) → explanations to described phenomena based on understanding of researcher and other persons → support and opposites from earlier theories → model that answers the research questions → evaluation of trueness of results and possibilities for generalising the results

Definitions of hermeneutic research are applicable in this thesis, in addition to design sciences. The research of the author includes inductive elements at a high level, although statistical and quantitative considerations are missing, which are typically related also to induction and to positivistic research, according to Olkkonen.

Olkkonen (1994) also discusses **theoretical research** in which **deduction** is applied. He explains that deduction aims to derive more specific statements out of generic truths. This kind of research approach was not considered in this thesis because it relates mainly to positivism. In this thesis, research questions were not defined and answered using mathematical models.

What can be said about **repeatability** of the research? According to Olkkonen (1994), positivism highlights facts and measurable results, whereas hermeneutical approaches cannot guarantee the independence of the researcher because hermeneutical research considers research material based on his/her understanding. Olkkonen considers this kind of material as soft and states that it is not certain that other researchers understand the same material in the same way. This is one weakness of the research presented in this thesis.

What can be said about **verifiability** of the results? Level of truth or reliability of results obtained using the hermeneutical research approach is considered lower than in results obtained using a positivistic approach, according to Olkkonen (1994). He also states that it is sufficient if hermeneutical research suggests only new hypotheses or research directions as its main results. Based on these arguments, the results of this thesis can be considered as acceptable. Suggestions for research directions are discussed in Chapter 7.

What can be said about **reliability** of the results? In defining, Olkkonen (1994) states that reliability of research describes the probability of obtaining the same results when replicating the research. He adds that this kind of consideration relates especially to statistical and positivistic research approaches for representing the level of truth of results. Olkkonen explains that in hermeneutical approaches evaluating the reliability of the results is more difficult: quantitative definition cannot be defined. The reliability of the results in this thesis relates also to the repeatability of the research that was discussed in earlier paragraphs. Thus it is not certain that the same results will be obtained if another researcher replicates the research. This is also a potential weakness of this research, although tools such as those presented in DRM aim to facilitate the achieving of reliability.

What can be said about **validity** of the results? According to Olkkonen (1994), it is difficult to evaluate validity of the results quantitatively, thus evaluation often involves qualitative consideration and judgement. In this research, validity of the research is based on earlier research and publications and also on an industrial case, upon which the main aspects of the suggested result of this thesis, the BfP, were tested successfully. Issues presented in this Chapter 6 can also be considered as an attempt to summarise, especially, the **scientific validity** of the BfP, whereas Chapter 5 aims to consider the **industrial validity** of the BfP. It is also important to acknowledge that several suggestions given in the BfP have been validated separately in other publications, but those cases are not presented in detail in this thesis.

7 DISCUSSION AND FUTURE RESEARCH

Two research questions were formulated in this thesis, as discussed in Chapters 2 and 6:

RQ1. How to structure the design information needed in the designing of modular product families?

RQ2. How to create the design information needed in the rationalisation of existing product variety towards a modular product family?

The answer to RQ1 suggests that division into five design information elements facilitates the designing of modular product families. These elements include:

- **Partitioning logic** defines viewpoints that affect to product structuring decisions from business and customer perspective.
- **A set of modules** includes building blocks of product variants of a product family.
- **Interfaces** (standardised) enable efficient defining of product variants in the order/sales-delivery process.
- **Architecture** describes how modules and their interfaces are related to each other. Architecture also considers layout issues such as space reservations.
- **Configuration knowledge** describes relations between product family elements and customer needs that cause the need for variety. Configuration knowledge can also present compatibilities of product elements or customer needs.

The answer to RQ2 suggests that the method known as the Brownfield Process (BfP) facilitates the creation of design information needed in the rationalisation of existing product variety towards a modular product family. The steps that make up the BfP are listed below. The content of the BfP was presented in Chapter 4 in detail.

- **Step 1: Target setting based on business environment**
- **Step 2: Generic element model of the Module System**
- **Step 3: Architecture: generic elements and interfaces**
- **Step 4: Target setting based on customer environment**
- **Step 5: Preliminary product family description**
- **Step 6: Configuration knowledge: generic elements and customer needs**
- **Step 7: Modular architecture: modules and interfaces**
- **Step 8: Configuration knowledge: module variants and customer needs**
- **Step 9: Product family documentation**
- **Step 10: Business impact analysis**

The extent of this thesis is limited. By studying the above research questions, issues and areas that were not considered in this thesis were also acknowledged. This section includes considerations for future research. Suggested needs for future research include areas related to the steps that make up the BfP, grounded theory type collection of data from the field and thus analysis of further requirements for the method and increasing of industry validity of the method. These are discussed in the next sub-sections.

7.1 Current state analysis

The role of design information that is needed and created in modular product family development was highlighted in this thesis. Some experiences were also discussed by

Pakkanen et al. (2013), but there is a lack of comprehensive and practical research results in this field that would increase understanding regarding at which level these issues of partitioning logic, set of modules, interfaces, architecture and configuration knowledge are defined in different companies and in real life situations in which all these design information elements exist. Thus this requires a **more extensive application of the BfP in different cases** or the **surveying of existing successful modularisation and product configuration cases** in which these aspects of design information can be recognised. If research by survey were to be made, the **defining of different maturity stages or options related to design information elements of the Module System** could be beneficial in order to facilitate discussion and the recognition of current state in different cases. The **surveying of existing processes for defining of each element of the Module System** could also be useful in the analysis of development need and for further suggestions related to this research area.

7.2 Product scope of the BfP project

Which products are reasonable for rationalisation by using the BfP and how are these products selected? Detailed answers or concrete tools to these questions were not given in the description of the BfP; thus this could also be a possible area for further research. Currently the BfP presumes that the scope for the BfP can be selected based on expertise without any specific analysis tools. A **scoping tool** could consider, for example, possibilities for increasing the commonality in product variety and in marketing aspects, such as sales volume, for each existing variant. This kind of tool could be beneficial in choosing existing products for the BfP development initiative.

7.3 Definition of generic elements

Another aspect that needs more research relates to how generic elements are originated. Referring to the current description of the BfP, a definition of these elements is strongly based on the common acceptance between different organisations and areas of responsibilities within the company. For a supporting definition of generic elements, more detailed guidelines could be beneficial in order to enable a good starting point for modularisation.

7.4 Documentation of interfaces

The main contribution of this thesis, the BfP, was applied to an industrial case company (Case A) that produces products for sheet metal processing. Typical properties of the case included the fact that the company had several similar kinds of technical solutions for sections of products and the company understood the importance of rationalising the existing product assortment. The challenge was how to start this kind of rationalising work because clear steps were missing. In this case, the main steps of the BfP facilitated the designing of a modular product family. All of the suggestions presented in the description of the BfP were not applied fully in the case. As an example, detailed interface specifications or interface control documents were not done or created in the presented case during the timeframe in which researchers participated. Case B did not include this. Although the importance of these has been highlighted in publications, extensive real life experiences regarding the usefulness of those items are missing. Thus in modularisation projects of the future, **interface documentation** aspects should be emphasised more.

7.5 Business impacts

In the last step of the BfP, the business impact model was presented. This model described relations between the elements of the Module System (partitioning logic, set of modules, interfaces, architecture and configuration knowledge), mechanisms (or in other words module drivers/dispositions/reasoning for modularisation) and life cycle phases. In order to facilitate the application of this model for evaluating business effects in real life cases, the model could be developed further towards **a business impact evaluation tool**. The structure of the tool could be, for example, question based. Questions should explain the link between different elements of the model and enable the user to select the most appropriate “decade” of money as an answer to a specific question.

Another issue would be to consider the relation between the business impact model presented in the last step of the BfP and the CSL approach presented in the first step. The question is, could the business impact model be used in a target setting based on the business environment? The CSL approach is a more open approach for the defining of objectives than is the business impact model, and thus applying the CSL relies more on answers and discussions of participants in the CSL workshop. The business impact model suggests more directly different mechanisms that might be relevant in different modular product family development cases. Thus when applying the CSL, there is a stronger need for a facilitator if the possible benefits, mechanisms or requirements that are typically considered relevant in modularisation are not mentioned or recognised in the workshop.

7.6 Information technology systems

IT-system perspective is an important part of knowledge management. In this thesis, the relation of the BfP suggestions to the IT-system perspective was not discussed in detail. Thus, one possible area for future research could be to study more comprehensively **how design information related to partitioning logic, set of modules, interfaces, architecture and configuration knowledge is managed in IT systems, what problems exist and how these problems could be removed**. In this kind of research, a flow diagram, as shown in Figure 4.25, as well as summary figures for each step of the BfP could be a starting point in analysing relations between different design information elements. **Iterations related to an increased ability to define requirements for the modular product family** when the designing proceeds are also interesting. Thus this would also be an important viewpoint if relations of the BfP to IT systems were to be studied, since the storage of design information and the development of design rationale can be beneficial in further product development.

7.7 Other fundamental considerations from a science viewpoint

The BfP can be considered to be a relatively heuristic and fuzzy method if definitions by Hubka & Eder (1996) are used. The contribution of this thesis, the BfP, is a result of research that has hermeneutical properties, as discussed earlier. Based on the literature review, several approaches that have more positivistic characteristics also exist in this field. These are mainly based on algorithms, mathematical models and indices. According to studied publications, these kinds of approaches have also been applied successfully in industrial cases. Although these approaches were not considered in this research paradigm, it could also be interesting **to study how a consideration of these kinds of positivistic approaches would relate to the BfP** if the designing could be described completely using quantitative definitions and variables.

8 FINAL SUMMARY

At a high level, this thesis considered product development and the product development process of artificial “man-made” objects. For this context, several relevant topics are related. As the literature revealed, a number of different production environments exist. These environments consider different beliefs and model solutions which describe each paradigm. For this reason, it is important to understand the environment in which products are developed. This study shows that in real life situations one cannot necessarily operate based on suggestions given by one paradigm, but that there might be a need to consider model solutions from different paradigms in order to stay competitive. A number of factors on which to focus are presented in publications considering competitiveness. These factors, such as cost, quality, time and resource use, are generic views whose consideration can be difficult during product development because all of the dispositions or relation chains for life cycle phases cannot necessarily be easily defined. However, being aware of these factors is nonetheless considered valuable in the rationalisation of existing product assortment towards a modular product family, including, for example, the defining of objectives for this task and the evaluating of the success of this kind of project.

Generic models, suggestions and categorisations are presented to support backgrounds in the rationalisation of product assortment. Design Science is one collection of this kind of knowledge. The role of this is also important in this work because this publication helps in the defining of fundamental properties regarding what kind of designing is considered in the research and to which categories the contribution belongs, as well as the use of by which characteristics it can be described. There exist also a number of generic design processes, some of which also consider aspects of modular product family development, but with varying quality. Thus these cannot be considered as a solution for the research problem of defining essential design information elements and process steps in modular product family development.

In media such as newspapers, innovations are often mentioned in order to increase competitiveness and to enable new business. The role of innovations cannot be denied in the rationalisation of existing product assortment, but the designing of a completely new product is rare in the manufacturing industry because of several risks. Thus consideration of existing products and business environments is still a relevant topic for academia when discussing product development.

This thesis considered product development focusing on design reuse, product variety, standardisation, modularisation, product platforms, product families and product configuration. Consideration of these topics comprises an effective tactic for enabling product variants to be provided for customers without forgetting the benefits of design reuse and commonality (similarities) in an industrial environment.

Based on the literature review, several influencing factors and impacts related to the above-mentioned product structuring tactics and strategies could be defined. The thesis suggested that influence factors and impacts support the defining of five key factors: partitioning logic, set of modules, interfaces, architecture and configuration knowledge. These key factors were considered as essential design information elements that form the Module System and facilitate the defining of a modular product family.

The literature review revealed that the number of approaches and methods suggested for these product development strategies is high, but design methods of modular product families in which every key factor, suggested in this thesis, is considered are rare, although the importance of these factors has often been discussed and empirical findings also support this. Thus this kind of contribution could be considered as a significant synthesis of existing research.

The design method known as the Brownfield Process (BfP) is suggested for supporting these key factors. The BfP includes ten steps which aim to facilitate the defining of design information related to partitioning logic, set of modules, interfaces, architecture and configuration knowledge. In each step, suggestions and example tools are presented.

The steps that make up the BfP have been tested in an industrial context. Findings reveal that this method facilitated the rationalisation of existing product assortment in a case in which the BfP was applied comprehensively. This rationalisation included the reduction of overlapping designs and the redesigning of solutions to fit several product instances. Thus it is stated that the BfP is suitable for industrial companies whose product assortment has increased to an unnecessarily high degree, but whose products include the potential for redesigning and increasing commonality, where the offering of a single standard product is not possible from a business perspective. There must also be a will to invest in product development because redesign requires effort. Suggestions for future research were focused on the further application of the BfP.

To conclude this chapter, and this thesis, research objectives were described from academy, author and industry perspectives at the beginning of this thesis in Chapter 2. From an **academy perspective,** this thesis and its contribution, the BfP, consider existing research in product development focusing on modular product family development that enables configurable products. The BfP has a clear connection to earlier research. This thesis includes an extensive literature review which explains the current state in the research field with its benefits and disadvantages and compares the proposed design support for this existing research. Thus this thesis can serve also as an introduction to this research field for new researchers. This review of the literature was also very important from the viewpoint of the **author of this thesis**. During the writing of this thesis, the author's knowledge regarding the major publications, authors and contributions has increased substantially. In addition, industrial cases in which the contribution, the BfP, was applied were beneficial. These cases demonstrated the benefits and difficulties that may exist in the designing of modular product families. For example, it is difficult to enable the benefits of modular product families if there are no possibilities for investing in product development and the realisation of design results. Obviously, this last statement is also relevant for industry. From an **industry viewpoint**, the main objective was to define design support that is worthwhile. This thesis includes a presentation of the BfP method for modular product family development. Steps of the method have been explained in order to facilitate its application in industrial cases. It is important to understand, however, that even the suggested method cannot produce satisfying results without the existence of an understanding of the product and business context in question. The cases presented in this thesis do, however, provide support that the method and its steps facilitate the defining of design information that is beneficial in modular product family development aiming for configurable products. Consequently, this Doctor of Technology thesis and its contribution can be considered important.

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