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Tero Juuti

Design Management of Products with Variability and Commonality

– Contribution to the Design Science by elaborating the fit needed between Product Structure, Design Process, Design Goals, and Design Organisation for Improved R&D Efficiency

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Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Konetalo Building, Auditorium K1702, at Tampere University of Technology, on the 19th of December 2008, at 12 noon.

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"If you always do what you always did,

you always get what you always got."

- Marvin Weisbord -

I Foreword

This PhD thesis is a result of research I have done during 1997- 2008. It has been a journey full of learning. I would especially like to thank my colleague Director Tommi Leino for enabling the working with operational development, at the same time carrying out research in Nokia Corporation as well as in other companies. It has been a privilege for me and I have obtained a lot of experiences from the research projects transforming them into tools and approaches for my daily job as mentor, coach and facilitator. Thank you, Tommi.

I wish to highlight the role of my colleagues in Nokia Corporation, as you are a great source of ideas, experiences, and challenges. The dialogues we have had enabled me to find the key issues of managing a big R&D organisation. Thank you, fellows. I wish to express my gratitude to Mikko Vandeleene for proof-reading and commenting this thesis.

I also wish to express my gratitude to the staff at the Tampere University of Technology. Professor Asko Riitahuhta has involved me in many research projects with Dr. Timo Lehtonen who has been a personal trainer in scientific thinking for me in research projects, as well as when I was crafting and finalising this thesis. Lately the discussions we have had in the Riitahuhta Research Group, an open cross functional team of industrial and research people, have been fruitful. Thank you, Asko, Timo, and the staff in Machine Design and in Production Engineering, and also the team in the Riitahuhta Research Group.

Nowadays, research is international activity by nature. I gratefully thank all the colleagues I have discussed with in NordDesign, ICED, and PLM conferences. Especially, I want to thank my colleagues in Denmark and in Switzerland.

One needs the loving of a family to write a thesis. I am very pleased to express my gratitude and love to my wife, Ulla and to our wonderful children Olli and Katariina, full of potential. You managed to give me the time and space in our garage where I am writing these finalising words. Also, my parents and parents-in-law contributed to this work by their support. I'll give plenty of hugs and kisses to all of you.

Tero Juuti
Tampere 9.12. 2008

II Abstract

The research objective is to find solutions for how companies manufacturing physical products are able to increase profitability and efficiency with products using variability and commonality. The focus of this research is on managing the product development of such products. This thesis serves the companies need to increase profitability and R&D efficiency to satisfy the expectations of shareholders in the stock market.

The aim of this research is to provide new insight and enhance knowledge in the field of Design Management as part of Design Science. Therefore, this research has two objectives: 1) To describe the development process of Technical Systems that have variability and commonality, and 2) To describe management tasks that improve the R&D efficiency when developing a Technical System that has variability and commonality. The objectives are transformed into three research questions:

1) Which elements of a Technical System enable variability and commonality?
2) How to develop a Technical System that has variability and commonality?
3) How to improve the R&D efficiency when developing a Technical System that has variability and commonality?

The research process follows the traditions of Design Science and supplements it by using the Cultural Historic Activity Theory. The data was gathered during 1999 to 2008 from the Nokia Corporation, the Finnish Maritime industry, and from the relevant, state-of-the-art literature in the research field. After the analysis of theory basis, the state of the art and data from the Cases, this research provides answers. The answer to the first research question is: Technical System elements enabling variability and commonality are Standard, Configurable, One-of-a-kind and Partly-Configurable Product Structure types. The answer to the second research question is to have:

1) Design Process for each product structure type
2) The fit between Product Structure type and Design Process type, and
3) The fit between Design Process and Project Management Process

This research answers to the third research question by listing actions by which the R&D efficiency can be improved. Those items are:

1) Managing the fit between Product Structure and Design Process
2) Managing the fit between Design Process and Project Management Process
3) Decreasing work effort needed for capturing ready-made synthesis
4) Managing the designing within Force Field, and
5) Managing the distributed design activities in many organisations using different operational modes.

This thesis discusses the research results, the research process, and future research topics. The conclusions are drawn upon the results and discussion. Based on the discussion and conclusion the researcher concludes that this research contributes to Design Science by elaborating the Management & Goal system and validating dependencies between design goals, the characteristics of Technical System and characteristics of Design Processes. Finally, it provides recommendations on how the management is able to increase R&D efficiency. This research describes development process for Technical Systems that have variability and commonality. It also describes management tasks that improve the R&D efficiency when developing a Technical System that has variability and commonality, and provides answers to the research questions thus fulfilling the research objectives. This research provides new insight and enhances knowledge in the field of Design Management as part of Design Science thus meeting the research aim.

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1 INTRODUCTION AND MOTIVATION

This chapter elaborates the motivation of this research for the reader. The benefits of designing commonality and variability for the company are presented using practical case from VAG Corporation. The cause-effect chain of the benefits using commonality and variability is presented elaborating how they have effect on profit and R&D efficiency. Every chapter in this dissertation has a short chapter summary between the orange lines. Summary of the chapter contribution to the research questions is provided in the end of the chapter, when relevant.

This research is about managing the development of products that have variability and commonality. Many companies have pursued the benefits of such products and some have even succeeded. But what have they changed in their products and how did they do it? Was it enough to make changes to the product only; did anything else change within the company or outside the company? These were the key questions when the study “Design for Configuration” was started anno Domini 1997.

Surprisingly enough, after eleven years these questions still remain valid in the industry. Competition has increased, the products need to be of high quality, and the profit for the company needs to cover all expenses and the company needs to satisfy employees, shareholders, and a variety of customer needs. No wonder why companies are constantly seeking ways to decrease product costs and to increase the efficiency of the company. The researcher himself has witnessed these in another role, in leading operational development in Nokia Corporation's R&D entity.

This research is also about Product Structuring – the art of deciding on the composition of a product, i.e. which components are used, what is the purpose of each component, what is the impact on the manufacturing, logistics, sales, maintenance etc. Product Structuring assumes that the decisions made in design have a positive or a negative effect on how the customers perceive and experience the value of the product, how easy the manufacturing is, and at the end of the day, how profitable the product is for the company.

This introduction uses the VAG Group as a practical example of a skilled transformation of the product–or to be precise, the Product Structure and the structure of the company towards mass customisation. The example has been used many times due to its practicality and also because cars are familiar to majority of people. It is used in this research to provide basic understanding of the phenomenon of mass customisation. The reader needs to note that the word “platform” has a variety of meanings and that there is no agreement and single definition of the word. The word platform usually indicates such properties or characteristics of the product that enable re-use for the company.

The VAG example shows how to have a variety of cars yet at the same time use the mass production. Mass customisation is an industrial paradigm enabling companies to have the benefits of mass production and the customisation of the product to meet customer specific needs (see Chapter 5.1.1). Hans Dieter Pötsch, Member of the VAG Board of Management, gave a presentation in the Deutsche Bank German & Austrian Corporate Conference in Frankfurt, on 5 June 2008. His presentation is titled “Roadmap to profitable growth” and it consists of the key motivation for designing products with variability and commonality. He states the objective simply as “Heading towards a fully-fledged product portfolio”. The portfolio of VAG is presented in Figure 1 [Pötsch 2008].

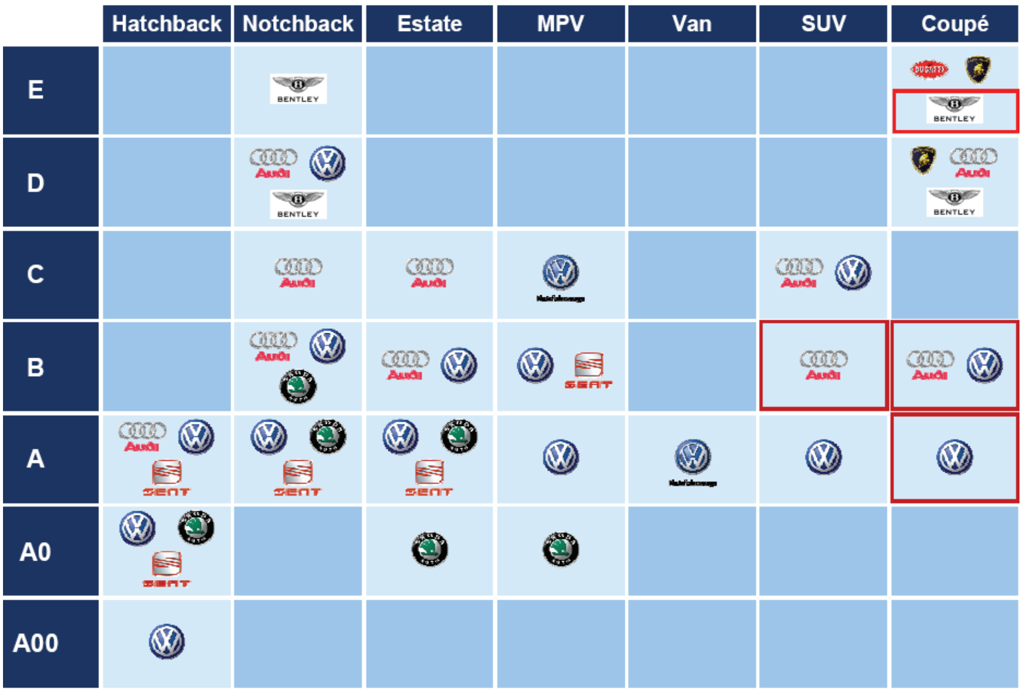


Figure 1. VAG product portfolio in Western Europe year 2008 [Pötsch 2008, page 13]. The customer segments are shown in columns and the platforms i.e. set of re-usable components, in rows. The make-label in the matrix indicates the car variants that are made from the particular platform to certain customer segment. The red box indicates new models in the portfolio.

In the presentation, the customer segments are shown in columns and the platforms i.e. set of re-usable components, in rows. The portfolio clearly shows their strategy to use the commonality of each platform in developing multiple products for various needs. Commonality increases the manufacturing volumes of a single component and thus lowers the unit cost. Commonality also decreases costs in the supply chain management and in after sales.

The A platform and its contents are visualised in Figure 2 by Eichhorn [Eichhorn 2001]. The A platform is used in VW Golf, VW Bora, VW New Beetle, Audi A3, Audi TT, Skoda Octavia etc. The platform components are indicated in grey. The grey parts are re-used for a number of products, and the re-use is enabled by the modularity of the product structure. The modularisation and the design goal of VAG are elaborated in Figure 3 [Pötsch 2008].

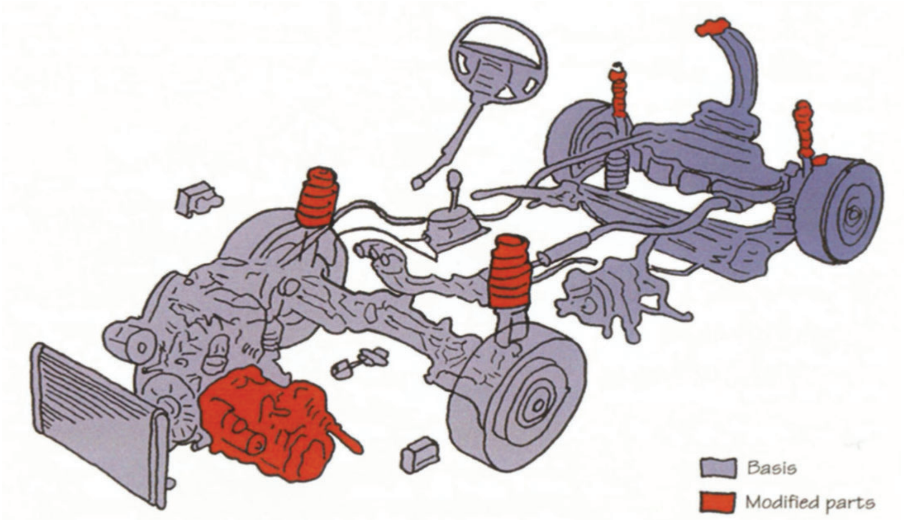


Figure 2. The contents of A-Platform in VAG [Eichhorn 2001]. The red colour indicates parts that do not belong to the A-platform and the grey colour indicates the parts of the A-platform.

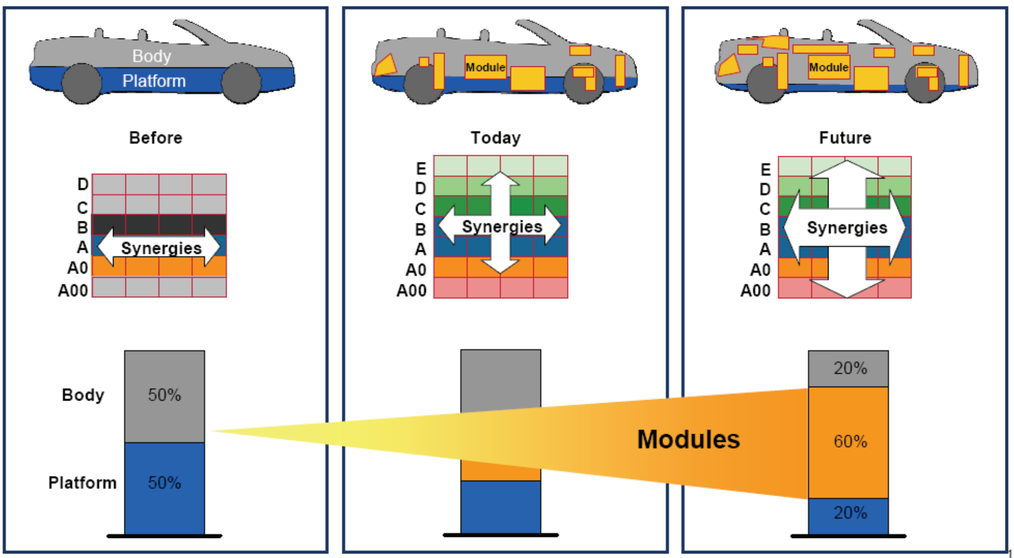


Figure 3. The role of modularisation in covering new segments [Pötsch 2008, page 19].

The design goal in VAG is to decrease the extent of platform and body and to increase the amount of modules. This will increase the flexibility to create different variants and benefit from the re-use of modules. Modularity is based on standardisation [Lehtonen 2007a] and the company needs to be careful about what they standardise, i.e. agree on the commonality between components or their properties. The platforms in VAG are a good example of standardisation, as at first the standardised platform served as a vehicle to decrease the unnecessary variation of components for the same purpose, but later on the platform was too big and actually decreased variability. Another example of standardisation in VAG is illustrated in Figure 4 [Pötsch 2008].

Standardisation enables the benefits of mass production and economies of scale. Consequently, the design for commonality and variability are fundamental design strategies for any company facing competition. Empirical studies and research papers demonstrate that commonality and variety have an impact on product competitiveness and improve R&D efficiency [Harlou 2006]. They also decrease the time to market: *"Functional, integrated, verified platform deliverables enable product integration to radically shorten the time to market"* [Nokia 2004a].

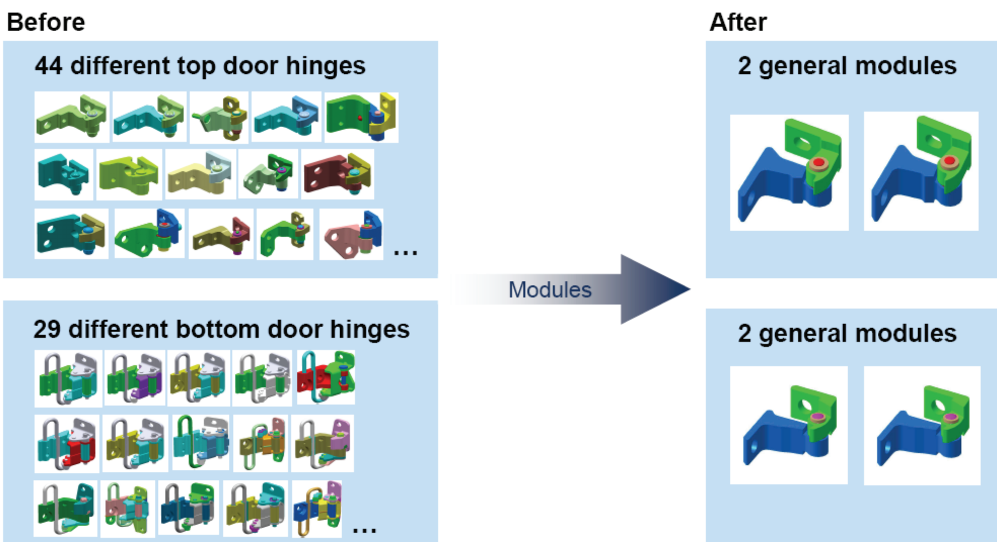


Figure 4. The result of standardisation of car door hinges in VAG [Pötsch 2008, page 22].

The challenge for Product Structuring is that a sufficient number of research results on designing variability and commonality do not exist. One challenge for the industry is that they need to implement this, with or without a solid theory basis. Another challenge is that modularisation and standardisation are not discrete, one-time events but a continuous process, as illustrated in Figure 3 and also highlighted by Holmqvist et al. [Holmqvist et al. 2004]. The motivation in this research is to elaborate on how to design products with commonality and variability, and what are the implications of such design activities to the company.

The cause-effect chain of the benefits from variability and commonality is presented in Figure 5. The cause-effect chain is created by the researcher and it is based on the inputs received from people working within the industry. It elaborates the importance of commonality and variability as characteristics of the Technical System to the profit and R&D efficiency. It describes why commonality and variability are the primary motivations of this research: they lead to improved R&D efficiency and profit for the company.

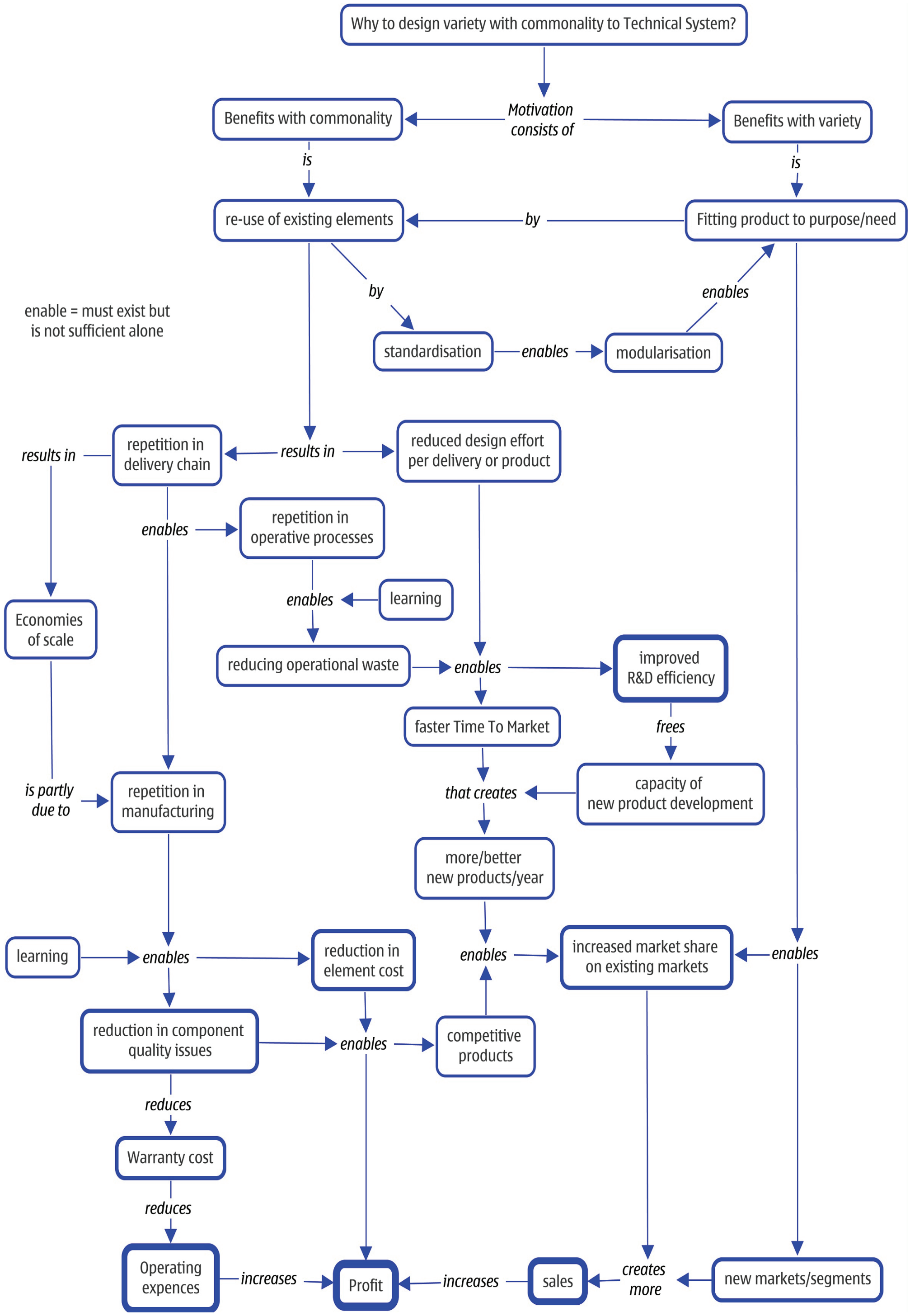


Figure 5. Cause-effect chain of the benefits using commonality and variability. The focus and motivation of this research lies in the areas of profit and improved R&D efficiency [Juuti 2008].

2 RESEARCH OBJECTIVE

The aim of this research is to provide new insight to and enhance knowledge in the field of Design Management as part of Design Science. Therefore this research has two objectives:

1) To describe the development process of Technical Systems that has variability and commonality.
2) To describe management tasks that improve the R&D efficiency when developing a Technical System that has variability and commonality.

The objectives are derived from the observations made on many Finnish and international companies. The observations are captured in Figure 5 and the cause-effect logic is validated with managers within the industry. The companies manufacturing physical products face fierce competition driving them to create new, competitive products fast and efficiently.

This research follows the mass customisation approach i.e. the product is competitive when it fits to the purpose of the consumer and adds value to the consumer. The researchers in this field of research know already that the use of different product parts or structures increase the company's ability to fit the product to the purpose and decreases component costs. Therefore, the approach is to study how products with variability and commonality can be efficiently developed by the R&D and how the development needs to be managed.

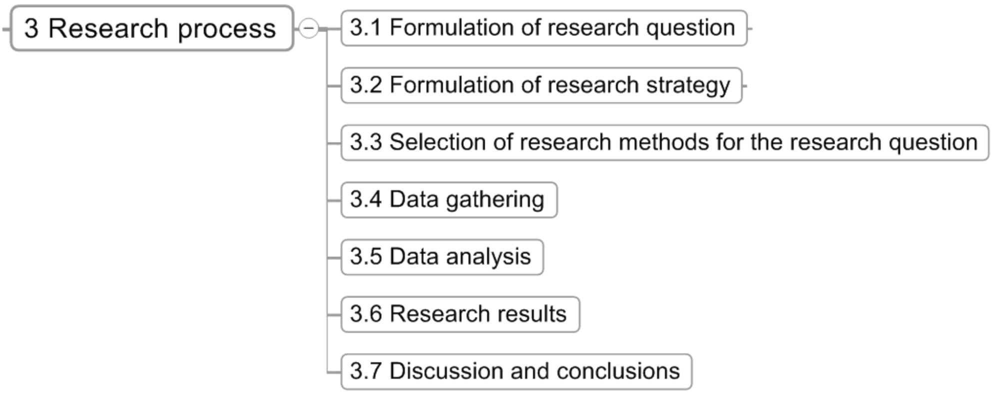
The shareholders are interested in company's operating expenses. This interest leads to the requiring of better R&D efficiency. It can also lead to extensive management efforts trying to measure the R&D efficiency. In this research the measure of R&D efficiency is the work effort per delivered product, module or component and the work effort is measured in man months.

The objectives are transformed into three research questions:

1) Which elements of a Technical System enable variability and commonality?
2) How to develop a Technical System that has variability and commonality?
3) How to improve the R&D efficiency when developing a Technical System that has variability and commonality?

The first research question is needed to recognise the elements that need to be developed. The second research question focuses on the development of the elements and products. The third question aims to find ways to improve R&D efficiency.

3 RESEARCH PROCESS



This chapter describes the outline of the research process elaborating how the research was carried out.

The research process is a synthesis of several aspects and the design follows the thinking presented by Professor Niiniluoto. He describes the philosophy of scientific research and how to create models and concepts in a valid manner [Niiniluoto 1997]. Each step of the research process is specified and the outline of the research process is shown in Figure 6 [adapted from Niiniluoto 1997].

3.1 Formulation of research questions

In the initial phase, the early research questions involved platforms and how to benefit from a platform mode of operations. Further thinking revealed, however, that the fundamental phenomenon is about re-use and the design goals enabling it. Therefore, this research does not cover platforms as such but focuses on the design re-use. Re-use is based on commonality that enables the economies of scale in manufacturing and in the supply chain. This is based on the repetition of identical tasks or steps in, for example, manufacturing; it is the key to the benefits of mass production.

The researcher is curious about how the design goals and design tasks have effect on the Technical System. The final research questions serve the purpose of finding solutions on how companies develop variable products and how they can improve R&D efficiency.

The basic approach is that the research questions are formulated based on the research objectives. Furthermore, the research questions lead to the selection of research methods. The research questions are chosen to gain insight to and knowledge on how products with variability and commonality can be efficiently developed by the R&D and how the development needs to be managed. The methods are chosen because they enable capturing of issues that are not observable just by reading documents. Some of the research methods were already tested and proven in the author's everyday work with operational development tasks as a member of a management team of an R&D organisation. The use of methods and role in management team has provided the author with wide access to relevant data for empirical studies and enabled research in the field. The data is gathered over a number of years with ethnography and Developmental Work Research, which is described in Chapter 4.6.

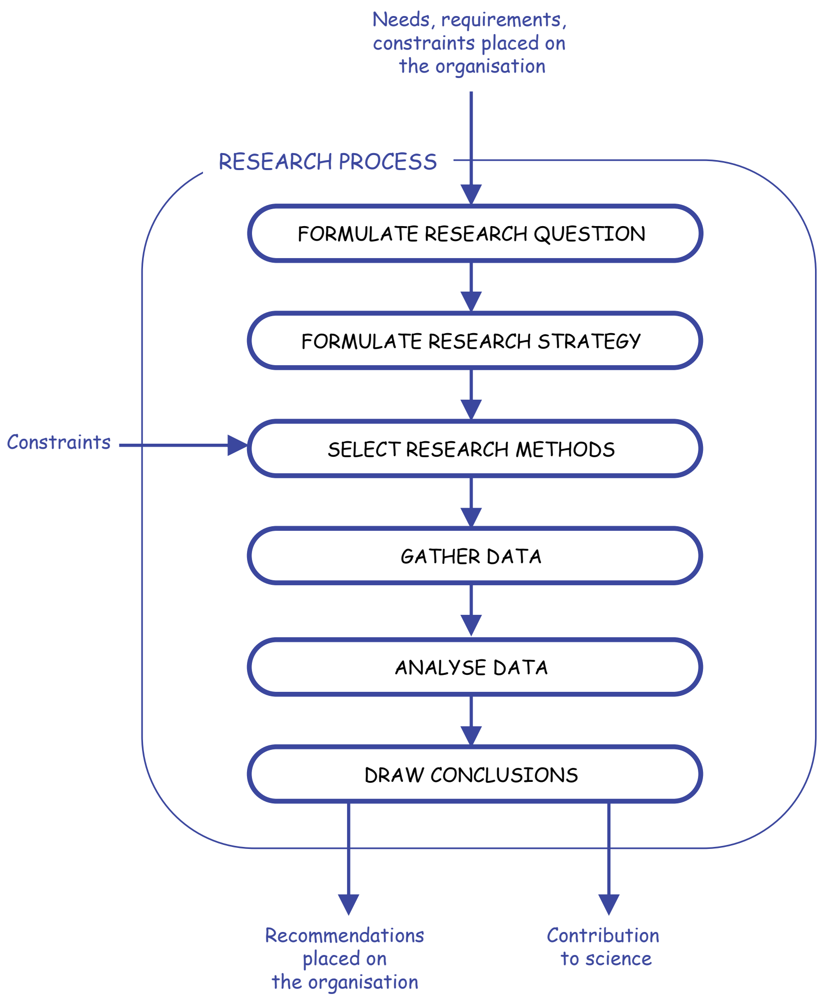


Figure 6. The outline of research process [adapted from Niiniluoto 1997].

3.2 Formulation of research strategy

The main drivers for the research strategy formulation were the ambition to contribute to both science and industry and the fact that the author was already working in a large R&D organisation. This baseline lead on to the following task sequence for developing new scientific results:

1) Formulation of research objectives and research questions
2) Selection of relevant scientific theories and models
3) Specify the research scope
4) Gather the data
5) Analysis of data
6) Research results
7) Discussion and Conclusions

3.2.1 Selection of relevant scientific theories and models

The theory base is chosen based on the need to understand product variability, product commonality and the developing of products having commonality and variability. The Design Science is selected as it provides relevant theories and models to be used. The Cultural Historic Activity Theory is chosen as it is found useful when improving the way how organisations operate thus meeting the needs of research objectives and research questions. Similarly the state of the art in literature and in companies is evaluated and such material is chosen that is relevant to the research objectives and research questions.

3.2.2 Specify the research scope

The research scope is defined further after the relevant theories and models are familiar to the researcher. The scope is limited to ensure some results are achieved. If the scope is too wide the researcher is able only “scratch the surface” and the underlying phenomenon remains unidentified and not understood. The research scope can be widened later on if the data analysis shows that there are no results on the phenomenon regarding the research objectives.

3.2.3 The researcher’s beliefs, assumptions and worldview

The researcher's worldview is based on the experiences and discoveries in previous research. The Konsta – Design for Configuration research project (1997-1999) [Pulkkinen et al. 2000] enabled us to observe an operational mode in which there was no need for design in the order-delivery process, yet the product was configured to meet the customer requirements. The work at Nokia Oyj enabled us to observe how to implement an asset accumulation strategy faster than the competitors. Cross-product component re-use provides economies of scale with low-cost components and the secure availability of key components as a result. Thus, it is reasonable to assume that the quality of the design goals is relevant for corporate success and it has also given the idea to start the research from the Product Structuring, Design Goals and Design Processes.

The starting point of this research is the assumption that mass customisation increases profit as described in Figure 5. This leads to question how to manage the Design Processes for mass customised products? The researcher also considers that the same Design Processes serves projecting companies with one-of-a-kind delivery. If the assumption of the mass customisation is changed it calls for different research project.

3.3 Selection of research methods for the research question

The research questions narrowed down a number of existing research methods. The opportunity to gather data over several years and access real-life data was a fruitful foundation for carrying out the research project. To study the fit between Technical System and Design Processes qualitative research methods were chosen due to the nature of the research. This research is entering to a novel field and it is enough to know the dependencies between items at this stage. Further research can utilise quantitative methods to provide insight on the dependencies.

The participatory approach is a pragmatic way to gather research data while carrying out everyday work tasks. Ethnographic studies fulfilled the selection criteria, and they appeared to be a suitable way to find answers to the research question by having interviews, facilitated sessions, workshops and dialogue with variety of people in the Case companies. Ethnography combined with Developmental work research (DWR), based on the Cultural-Historic Activity Theory (CHAT) provided suitable tools to examine the phenomena of Design Processes and Technical Systems. CHAT is explained and further elaborated in Chapter 4.6.

Other methods were desktop studies and following research projects in other companies. Desktop studies using multiple scientific information sources from Springer, ScienceDirect and Wiley were performed to analyse state-of-the-art theories relevant to this research. The research projects in other companies had a bit different scope, yet they enabled the gathering of empirical data relevant to this research.

3.4 Data gathering

The data was gathered during 1997-2008 from multiple sources: Master of Science theses, interviews, workshops, lectures, trainings, literature, peer-to-peer meetings with other researchers, technical documentation of project plans and technical system specifications. A major amount of data was gathered from Nokia due to the 9-year ethnographic studies in the company. The Cases that were from different parts of the operational flow were selected to have different viewpoints on the research subject.

In the case of Nokia, the platform mode of operations is elaborated in detail to provide an understanding of the different motives of Activity Systems resulting in conflicts between Activity Systems inside the operational mode. The data and the summary of each case are presented. The Case A and B are treated as individual cases as they contribute to the research questions alone. The Cases from C to H are in a sense "sub cases" as they take place within Case A because the projects operate within Nokia R&D and in Case B because the projects operate within platform mode of operation. The "sub cases" are used to provide further insight and knowledge to the research questions.

The researcher's role in Nokia can be described as participatory observant. The day job as Operational Development manager consists of organising and facilitation of meetings, workshops and other sessions to identify what is working already and which items (issues, problems, and challenges) need to be improved. During the sessions several facilitation methods are used and solutions to the items are created, planned, and scheduled.

Facilitation is an approach for managing group sessions and it is based on the very idea that facilitator manages the process and remains neutral to the content. This is needed because otherwise the participants can not trust the facilitator and their focus goes to finding out whether the facilitator has a hidden agenda and what the hidden agenda is. The findings of the sessions and observations are documented using Activity System model (see Chapter 4.6) as well as field notes, a collection of observations during 1999 – 2008.

The research for Case I was carried out with the Finnish maritime industry during 2005-2007 by researchers Lehtonen, Roikola, Taneli, and Riitahuhta. The objective was to create a new operating concept for the whole shipbuilding network. Three different operating modes were found already existing and the fourth was a new concept for the operational mode of the network. Empirical method was used in studying the different ways of making ship delivery. The information was gathered from shipyard quality management books, documentation from previous deliveries, and by interviewing the personnel in the shipyard and in the marine cluster companies. The process models were drawn according to the information exchange model, and thus the sequence of design decisions can be seen. The empirical material is presented in more detail in the final report of the research project [Lehtonen et al. 2007b].

3.5 Data analysis

The analysis of the data is based on empirical findings. The data is mapped to the tables to study the dependencies between items. Systemic models of the Activity System are drawn using CHAT. The dependency between the Design Process and the Technical System is analysed and the differences between the Design Processes and design tasks. They are analysed comparing the different processes for the different design goals in the Nokia cases.

3.6 Research results

The results are based on the theory basis, the state of the art, and empirical study on the Design Processes in two companies to identify the characteristics of Technical System, Design Process and design goal for the research questions. Logical conclusions are drawn to provide insight to the research questions and models are created describing the relevant issues and phenomena. The results are then formulated into answers to the research questions.

3.7 Discussion and Conclusions

Conclusions are based on the results of the previous steps and the contribution of this research is considered. The discussion contains issues that are disputable, i.e. the empirics contained conflicting data or the theoretical base and the empirics conflicted. This step has another important function serving as a mirror to reflect on how the research process was carried out as well as assess the quality of research by analysing what might disturb the validity. Validation is carried out with triangulation with people from different industries and with researchers in this field. Future research topics are proposed based on the discussion and conclusions.

Contribution to this research

This chapter describes the research scope and research process and elaborates how the research is carried out and which research methods are used.

4 THEORY BASIS

This chapter describes the relevant theoretical base and concludes how the models contribute to the research questions.

4.1 Design Science

Design Science (DS) described by Hubka et al. [Hubka & Eder 1988] is an acknowledged set of knowledge by the researchers in the field of engineering design and product structuring. Design Science comprises four areas of knowledge:

1) Theory of Technical Systems,
2) Design object knowledge,
3) Theory of Design Processes, and
4) Design Process knowledge.

4.1.1 Theory of Technical Systems

The Theory of Technical Systems (TTS) [Hubka et al. 1988] defines the purpose and functionality of a technical device by means of a transformation system. The transformation system consists of a technical process, operands, and operators. The operands are transformed in the process. The operators drive the process forward. The transformation can apply to material, energy, and information. The transformation system is shown in Figure 7.

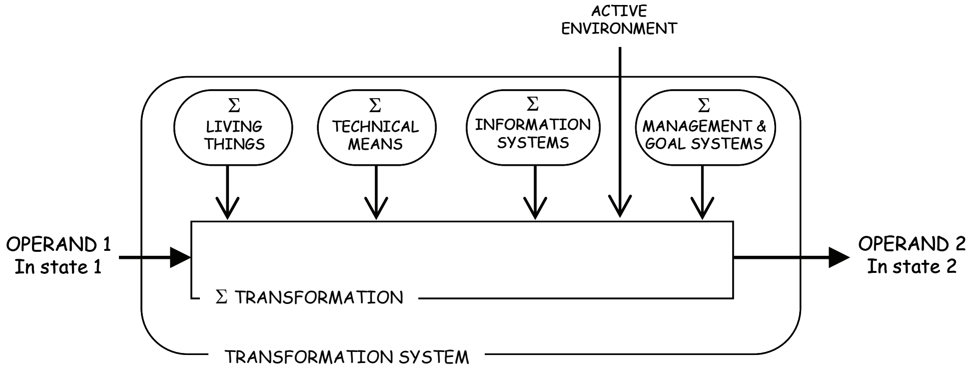


Figure 7. Transformation system. Design management operates mainly with management and goal systems and active environment [Hubka & Eder 1988, page 102].

Figure 7 illustrates the elements of the transformation system: a sum of living things (a human system), a sum of technical means (a technical system), a sum of information systems, a sum of transformations (a technical process), and the operands. The living things, technical means, and information systems are the operators in a transformation system. The transformation system is enabled by the co-operation of the operators. In a technical process, the input operands are transformed into desired output operands.

The process contains a set of partial processes or operations that have to be sequentially executed in order to achieve the goal. There exists a causal chain of transformations. The partial processes may also require additional processes in order to perform. The human system includes everyone participating in the process. All environmental operators connected to the process are defined as environmental systems. An information system, for example, can be considered as a part of the environmental system [Hubka et al. 1988].

The capability of the Technical System can be understood as an ability of the technical system to perform the required functions. Functions are realised by organs as constructional elements or components of the technical system. The technical system is hierarchical in nature and the functions, organs, or constructional elements are often divided into smaller structures in a hierarchical manner. Thus, there exist partial functions, partial organs, and partial constructive elements that work together to perform a particular function.

4.1.2 Theory of Design Process

The second part of Design Science is theory of Design Process (DP) [Hubka & Eder 1988]. It is based on a similar philosophy as the TTS. The “designing transformation process” comprises the Design Process, engineering designers, working means, design information, design management, active environment, and operands; see Figure 8.

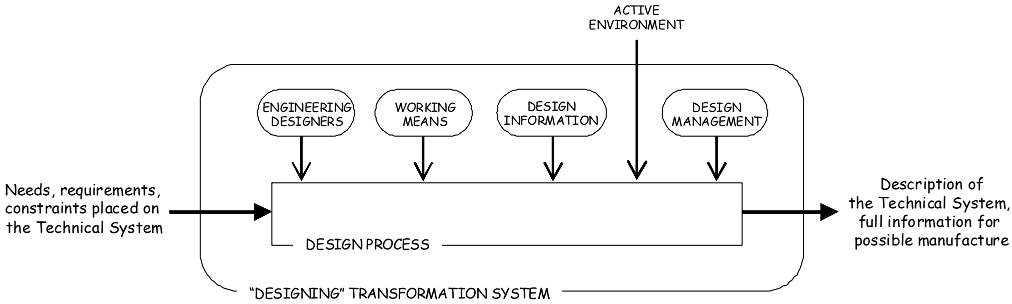


Figure 8. "Designing" the transformation system. Design management is illustrated as one input to Design Process but this research proposes wider understanding consisting of design information, means of working, inputs, outputs, and active environment [Hubka & Eder 1988, page 126].

A Design Process consists of design technology such as methods, strategies, tactics, and design principles. The engineering designers are the people who carry out the design tasks. The working means consist of the designers' own activities and tools such as computers. Design information is the data needed about the design object during the Design Process. Design management consists of determining the tasks, planning, working methods, the complete documentation, and other leadership issues. An active environment consists of the time and place for designing as working conditions and the working climate. The operands are the needs and requirements on the technical system as input and a description of the technical system as output. [Hubka et al. 1988]

4.1.3 Design Object knowledge

The question to be answered is "how do I achieve this structure, property, and further features?" A design object has particular properties or structures that are applicable due to e.g. the technology available and the selected solution principles. The variety of design objects, both in size and technologies used, from nano-robots to 2000 MW power plants impose a multitude of designing challenges that differ from each other. This concept is described as branch knowledge [Hubka et al. 1988].

4.1.4 Design Process knowledge

Design Process knowledge is *"practical knowledge about designing"* [Hubka et al. 1988]. Typically, this knowledge appears in the form of procedural models and methods. Some methods operate on a very detailed level, such as the methods that support the completion of individual design steps. There is a lack of broad application, as even teams prefer defining the procedural models for themselves. One procedural model is illustrated in Figure 9.

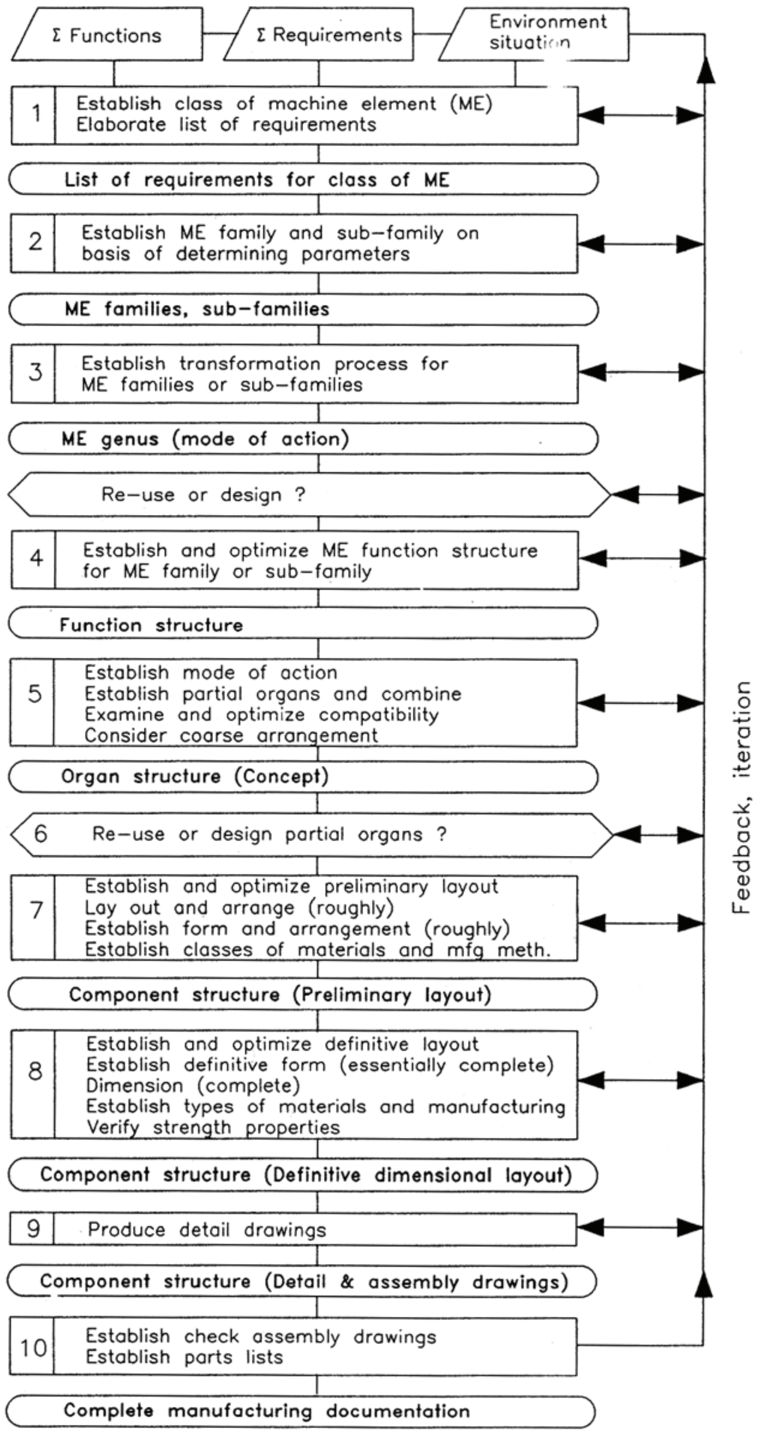


Figure 9. The general procedural model for Designing at Novel Machine Elements [Hubka & Eder 1988, page 197].

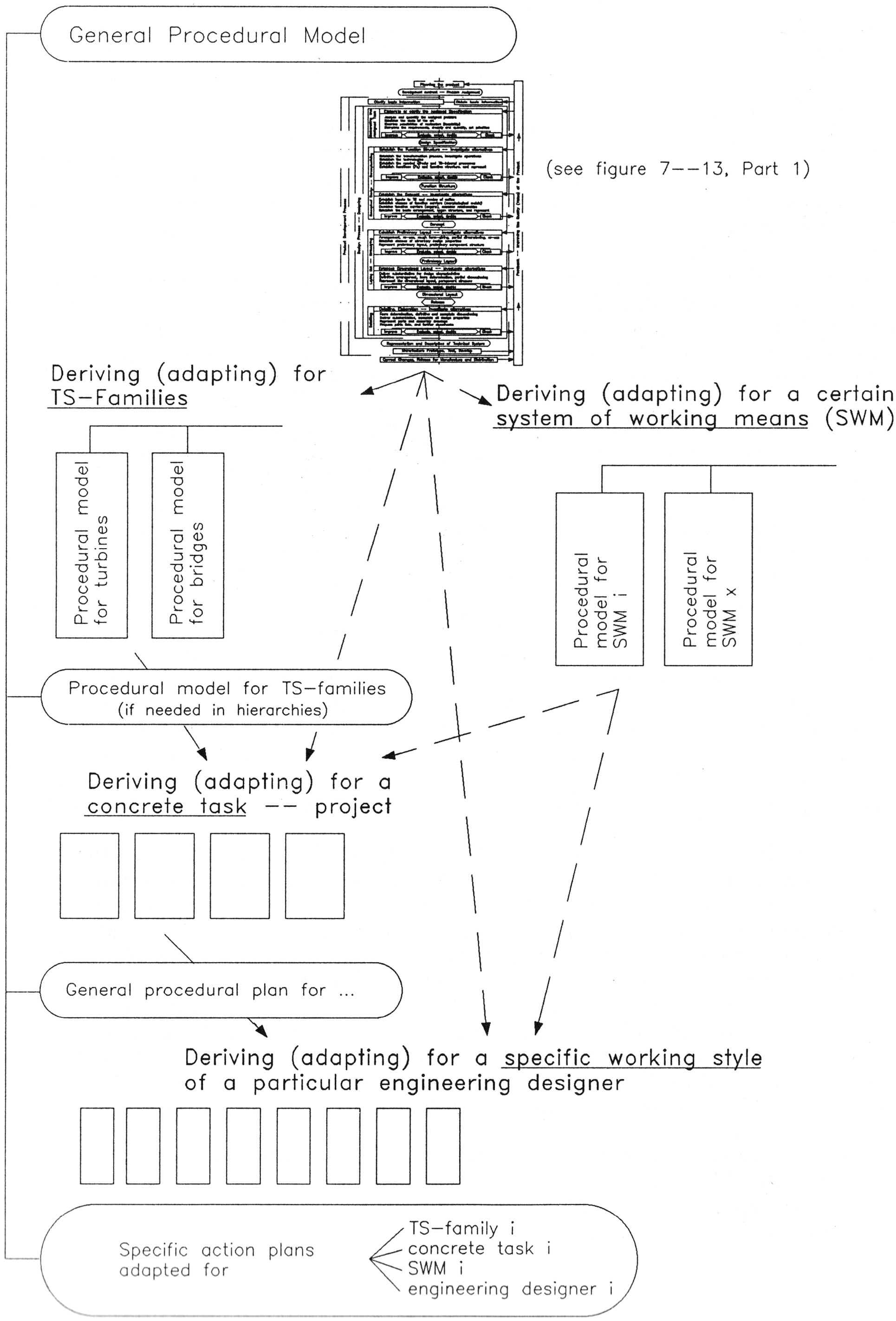


Figure 10. Derivative path from general procedural model to specific design action plan. [Hubka et al. 1988, p138]. Design management creates such an action plan and it is called adapted Design Process.

Hubka also presents a model on how to derive a specific procedural model from the general procedural model, for example to the different TS families in Figure 10. They state: *"A researcher would normally consider such an idealised model with broader validity as a satisfactory result. It can, however, serve a practitioner only as a preliminary model for working out concrete procedural plans. These must reflect the situation and design problem to be processed."* [Hubka et al. 1988] Hubka states the need to align design tasks and design problems and thus this research considers this a request for more practical and concrete Design Processes for industrial use as abstract level descriptions do not serve the design task as such.

4.2 Theory of Domains

The Domain Theory [Andreasen 1980] approaches the product synthesis from the viewpoint of four domains: transformation, function, organ, and part domain. The four domains present different viewpoints to a product, and design steps can be seen progressing from abstract to concrete in each domain. See Figure 11.

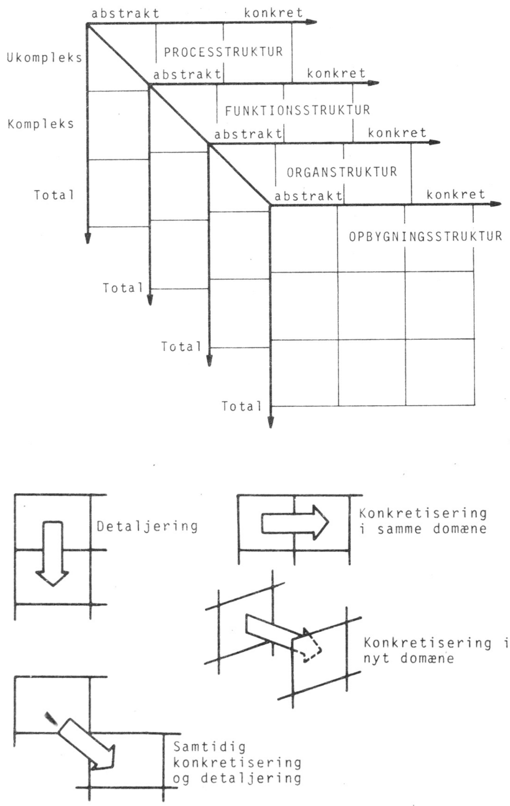


Figure 11. Theory of Domains and four genetic viewpoints with abstract to concrete and simple to whole dimensions [Andreasen 1980].

The transformation domain describes the transformation process which occurs when using a product. The performance of a product is seen as a transformation of energy, information, and/or material. The transformation process consists of a causal chain of transformations. These transformations should correspond to the purpose of a device. (Andreasen et al. 1997)

Functions describe the effects that are required in order to realise the transformations desired. These functionalities are specified in the functional domain. While realising one function, there might exist a need for simultaneous support functions. The organ domain describes the entities that are meant to execute the effects needed. Organs are thus often referred to as function carriers. The organ domain also describes the relations among the organs. Organs are realised by the parts of a product. The part structure and the couplings between the parts are described in the part domain. Parts are meant to contribute to the organs' mode of action [Andreasen et al. 1997]. See Figure 12.

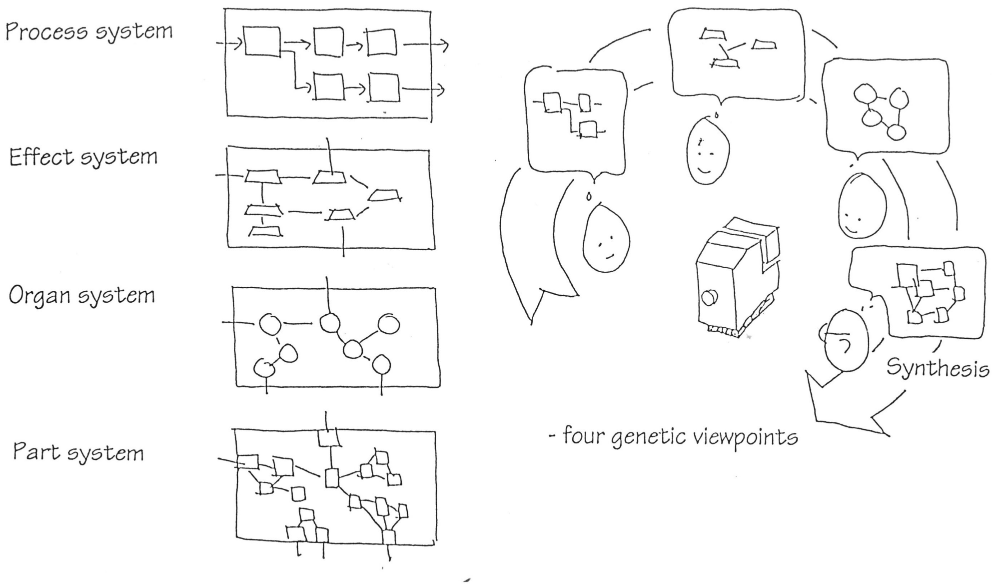


Figure 12. The four genetic viewpoints and their correspondence on four domains [Andreasen et al. 1997].

The synthesis is represented as moving from the process system towards a part system via an effect system and an organ system. Andreasen et al. propose that ideally this is the case when reaching for a synthesis, but they also recognise that other paths are also possible when reaching for a synthesis; see Figure 13.

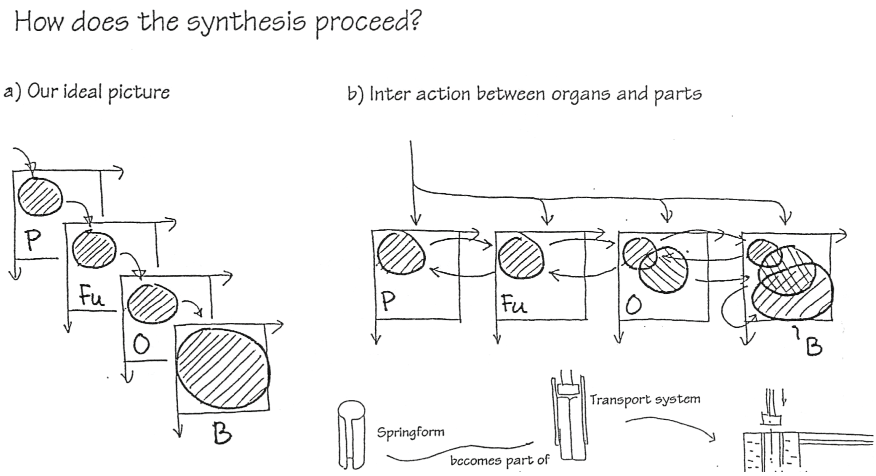


Figure 13. *The pathways to synthesis according to Domain Theory. In some cases part domain is already partly fixed due to re-use of components as illustrated in b) [Andreasen et al. 1997].*

They present genetic views to a product where the structure of a certain domain is partly defined by the previous domain. The synthesis of design is described in the Domain Theory.

4.3 Product Structuring

Product structuring is an approach that focuses on product structure, and the product structure is optimised using a variety of viewpoints. Product Structure is defined as *"the structure of a product is the way its elements are related to each other in a system model, based on a chosen view. A systems model is a model, where an object or a design is seen as elements and relations"* [Andreasen et al. 1996]. This philosophy is based on the notion that *"behaviour and function of the product depend on the structure"*. The task of creating product structures is called product structuring. Viewpoints to the Product Structure are presented in Figure 14. The architecture plays a major role in Product Structuring and there are many studies researching this matter [Harlou 2006] [Lehtonen 2007a], Harlou defines it as: *"architecture is a structural description of product assortment, a product family or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces with the surroundings"*.

In relation to this research, Riitahuhta et al. [Riitahuhta et al. 1998] have proposed a model in which the architecture of a product family plays a key role and the different viewpoints surround it. The viewpoints exist to create variety, to create kinship i.e. commonality, and to limit complexity. In addition, the market input and the different phases of the product life-cycle need to be considered. The model is presented in Figure 15.

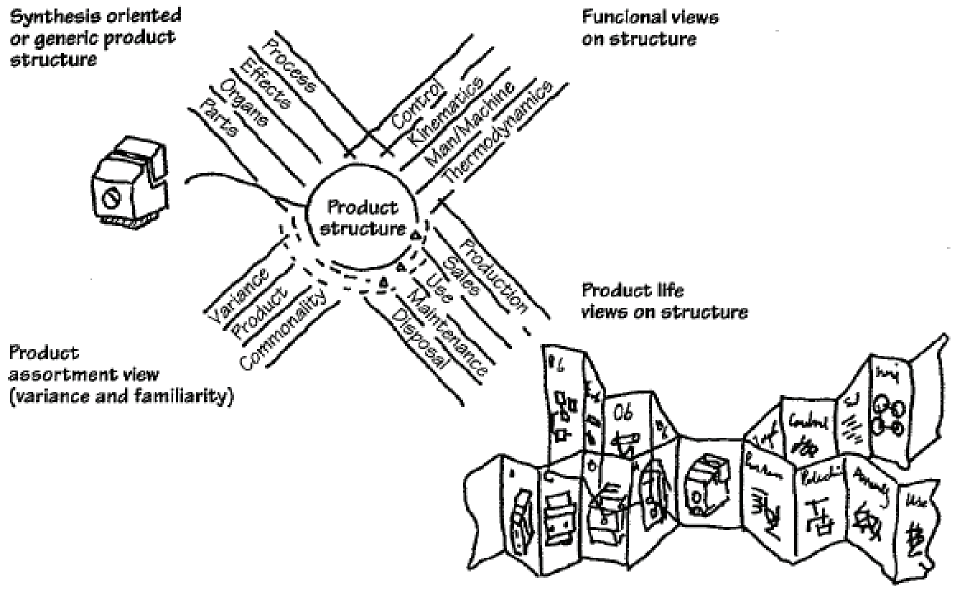


Figure 14. Viewpoints to product structure [Andreasen et al. 1997]. This research approaches the design management for profit and R&D efficiency from product assortment viewpoint assuming variance (variability), product (product synthesis) and commonality are the main contributors towards research objectives.

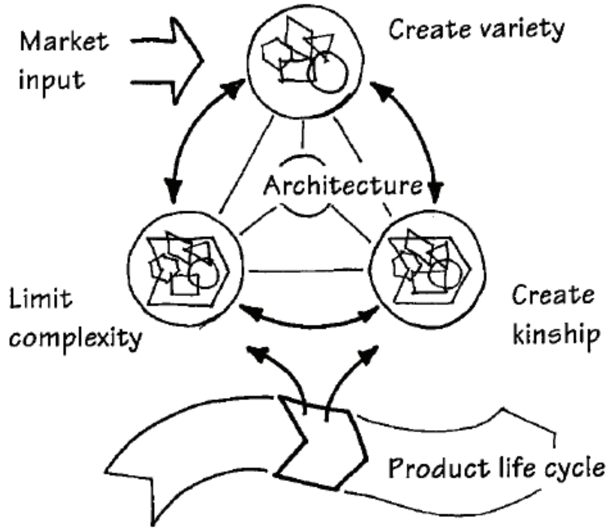


Figure 15. Circumstances related to the product family's architecture [Riitahuhta et al. 1998, p. 171]. The market inputs, product complexity, kinship (Technical System characteristic is commonality) and product lifecycle need to be taken into account when creating variety (Technical System characteristic is variability).

4.4 Design Management and Design Coordination

Design management plays a role in the competitiveness of new products and investigates the provisions to achieve it [Hegde et al. 1992]. Design coordination is a concept for design management and it is a high-level concept of the planning, scheduling, representation, decision making, and control of product development with respect to time, tasks, resources, and design aspects [Duffy et al. 1993]. The goal of design coordination is to manage the Design Process in such a way that all requirements are met and in addition the Design Process is carried out as efficiently as possible.

The Design coordination framework is a collection of eleven models which are considered to be essential to design coordination [Andreasen et al. 1994]. Each model describes a certain aspect of the product or the Design Process. Design coordination can be explained on the basis of relationships between the models. The models are described in Figure 16.

1 - Model of Product Development

Product development links needs capture to the introduction of the product to the market place. The content of product development models differs widely, from simple problem solving models, via engineering design focused models, to models showing interrelated functional activities of a company, leading to establishing a new business [Andreasen et al. 1994].

2 - Model of decomposition

Decomposition is the product breakdown into subsystems, each of which requiring design tasks. There are also design tasks which cannot be precisely related to subsystems, so the decomposition model is not a complete activity structure model [Andreasen et al. 1994].

3 - Model of disciplines and technologies

Product development changes technologies and know-how into new business possibilities. The R&D organisation has to gain new insights and ideas for use in the design activity. The R&D organisation have to be multidisciplinary in accordance with the needs of the product for creating mechanical, electronic or software solutions, or to create a control circuit, a man/machine interface, optimisation of a fluid flow system etc. [Andreasen et al. 1994].

4 - Product life model

Designing is closely linked to foreseeing product life phases, primarily the "use" phases but also establishment, maintenance and liquidation. Each life phase may be seen as a system; the product interacts with this system and the effectiveness of that interaction determines the performance and ease of performing/surviving the actual phase [Andreasen et al. 1994].

5 - Synthesis Matrix model

The synthesis of the artefact is the core of the product development activity. Each subsystem or larger parts of the product may be treated in a separate design activity. The design activity may be unstructured or captured in steps with defined phase results like, for example, a concept. Adopting the concept of Concurrent Engineering Andreasen proposes a parallel product and production engineering process. The phases are synchronised and performed interactively and there are two results: a product and a production result [Andreasen et al. 1994].

6 - Life phase system model

The identification or quantification of a life phase system has as a result a contribution to the specification of the life phase system and the life phase conditions. The responsible agents for the life phase (like the fabrication, assembly, transport or service department) need to receive these explicit results for control, adjustment or as a specification for the future life phase activity, like input for production preparation [Andreasen et al. 1994].

7 - Product development goal/result model

The product development activity is normally controlled by goal specifications. The specifications define demands and optimisation criteria and specific required elements or features of the solution, with the basic idea to capture the properties of the ideal solution covering the perceived need. The goal structure relates to a degree the decomposition structure. The specification elements (demands) cannot be related to the system elements beforehand, unless the solution is already well known. So the relation between the specification and the system elements is normally very complicated [Andreasen et al. 1994].

8 - Product development task model

The tasks of the team manager and the product development team may be formulated in a business specification which defines the purpose and goal of a project seen from a business point of view and act as a contract between the management and the team [Andreasen et al. 1994].

9 - Activity model

Many companies utilise a general master model of the product development activity as a basis for establishing a plan for an actual project. Where the model of the product development activity mentioned in Frame 1 serves the overview and monitoring of a set of activities (mainly showing strategy and tactics plus milestone actions), the activity model serves the control of teams and individual activities. The model could support the creation and maintenance of the project plan under dynamic changes and support the reuse of plans from earlier projects [Andreasen et al. 1994].

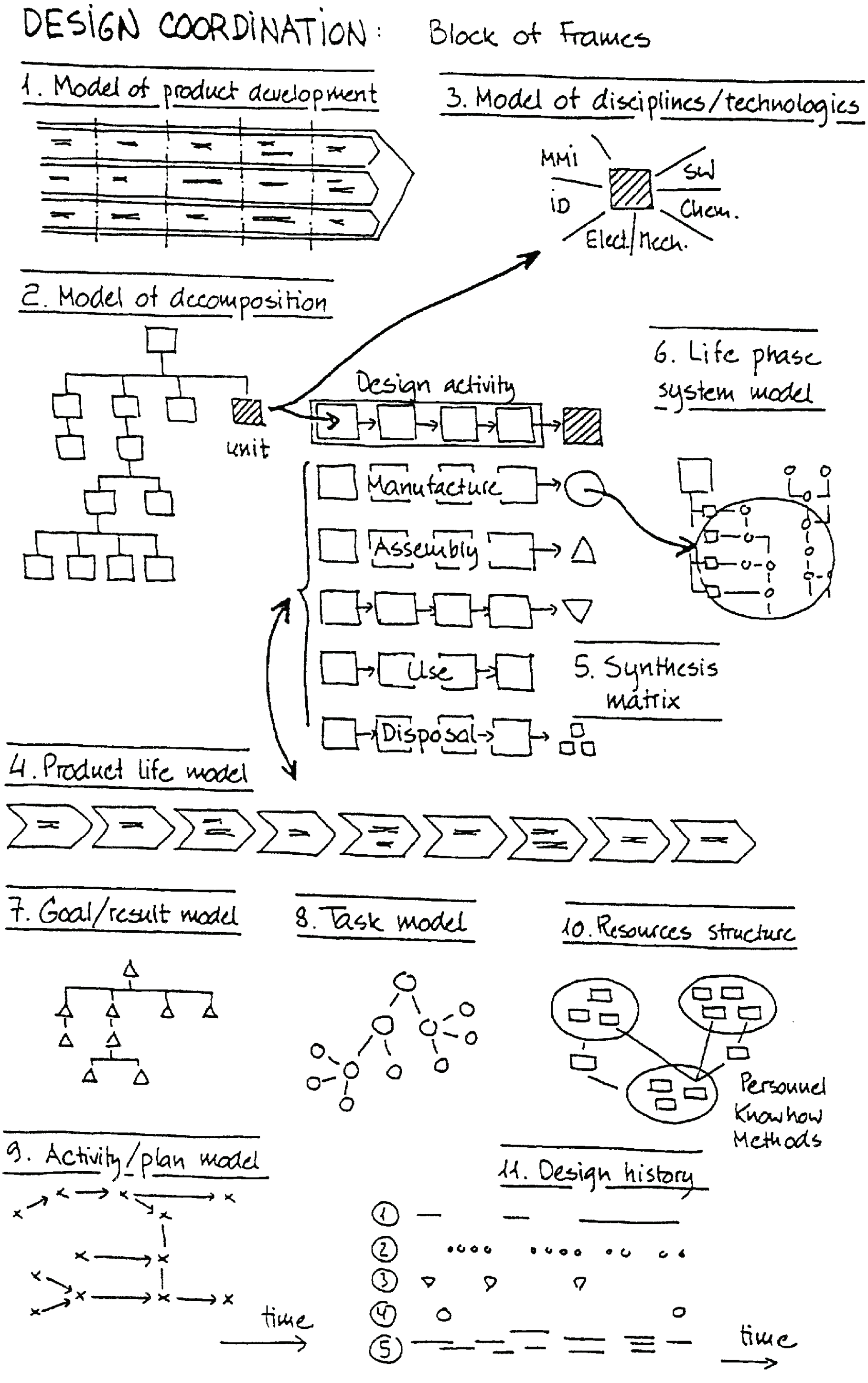


Figure 16. The Design coordination framework. The design management is facilitated by creating connections between these models in design coordination [Andreasen et al. 1994].

10 - Resource model

An important task in design management is the allocation of resources. What are allocated are knowledge, skills and methods, carried by individuals, teams and equipment [Andreasen et al. 1994].

11 - Design history model

A design history model reflects central aspects of the product development activity, such as decisions and their rationale; related to product-oriented solutions, design strategies, plans, allocations etc. [Andreasen et al. 1994]. The use of such a design history could be to support re-use or any kind of insight obtained by previous projects.

4.5 Three-level model of activity

Alexei Leontjev formulated the concept of activity as a systemic formation and unit of analysis for human sciences [Leontjev 1978]. Activity is a collective system driven by an object and motive. It is realised through individual actions driven by goals. Actions, in turn, are realised by means of routinized operations, dependent on the conditions of the action. To understand and facilitate development, one needs to study and change entire collective Activity Systems, their objects and motives, not merely separate actions and skills [Leontjev 1977]. The three-level structure of activity proposed by Leontjev is depicted in Figure 17.

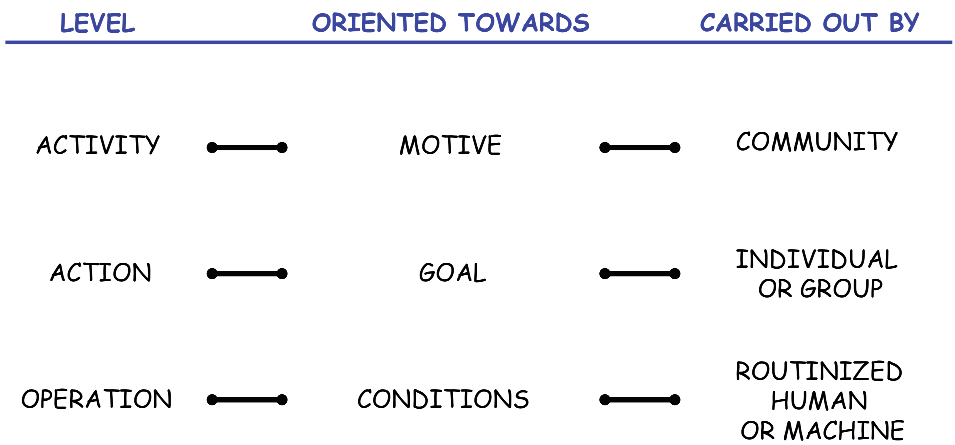


Figure 17. The three level model of activity. The mediated activity emerges when two Activity Systems share the same motive and agree division of labour to achieve together the goals, derived from motive, with individual actions [Engeström 1998].

The uppermost level of collective activity is driven by an object-related motive; the middle level of individual (or group) action is driven by a conscious goal, and the bottom level of operations is driven by the conditions and tools of the action at hand.

4.6 Cultural – Historic Activity Theory

The cultural-historical theory of activity [Vygotsky 1978] was formulated by Lev Vygotsky in the 1920s and it was based on Leontjev's work. According to Vygotsky, psychology in the 1920s was dominated by two unsatisfactory orientations, psychoanalysis and behaviourism. He was active in critique towards the work of Piaget and Stern (see e.g. Piaget, J. "Structuralism" 1970 and Stern, E. "Problems of cultural psychology" 1916/1990) thus clarifying his own hypothesis and theory. Vygotsky and his colleagues A. R. Luria and A. N. Leontjev formulated a completely new theoretical concept to transcend the situation: the concept of artefact-mediated and object-oriented action [Vygotsky 1978]:

"An object is both something given and something projected or anticipated. A thing or phenomenon becomes an object of activity as it meets a human need. In this constructed, need-related capacity, the object gains motivating force that gives shape and direction to activity. The object determines the horizon of possible goals and actions. The artefact-mediated means…that person is creating e.g. signs or language while solving object related problem. The signs, language or other artefacts serve as instruments while they mediate or facilitate the thinking enabling higher level psychological processes".

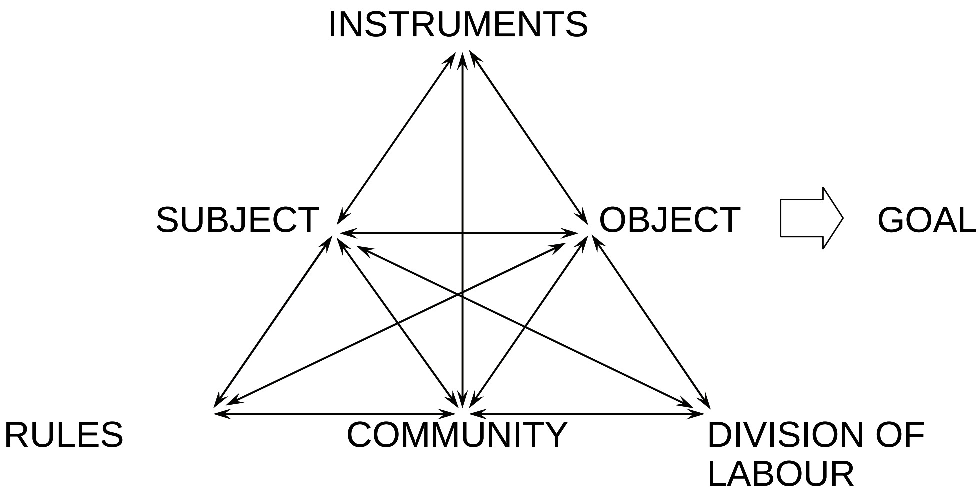


Figure 18. An Activity System model and its elements. The theory elaborates how organisations learn and evolve using the elements and cultural-historic approach. The arrows represent dependencies between elements and potential origins of conflicts in the Activity System [Engeström 1998].

In the model, (see Figure 18) the subject refers to the individual or sub-group whose agency is chosen as the point of view in the analysis. The object refers to the 'raw material' or 'problem space' at which the activity is directed and which is moulded and transformed into outcomes with the help of physical and symbolic, external and internal mediating instruments, including both tools and signs.

The community comprises multiple individuals and/or sub-groups who share the same general object and who construct themselves as distinct from other communities. The division of labour refers to both the horizontal division of tasks between the members of the community and to the vertical division of power and status. Finally, the rules refer to the explicit and implicit regulations, norms, and conventions that constrain actions and interactions within the Activity System. The arrows represent dependencies between elements and potential origins of conflicts in the Activity System.

Collective activity is connected to object and motive, of which the individual subjects are often not consciously aware. Individual action is connected to a more or less conscious goal. Leontjev [Leontjev 1978] pointed out that the concept of object is already contained in the very concept of activity; there is no such thing as objectless activity.

An Activity System is always heterogeneous and multi-voiced. Different subjects, due to their different histories and positions in the division of labour, construct the object and the other components of the activity in different, partially overlapping and partially conflicting ways. There is constant construction and renegotiation within the Activity System. Coordination between the different versions of the object must be achieved to ensure continuous operation. Tasks are reassigned and redefined, rules are bent and reinterpreted. There is also a never-ending movement between the nodes of the activity. What initially appears as an object may soon be transformed into an outcome, and then turned into an instrument, and perhaps later into a rule [Engeström, 1987].

Activity is a collective, systemic formation that has a complex mediational structure. An Activity System produces actions and is realised by means of actions. However, activity is not reducible to actions. Actions are relatively short-lived and have a temporally clear-cut beginning and end. Activity Systems evolve over lengthy periods of socio-historical time, often taking the form of institutions and organisations. The evolution is studied and improved with Developmental Work Research (DWR), developed by Yrjö Engeström [Engeström 1991].

The Activity System is used to analyse the organisation, and one primary method is to identify conflicts between the elements of the Activity System and between Activity Systems [Engeström 1998]. The DWR method is used when analysing the Activity System internal conflicts as well as the interactions and conflicts between the Activity Systems. The basic assumption in this approach is that the Activity System is able to evolve when a culturally more advanced central activity is developed (see Figure 19). The central activity is the basic purpose of the group of people; in the industry it is called a mission. The DWR approaches the Activity System from a learning point of view, and the conflicts are treated as potential occasions for the Activity System to learn and improve.

The DWR-method enables elaboration on how the organisation learns, evolves and transforms towards more advanced ways of working. When learning takes place the Activity System has more advanced instruments, division of labour and rules enabling same results with less effort or more innovations with same effort.

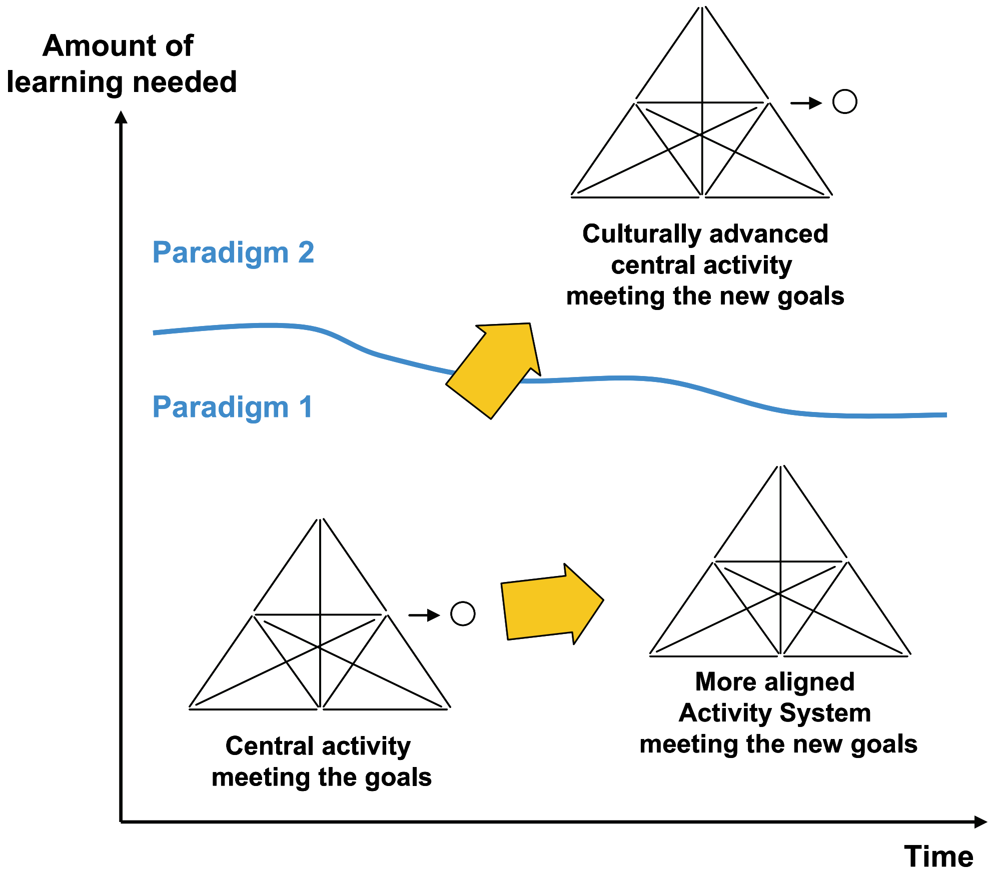


Figure 19. A culturally advanced Activity System. When learning takes place the Activity System has more advanced instruments, division of labour and rules enabling same results with less effort or more innovations with same effort. Much more effort is needed to reach new paradigm, and to have culturally advanced central activity as well as enabling elements of Activity System in place.

Figure 19 illustrates the amount of learning effort needed for the Activity System to move from one paradigm to another. The paradigms relevant to this research are described in the next chapter.

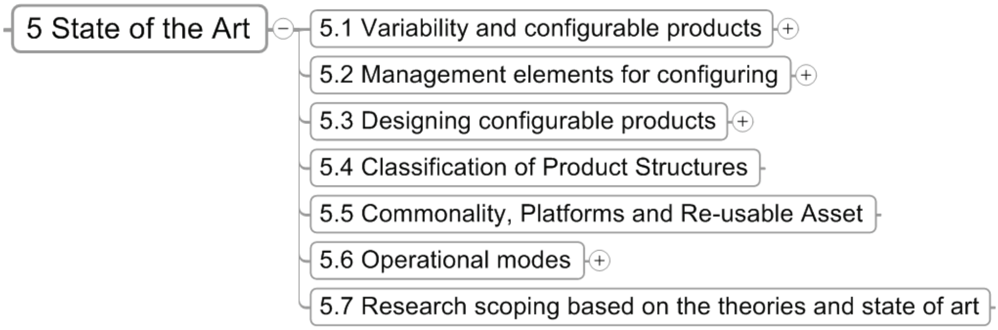
Contribution to the research questions

The Product Structuring models in Chapter 4.3 contribute to the research question 1 by describing characteristics of product family architecture that serves as a module system for a configurable product. The Activity System Theory in Chapter 4.6 contributes to the research question 2 by indicating fit needed between Technical System and Design Process. The Design Science in Chapter 4.1 contributes to the research question 2 by presenting the design management as one element having impact on the Design Process by setting acceptance criteria on the design (see Figure 8). Chapter 4.4 contributes to the research question 2 by defining framework for Design Coordination. Activity System Theory in Chapter 4.6 contributes to the research question 2 by indicating the dependency between Technical System and Design Process.

The Activity System Theory in Chapter 4.6 contributes to the research question 3 by indicating learning needs when the Activity System desires to deliver more advanced and complex technical systems. The theory basis in Chapters 4.5 and 4.6 contributes to the research question 3 by indicating the need of aligning the motives of several Activity Systems thus minimising conflicts that consume work effort.

The literature on Management & Goal systems was scarce, and the researcher discussed the matter with several seasoned researchers in this field in the summer of 2008. The researchers concluded that there is a clear lack of literature on the design management. The research on the Design Coordination is very much oriented to IT-systems and tools which do not lie within the scope of this research. The lack of relevant research in this field can be observed in the rather short list of references at the end of this thesis.

5 STATE OF THE ART



This chapter describes the state of the art in relevant literature for this research and concludes how the literature contributes to the research questions.

5.1 Variability and configurable products

5.1.1 R&D paradigms by Victor & Boynton

Victor et al. [Victor et al. 1998] have studied different engineering paradigms. They emphasise the importance of a learning system in the development and introduce a model of development that they call "the right path". The idea of the model is that an organisation creates new knowledge over time. It is possible for the company to reach higher and more demanding levels only by learning. Therefore, they state that it is important for organisations to follow the steps of the model that are illustrated in Figure 20 [Adapted from Victor et al. 1998].

The first step of the model is the level of craftsmanship. Craftworkers utilise their professional skills and expertise with general-purpose tools. Craftsmanship is about applying personal knowledge to create value. This knowledge is described as tacit, personally held knowledge connected with experience, technology, and tools. The knowledge gained from craft-work enables moving forward and reaching the level of mass production.

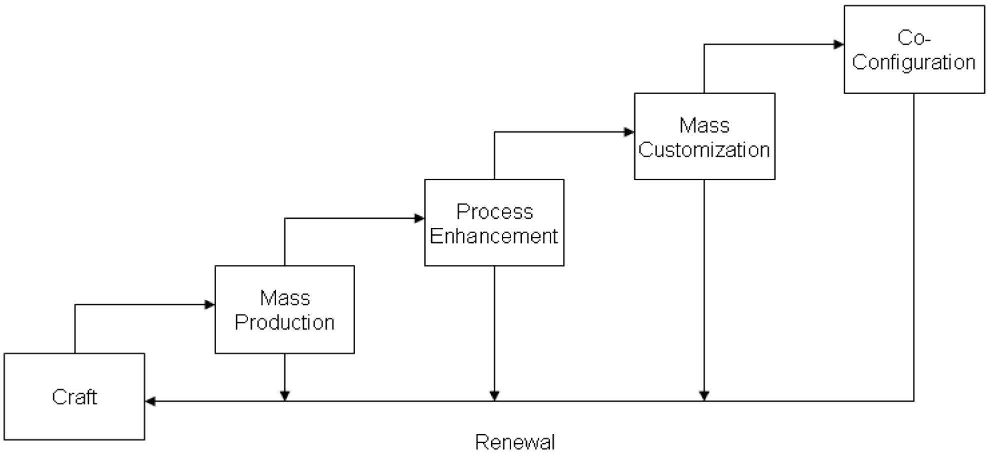


Figure 20. *The potential paths enabled by organisational learning [Adapted from Victor et al. 1998]. Each arrow represents learning needed to move to a different mode.*

It is very important for organisations to understand the leverage of this knowledge. Working with mass production and learning from it enables the making of low-cost products and creates a foundation for process enhancement work. According to the model, it is impossible to enhance processes without making an effort to learn about mass production. Reaching the level of mass customisation requires learning and knowledge from process enhancement.

In this context, processes comprise not only manufacturing but also new product development, supply chain management, administration etc. On this level, the operations of the company are very agile, so the company has the ability to respond to rapidly changing markets. The most sophisticated level of the model is the level of co-configuration. Co-configuration refers to creating products and services that are not only made to order, but also constantly remade and reconfigured. This is a continuous and endless process that requires partnership links between the customer, the company, and the product or service.

The right path is based on learning and utilising the gathered knowledge. Knowledge and learning provide an opportunity for taking the next step in the hierarchy of the model. Renewal means going back to the craft level and seeking new assets via new ideas [Victor et al. 1998].

5.1.2 Configurable products and R&D paradigms

Mass customisation is a way of working that aims at producing products by utilising the benefits of mass production and one-of-a-kind production at the same time. The final product aims at meeting customer needs as perfectly as possible. Variation to product assortment is created by combining pre-defined and pre-designed elements, such as modules. These elements are taken from the company's platform [Soronen 1999].

Configurability as part of mass customisation was studied in the Konsta project. Konsta - Design for Configuration was a research project carried out in cooperation with the Finnish industry and funded by the Finnish Funding Agency for Technology and Innovation (TEKES) during 1997-1999. The objective was to describe how to design configurable products with the benefits of mass customisation. During the research, configuration was positioned as part of mass customisation between mass production and project deliveries.

One possible operational mode when operating in the area of mass customisation is product configuration. The idea of configuration is to deliver products customised according to individual requirements. Nevertheless, all customer requirements cannot be fulfilled without order-specific engineering. The aim of configurable products is to better cover the scope of nearby requirements [Tiihonen et al. 1998; Lehtonen et al. 2003].

5.1.3 Definition of a configurable product

A configurable product refers to a general description of a product from which individual product variants can be formed. Variants of configurable products are created within the limits of a configuration model. A configurable product can be understood as a product family which is based on pre-designed elements such as modules [Tiihonen et al. 1999; Lehtonen et al. 2003].

5.1.4 The goals and benefits of configurable products

Configuration is one instance of a mass customisation paradigm between mass production and one-of-a-kind production. The benefits gained from configurable products thus strongly depend on the corporate approach. The objective is to meet customer needs and maintain profitable business. It is one way to manage customer needs without a customer-specific engineering effort. Configuration contributes to the following goals [Tiihonen et al. 1999]:

1) Managing and satisfying customer needs,
2) Delivery time,
3) Managing cost,
4) Managing product quality,
5) Managing product portfolio, and
6) Brand management.

Configuration is a company-level mode of operation, and the Order-Delivery process lies at the very core of this philosophy. The idea is to separate the Design Process and the Delivery Process with systematic product configuring. The modular Product Structure and the collection of configuration rules and constraints enable a systematic configuring task in the order-delivery process. Configuration is not only an R&D issue, as the sales personnel must also commit themselves to the corporate policy of offered products. This means that promises to customers must remain within the limitations of a configurable product [Tiihonen et al. 1999].

When comparing configurable products to one-of-a-kind products, the main benefits are related to economies of scale and systematised working methods. Re-use of design and product elements ensure a better quality and a shorter lead-time. In addition, the management of operations in production is simplified. The main disadvantage in configurable products, compared to one-of-a-kind products, is that customer needs are not met on the same level. When transforming from one-of-a-kind offering to a configurable offering, the product assortment must be carefully examined. Customer needs must be similar enough. The number of deliveries must also remain on a relatively high level [Tiihonen et al. 1999].

5.1.5 The operational mode with configurable products

The operational mode with configurable products is according Tiihonen [Tiihonen et al. 1996]:

1) Each delivered product individual is adapted to the individual needs of an individual customer.
2) The product has been pre-designed to meet a given range of different customer requirements.
3) Each product individual is specified as a combination of pre-designed components or modules.
4) The product has a pre-designed structure.
5) The sales-delivery process requires only systematic variant design.

These definitions distinguish configurable products from standard products or from one-of-a-kind products. The first point of the definition marks a clear difference from standard products. The difference between one-of-a-kind products and configurable products is easily seen in the context of the last point of the definition.

5.1.6 The framework of product configuration

Dr. Pulkkinen [Pulkkinen et al. 2000] has proposed a framework explaining key issues of configuring task. The framework in Figure 21 consists of Activities of Configuring, Product Structures for Configuring, and IT-support for Configuring.

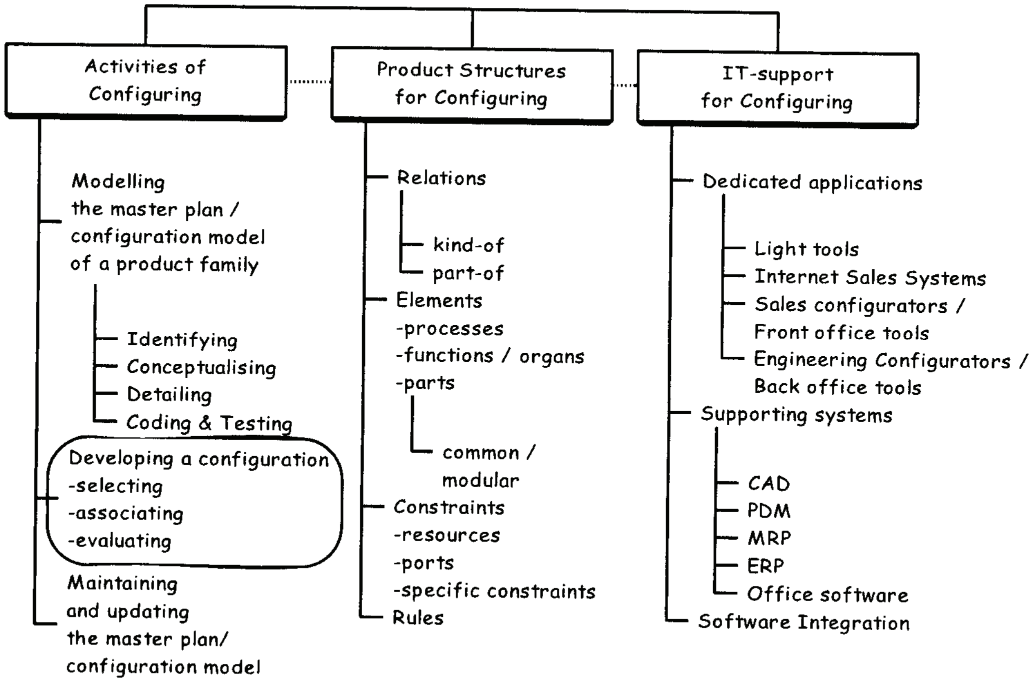


Figure 21. *The framework of product configuration [Pulkkinen 2007, page 89]. One challenge with configurable products is to modelling and updating the configuration model.*

5.1.7 Configuration task

According to [Pulkkinen 2007] a configuration task is defined as a task performed during the order-delivery process when selecting, associating, and evaluating from multiple options to modify the product to meet customer needs. This definition rules out any design work performed in the order-delivery process, and it has been the practice in companies making profit with configurable products. The design was carried out in a separate development process beforehand. A configuration task is not necessarily performed at one time; it can be refined a few times along the order-delivery process, as described in Figure 22.

Customer needs are captured in the sales configuration. The specification of a product instance is used in the engineering configuration task. The detailed description of a product instance is used in assembly and manufacturing. Sometimes, there is also a need for production configuration to specify certain components and their impact on assembly and manufacturing. A state-of-the-art method was to utilise sales configurators that enable a definition of each product individual without deep knowledge of the product or the technologies used. The design rules were captured, analysed, and formulated as rules or constraints for the sales configurator. The salesperson was then able to use the configuration knowledge in a fast, efficient, and reliable product configuration task.

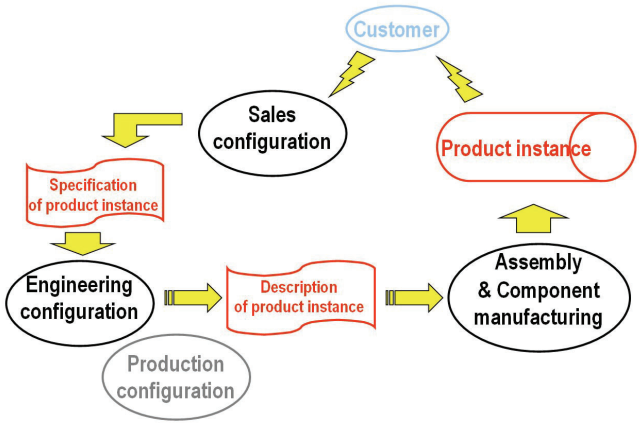


Figure 22. Configuration tasks in an order-delivery process [Lehtonen 2007, page 71.]. The black balloons are tasks and red colour indicates an artefact.

Configuration knowledge can be connected to the understanding between customer requirements and product properties. It is also important to know the relations between the elements in a product, i.e. knowledge about which combinations of elements can be produced, captured in the configuration model. The configuration model is the foundation for configuration tools which are developed to assist in the configuration task. An example of such a tool might be an information system or merely a simple selection form. Software tools that are used to determine configurations are called configurators [Tiihonen et al. 1999]. The role of configurator and the configuration task are illustrated in Figure 23.

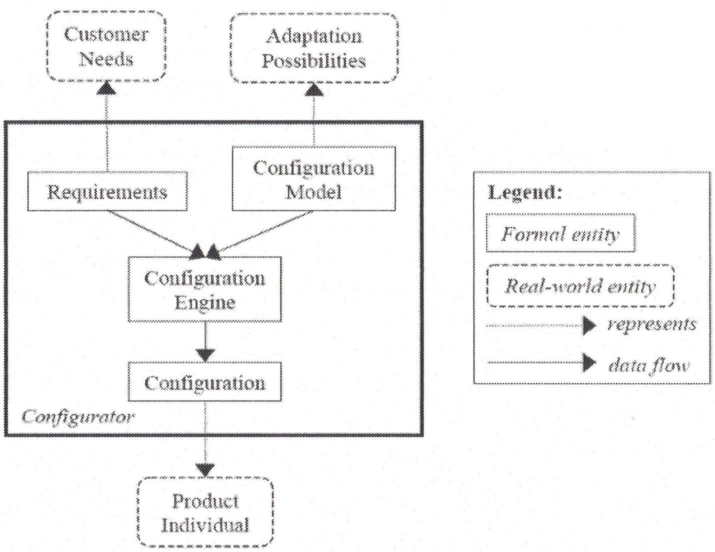


Figure 23. A configuration task with a configurator [Soininen 2000, page 9].

The configuration model by Soininen [Soininen 2000] consists of configuration knowledge, used by configuration engine that matches customer needs and product individual. The configuration knowledge is created during Design Process. The configuration is the set of specifications needed for manufacturing and assembly of the product individual.

5.1.8 Intermediate summary of the state of the art

The following concept map in Figure 24 is a synthesis to provide an overview of the key concepts regarding configurable products, based on Tiihonen [Tiihonen 1999], Pulkkinen [2007], and Lehtonen [2007].

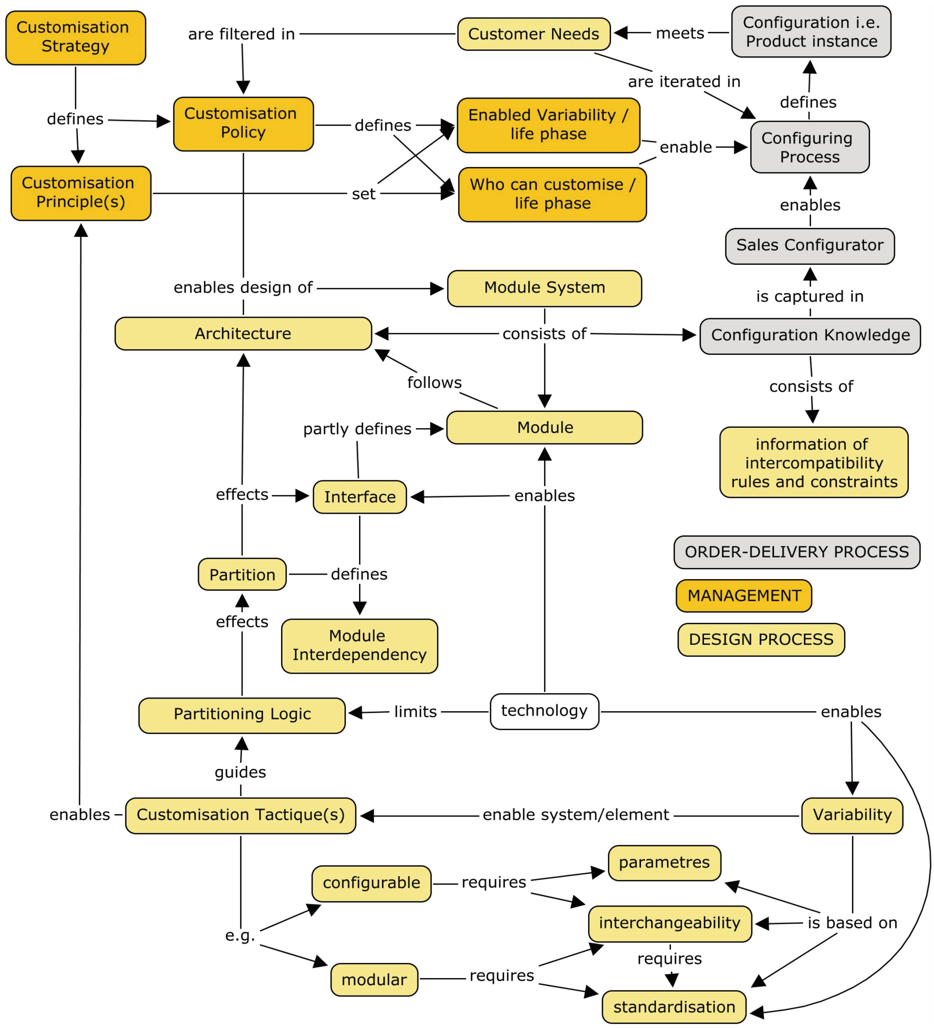


Figure 24. Summary of the configurable product key concepts and their relations. Gray colour indicates items with Order-Delivery process, yellow issues with Design Process, and orange issues with management items.

The grey part and the orange part have been covered already; the yellow part will be covered in the next chapter. The Order-Delivery process is separated on the upper right-hand corner, and the management items are shown in the upper part of the map. The map represents the main relations of key concepts and the colours indicate the classification of the concepts to 1) Management, 2) Order-delivery process, and 3) Design Process related concepts.

5.2 Management elements for configuring

5.2.1 Separation of Design Process and order-delivery process

One essential characteristic of a configurable product is that the Design Process and the order-delivery process of a product are separated. All the design is already performed, and the product is adapted in the order-delivery process. If the product is complex, the configuration rules and constraints need to be available for the salesperson. This information is called Configuration Knowledge [Tiihonen et al. 1999]. Configuration Knowledge is the information that enables the creation of one variant from the module system without engineering design. Hvam et al. [Hvam et al. 2006] has presented a model highlighting the degree of completed specifications in the different modes of operation from the manufacturing viewpoint, as depicted in Figure 25.

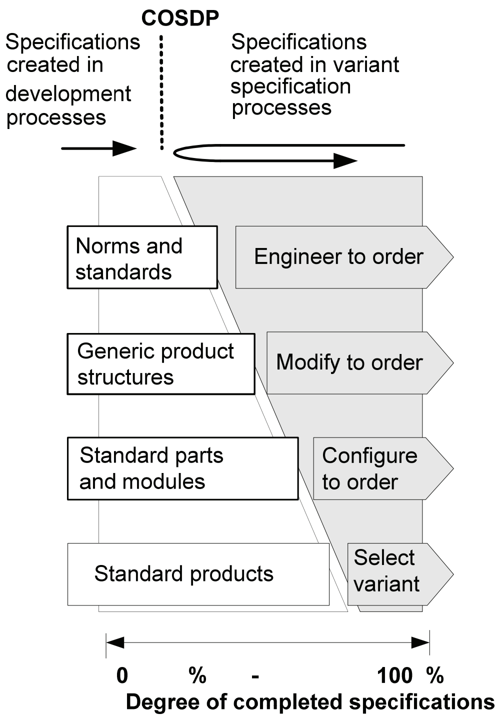


Figure 25. The customer- order specification decoupling point in different modes [Hvam et al. 2006].

In configuration, the degree of completed specifications is quite high in comparison to the modify-to-order or the engineer-to-order operational modes. The customer-order specification decoupling point is indicated with a line between the white and grey areas in each mode [Hvam et al. 2006]. The separation of the Design Process and the order-delivery process is based on design re-use. Duffy et al. [Duffy et al. 1995] have proposed the separation of Design by re-use and Design for re-use, as illustrated in Figure 26.

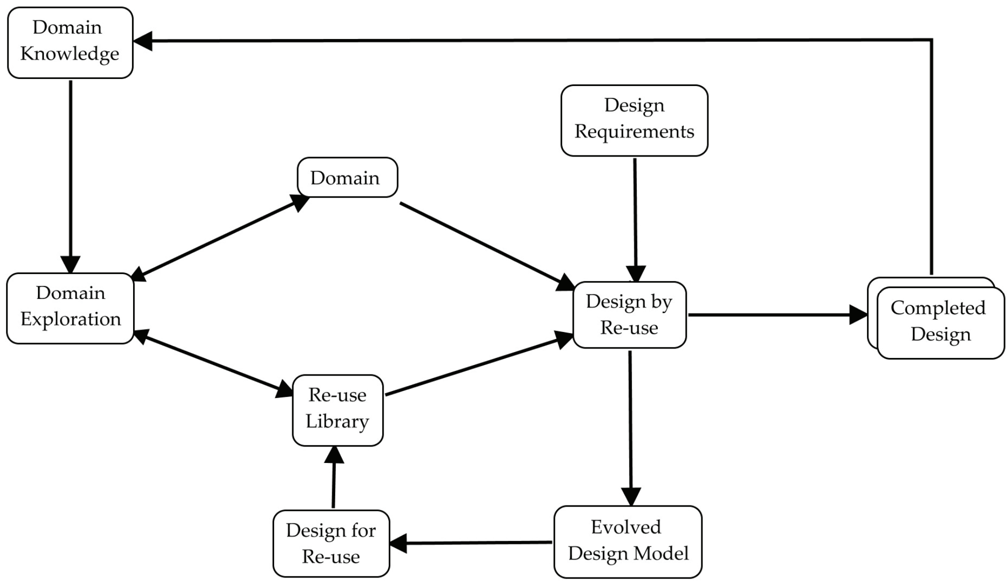


Figure 26. Design reuse framework [Duffy et al. 1995]. Design for re-use and design by re-use are separate design tasks.

This model emphasises the fact that design by re-use and design for re-use are two different design tasks and they need to be separated. The framework is developed to support computer tool development and does not address human aspects, e.g. how the task design by re-use happens in practise. In configuration, the configuration task is based on design by re-use but it is not considered a design task by definition [Tiihonen et al. 1999], thus the human aspects are not considered there.

5.2.2 Product policy and Customisation policy

One important management method with configurable products is the product policy or the customisation policy which defines which product variants the company wishes to provide for the customers and which parts of the variability are available for the customer, as shown in Figure 24. The purpose of the customisation policy is to manage the amount of potential variations and the implications over the entire company. This is particularly important if the company is approaching configuration from the project-delivery viewpoint where the core of the business is to gather customer-specific requirements and to deliver a one-of-a-kind, customer-specific solution.

5.2.3 Elimination of delivery-specific design

Running a profitable business with configurable products is partly based on eliminating delivery- or customer-specific design. It frees capacity in R&D for new product development, but more importantly, it eliminates the creation of one-of-a-kind components and modules. This enables a mass production of components, and as there are no design activities in the order-delivery process, the only possibility to deliver a customer-specific variant is to re-use the existing components.

5.3 Designing configurable products

5.3.1 Standardisation and modularisation

Standardisation is a design tactic needed when a company is shifting to mass production from craftsmanship in its products and manufacturing [Victor et al. 1998]. The objective is to decrease unnecessary or undesirable variation or deviation of a specific property or behaviour in the Technical System. Standardisation is an agreement on the common properties and behaviour of the Technical System or one of its elements. This can take place on many levels, even on the industry level in the form of ISO standards, for example. In the industry and in research, people tend to mix up standardisation and modularisation. Lehtonen states that standardisation enables modularisation [Lehtonen 2007a]. Ulrich argues: "*...we will argue that independence of components is the property of a design that allows standardisation and interchangeability*" [Ulrich et al. 1991]. The interchangeability is one of the design tactics used in modularisation as illustrated in Figure 27.

5.3.2 Modularisation, modularity types, and module drivers

A number of definitions of modularity exist in literature, and the definition of modularity used depends on the particular viewpoint to modularity [Lehtonen et al. 2003]. For example, Pahl et al. [Pahl et al. 1996] distinguish function- based modules and production-based modules. Borowski [Borowski 1961] has presented a special building block system called Baukastensystem. Ulrich et al. [Ulrich et al 1991] have defined modularity as a relative property of a product. Thus, a product can be more or less modular. Modularity is seen as the usage of independent and interchangeable units. This enables the creation of product variants. Modularity is a relational property and depends on the technologies; manufacturing processes used in the product and in the whole network needed to produce fully functional products to the customers.

According to [Ulrich et al. 1991], modularity arises from the way a product is divided into components, and it depends on the two characteristics of design:

1) the similarity between the physical and the functional architecture of the design, and
2) the minimisation of incidental interactions between the physical components.

[Ulrich & Tung 1991, pp. 77-78] divide modular structures into five types, as shown in Figure 27. Component-swapping modularity refers to a situation where alternative types of components are paired with the same basic product. In this case, the aim is to create variants of the same product family. A complementary case is defined as component-sharing modularity. In this case, the same component is used in multiple product families. Components that are varied using cut-to-fit modularity are represented as a parametric modularity. For example, cable assemblies having different lengths with standard connectors can be included in this category. Bus modularity represents a case where components with particular interfaces are connected on a common track. Sectional modularity describes a situation where components are connected together at their interfaces. In this case, there does not appear a particular element for the components to which to be connected.

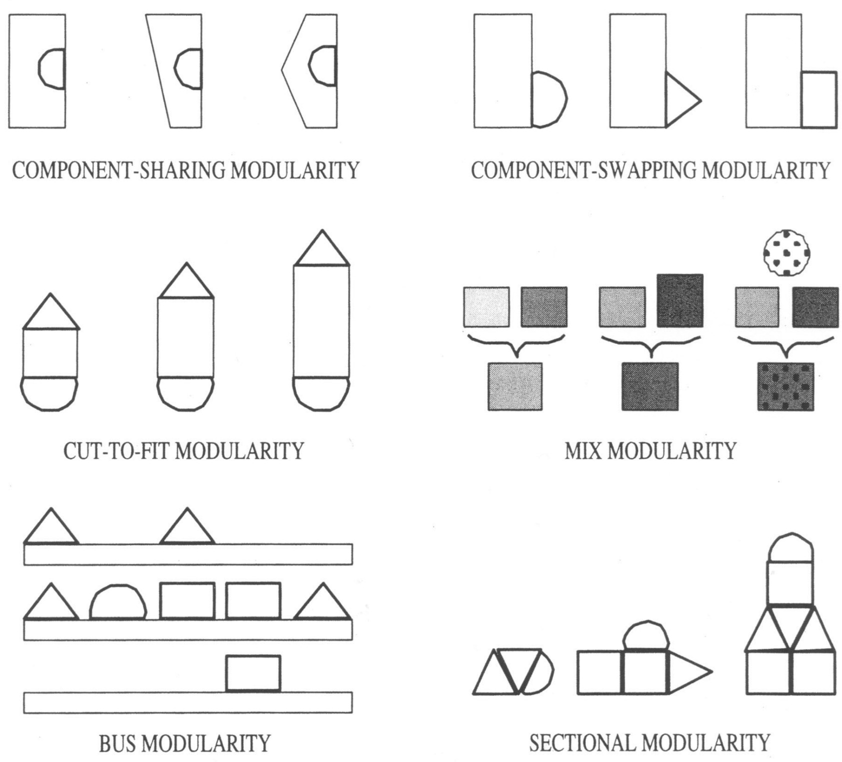


Figure 27. Types of modularity used as design tactics in modularisation [Abernathy &Utterback 1978, according to Pine 1993].

Modularisation is closely linked to mass customisation. One reason for designing modular products is to create variety to the product offering. Design re-use and the division of design work are also considered as benefits of modularisation. However, there exist a number of viewpoints on and definitions of modularity. In general, modularisation can be regarded as a way or a design tactic to structure a product.

Dr. Erixson describes module drivers that are used as design goals when developing modular products [Erixson 1998]. The module drivers are part of a method called Modular Function Deployment that consists of five steps: Clarify customer requirements, Select technical solutions, Generate concepts, Evaluate concepts and Improve each module. The module drivers are used in step three and they are classified based on different organisational functions. The module drivers per organisational function are:

Design and development:

- *Carry over* - creating separate module for coming product generations,

- *Technology push* - creating separate module due to anticipated technological changes, and

- *Planned design changes* - creating separate module to enable changes in the product easily

Variance (Sales):

- *Technical specification* - creating separate module due to changing requirements

- *Styling* - creating separate module due to changing trends and fashion

Production:

- *Common Unit* - creating separate module with same physical form to be used in many/all variants
- *Process/organisation* – creating separate module due to manufacturing process or division of work

Quality:

- *Separate testing* – creating separate module because the functionality can be tested separately

Purchase:

- *Black box engineering* – creating separate module because it can be delivered as a black box

After sales:

- *Service/maintenance* - creating separate module because ease of repair

These module drivers are used in Module indication matrix and they are the key elements in the modular function deployment method. The method leaves room for other, company specific module drivers, also. Erixson does not elaborate why these drivers are chosen and how to choose company specific drivers. Stake [Stake 2000] has studied further the module drivers and describes Module Driver Hierarchy where the module drivers are grouped into two different groups; Product family-oriented drivers and functional encapsulation-oriented drivers.

Martin has focused on the driver "variance" and describes method called Design for Variety consisting of Generational Variety Index and Coupling Index [Martin 1999]. The Generational Variety Index maps how external factors will require changes in the future generations of the product and what is the estimated development cost of the new components. The design team uses the cost to determine what to standardise and modularise. The development cost cannot be considered as the only criteria for standardisation as described by Erixsons module drivers. The Coupling Index indicates the strength of the coupling within the product and how changes propagate to other components. The method enables development of product architecture receptive to future changes and variety but does not take stand on Design Processes.

5.3.3 Module system and modularity

The first known description for a modular system is from Karl-Heinz Borowski [Borowski 1961]. He states that a building block system should be called Baukastensystem only if it consists of standardised elements that can be joined together by obeying the planned rules. He defines 9 different cases as types of Baukastensystem.

Borowski defines the baukastensystem as follows: it consists of elements (Baustein) of various size ranges (Rangstufe) within selected solution level (Auflösungsgrad). "An element is as undivided entity within the system", which refers to the fact that it has a continuous interface in a physical or other sense. In addition, "only an element that belongs to a system with configurations ought to qualify for a constructional element" [translated from Borowski 1961]. In context of modularity, the Baukastensystem has a few important properties. Combinations are created by using pre-defined, standardised elements with defined interface. Also non-modules are accepted and the combinations of non-modules and modules.

Lehtonen et al. [Lehtonen et al. 2003a] have defined a module by two criteria and this definition is also known as m-modularity. According to this definition, a part or subassembly is a module when:

1) It has a defined interface, which determines its connection to other modules, and
2) It is a member of a set of parts or subassemblies that forms a module system.

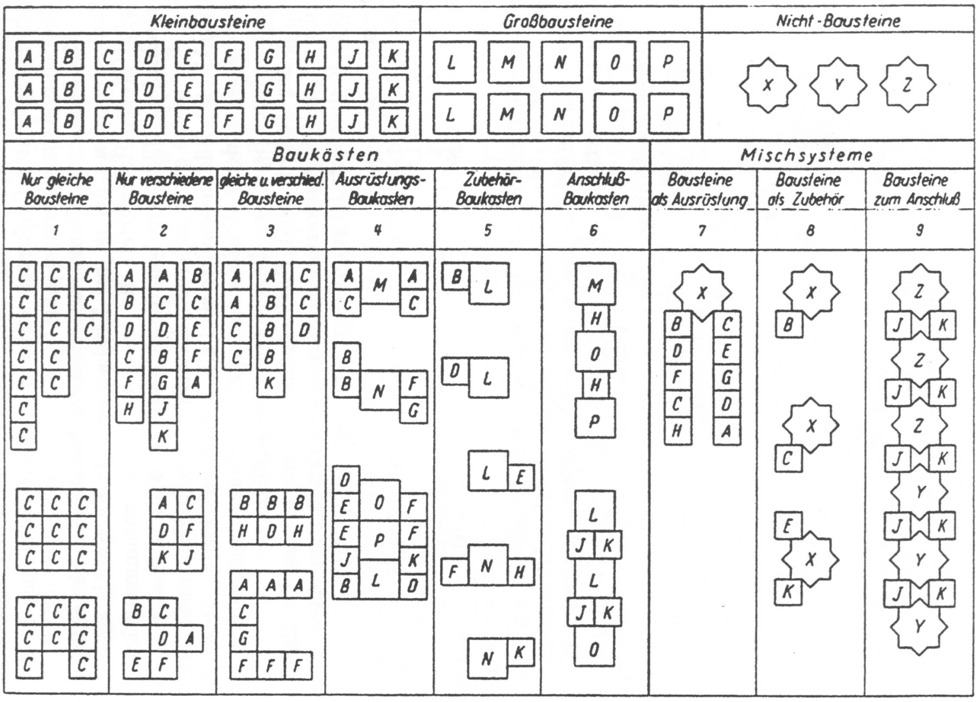


Figure 28. Meta models for building block systems [Borowski 1961].

According to Lehtonen et al. [Lehtonen et al. 2003a] a system can be considered to be module system, if at least one of the five types of modularity (see Figure 27) defined by Ulrich & Tung [Ulrich et al. 1991] exists. A module system enables interchangeability of modules i.e. one module can be replaced by another module with different properties. Another possibility is to use the same module in various products.

5.3.4 The Design Processes and methods for a module system

There are many proposals for Design Processes [Andreasen et al. 1987] [Hubka 1996] [Pahl et al. 1996] [Pugh 1990] [Stevens et al. 1998] [Ulrich et al. 2000] [VDI 2004]. Most of them do not pay much attention to variability or commonality as the design goal as they focus on the development of a single product, not a product family. A number of companies are manufacturing variable products, but the design processes are described in internal documents only and they are not disclosed to the public. A model shared in public is by Lehtonen [Lehtonen 2007a], proposing a Design Process for developing new modular product or product family, as shown in Figure 29.

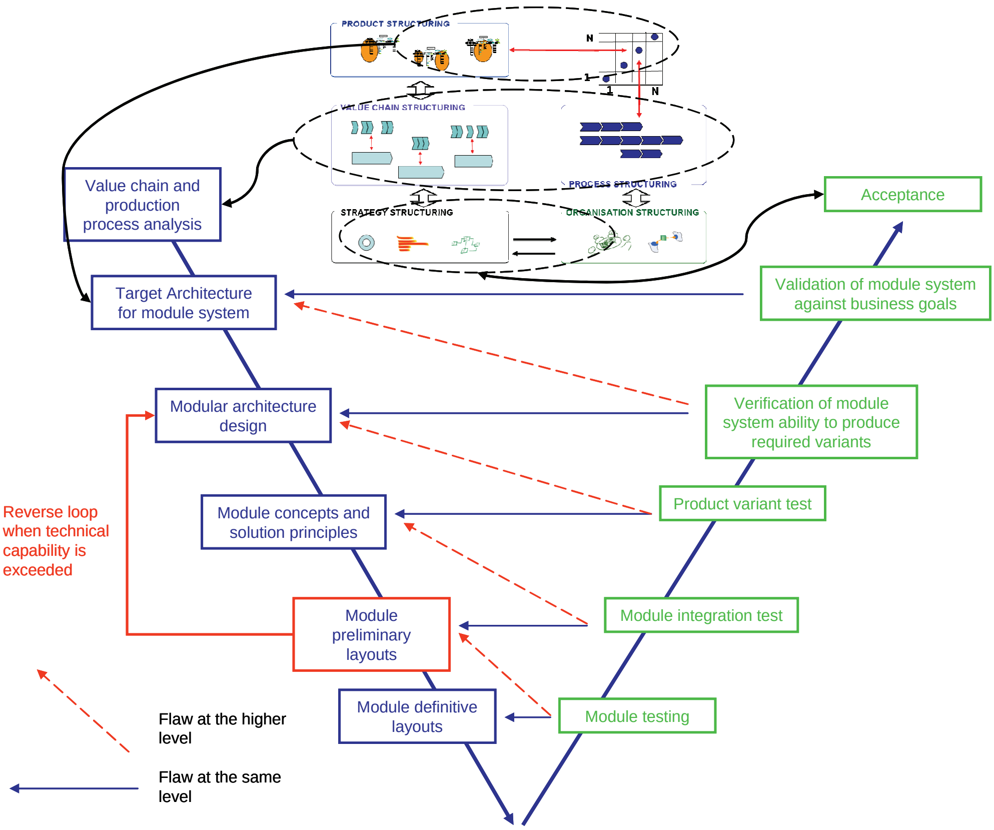


Figure 29. A design process model for new modular product. The model implies that designing target architecture for the module system takes place after the value chain analysis is done [Lehtonen 2007, page 172].

The phases of the process follow the V-model [Mooz et al. 2003] of Systems Engineering [Stevens et al. 1998] [VDI 2004]. The underlying idea is to start the Design Process from value chain analysis and at the end of the process to validate the module system against business goals. This method is especially targeted for cases where the development starts from scratch, i.e. actual products do not yet exist.

Another model is from Kohlhase and Birkhofer [Kohlhase et al. 1996]: it proposes a design of modular system using computer-aided optimisation methods. Here, the idea is to develop a modular system according to this process. The variant products are then developed with a product focus, i.e. in a product-oriented manner following a systematic Design Process [VDI 2004].

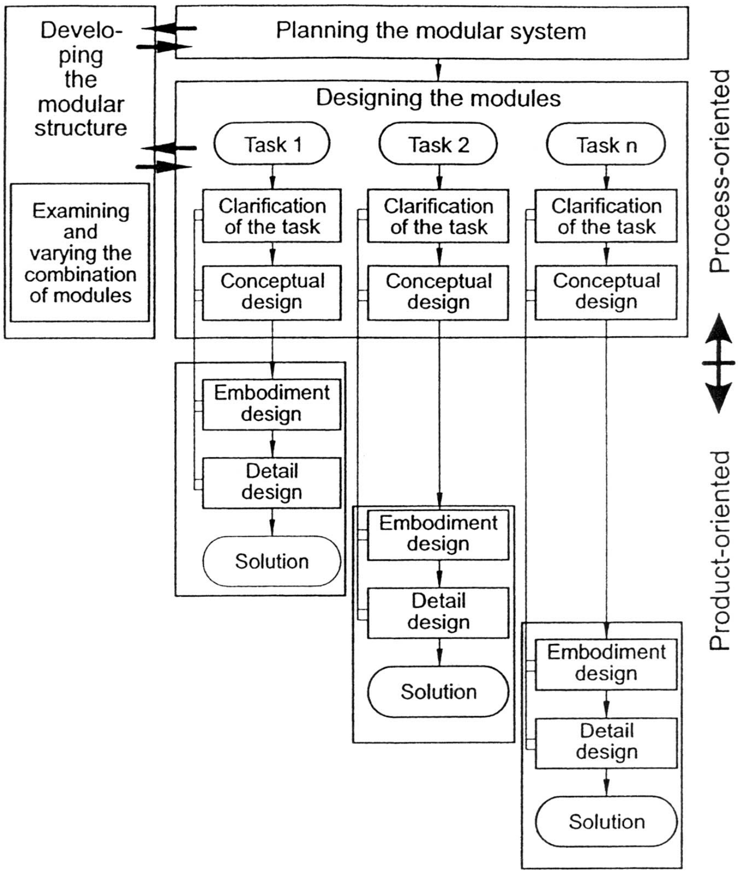


Figure 30. The development process for a modular system [Kohlhase et al. 1996].

This model operates on rather a high level and does not offer practical support for developing the modular structure, but emphasises the clarification of the design task.

5.4 Classification of Product Structures

The observations in previous studies give grounds to assume that there are different types or classes of structural elements. Based on that premise Juuti et al. [Juuti et al. 2006] describes four different Product Structure types:

1. A One-of-a-kind Product Structure has one goal: a unique synthesis that meets the needs. It is designed for a particular solution, and the objective is to achieve a technical system that meets the needs. This type can contain unique parts and standardised parts.

2. A Standard Product Structure has two goals: mass production and product synthesis. The goals for standardisation can be re-use within one product, re-use across products within the company, or re-use in multiple industries and value chains. The standardisation consists of three different design goals:

1) Re-use within one product,
2) Re-use across products within the company, and
3) Re-use in multiple industries and value chains.

The standard PS type contains standardised parts.

3. A Configurable Product Structure is a product structure with three goals:

1) Variability in such a manner that no engineering design is needed in the order-delivery process,
2) Commonality by re-use, and
3) Product synthesis.

It consists of standard parts and configurable parts. Variability is achieved via configurations: re-using a particular combination of standard parts, modular parts, and/or module system parts.

4. A Partly-Configurable Product Structure has three goals:

1) Product level synthesis,
2) Commonality by re-use, and
3) Variability by configuration or modularisation.

The goal for the product synthesis can be on the product level or the element level which can be a separate product itself. It may contain standard parts, configurable parts, one-of-a-kind parts, and partly-configurable parts. It is a combination of the other product structures defined above. This is aligned with the findings of Pulkkinen [Pulkkinen 2007].

5.5 Commonality, Platforms, and Re-usable Asset

Asset thinking is a state-of-the-art method in companies and it guides the focus on any elements that could provide competitive advantage when maintained and re-used on purpose. Several concepts, such as platform and product family, are based on the re-use aspect. Asset is not a universal virtue, as it depends on the business logic and strategies of each company. Asset thinking comprises the management and maintenance of the asset, i.e. the life-cycle aspect, and if the life-cycle of the asset is not managed properly it will turn into a liability which when used will result in poor competitiveness and profitability [Juuti et al. 2004].

Comment: A good example of asset thinking is Nokia; in the late 1990s, there was little asset (re-usable components), but during 2000-2008 Nokia gained considerable profit and added value from asset developed in the early 2000s. Some of the competitors had a similar strategy but they were slower in accumulating the asset. It is critical also to manage the speed of asset accumulation and not only to accumulate a "right" asset.

In literature there are many definitions in which platforms are representation of commonality and kinship. Kristjansson et al. [Kristjansson et al. 2004] have studied this problem and found various definitions for platform. The summary of the definitions is presented in Table 1. The definition of platform implies what is considered as an asset for the company, see e.g. Meyer & Lehnerd row 1 in Table 1 [Meyer et al. 1997].

Table 1. Summary table on definitions on "platform" [Kristjansson et al. 2004].

		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]												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		X
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		

Platforms are often associated with modularisation. There exists a variety of definitions for the term platform in the context of product development. It is essential to highlight the meaning of the term 'platform' in a certain context. Kristjansson et al. [Kristjansson et al. 2004] define a platform as *"collection of core assets that are re-used to achieve a competitive advantage."* The relevance to this research is that re-use is the common denominator in all these definitions and that is why this research focuses on re-use of assets rather than on platforms.

Designing a product with commonality and variability requires company-level measures [Andreasen et al. 2001] to harvest the benefits. An example of distributed effort with a platform mode of operations is illustrated in Figure 31 [Andreasen et al. 2001].

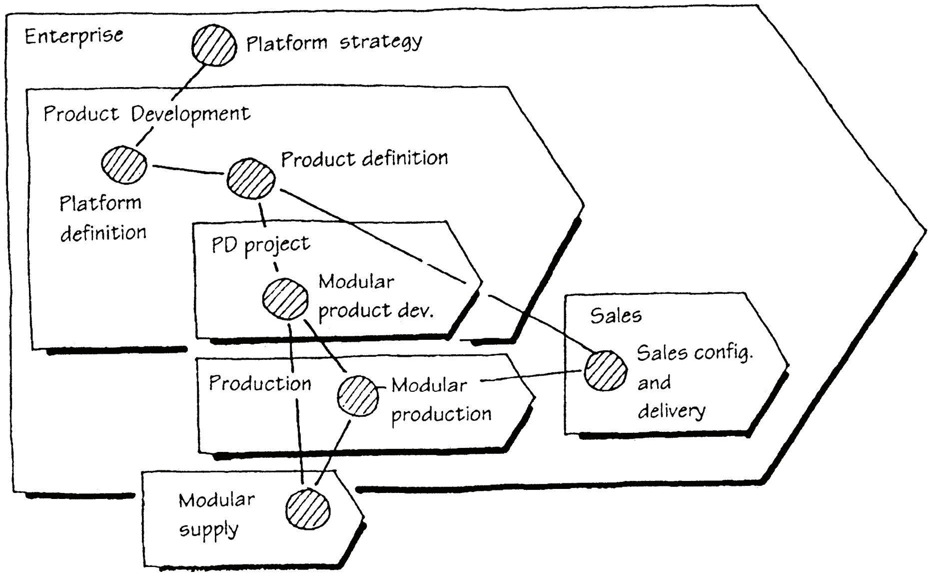


Figure 31. The distribution of platform efforts throughout the enterprise [Andreasen et al. 2001].

In this example, the efforts with platforms are distributed to enterprise-level strategy work, in product development to platform definition, product definition, and in a product development project that needs design by re-use and design for re-use in a modular product development. The production, sales, and suppliers are also involved in order to have success with the selected operational mode.

5.6 Operational modes

5.6.1 Operational modes and product structure

The platform mode of operations is a result of evolution in the company network. Andreasen et al. have described the evolutionary development steps [Andreasen et al. 2001] as follows: the first step has little or no modularisation, and relatively independent products with no co-ordinating modularisation are developed over time, as described in Figure 32.

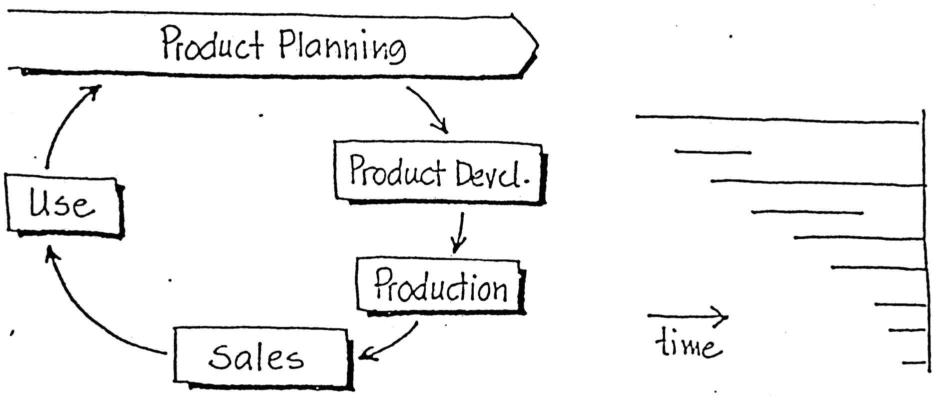


Figure 32. Independent development of products [Andreasen et al. 2001].

The second step is a situation depicted in Figure 33 where product families exist and they are market-oriented. Each family may be defined as a systems definition or architecture of the family. Each family requires additional, high-level planning and definition effort.

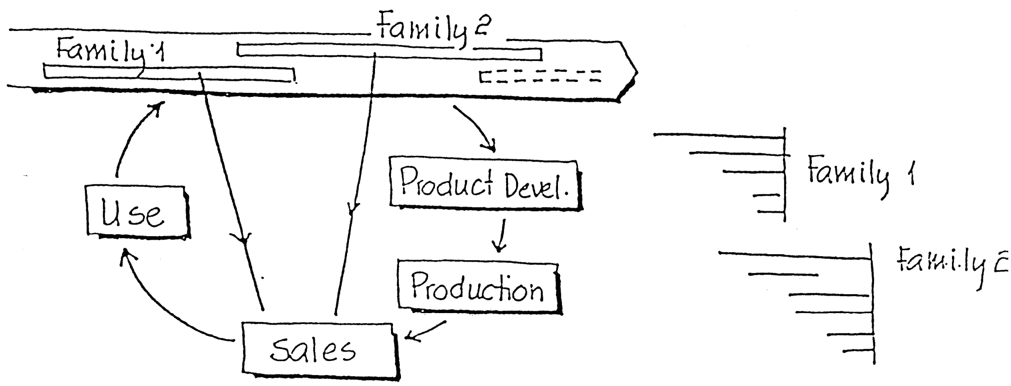


Figure 33. *Product Families as a marketing strategy [Andreasen et al. 2001].*

The next step involves an architectural definition of the product family to determine the pattern of production and supply, where all sold products are created as a set of modules. The database contains production, sales, and product-life-related knowledge about the products. Coherent patterns of activities are emerging in the functional areas of the company; as illustrated in Figure 34.

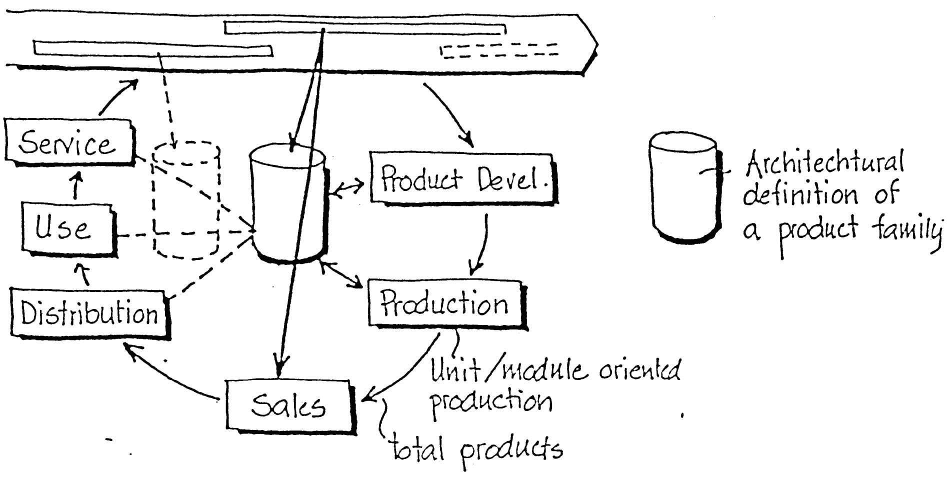


Figure 34. Architecture- related manufacturing [Andreasen et al. 2001].

The fourth step is related to a platform definition of the company's assets in the form of product technology, knowledge, and mastered skills, articulated in coherent architectures. All company functions plus supply have introduced a pattern based on the modular structure of the products or the knowledge. The configurator or knowledge base contains insight about all product and business aspects, available for all company functions, as shown in Figure 35.

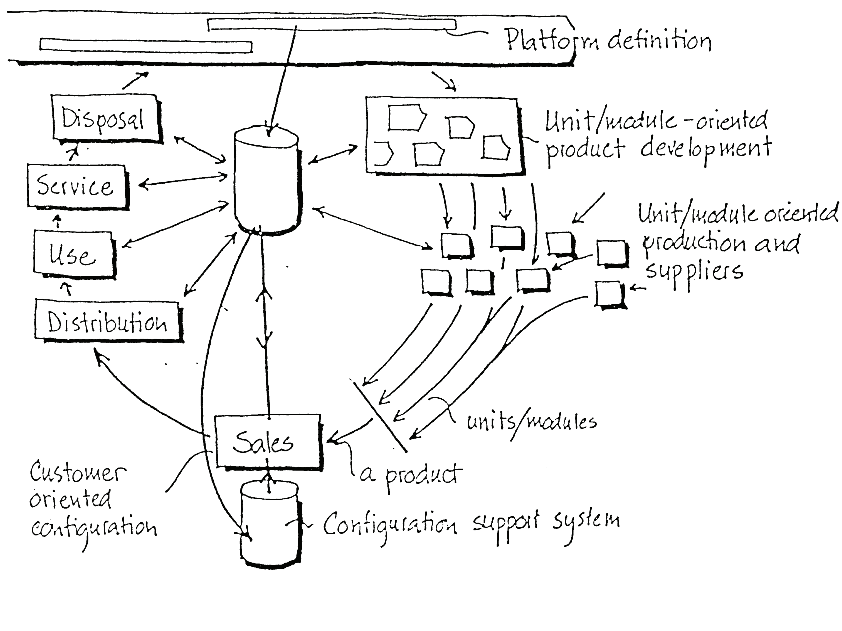


Figure 35. Platform-oriented manufacturing or Mass-customisation [Andreasen et al. 2001].

In the fifth step, as presented in Figure 36, the platform is dynamically and continuously updated and based on dynamic knowledge management operations. In this step, the suppliers become developers and manufacturers of modules, based on their expertise, so that new industrial patterns emerge. This is called Dynamic Modularisation described further by Lehtonen et al. [Lehtonen et al. 2003].

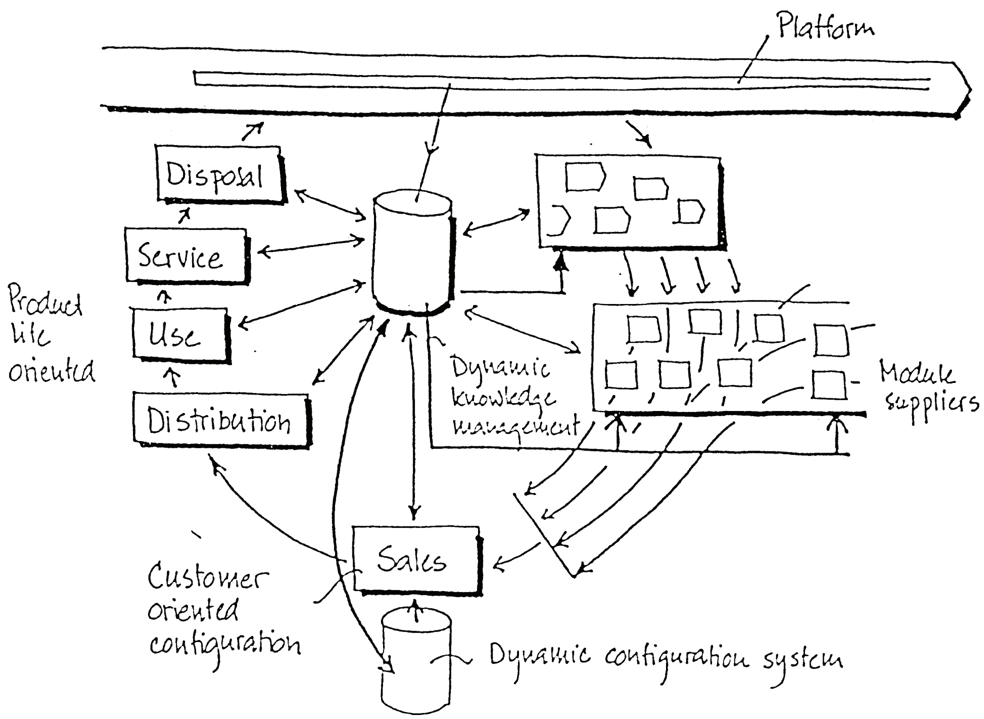


Figure 36. Dynamic Modularisation [Andreasen et al. 2001].

These models illustrate the role of product structure in a company-wide context and different operational models serving the value creation and business models.

5.6.2 Operational modes for developing new products

Several companies have chosen to have multiple ways to develop new products [Harlou 2006]. An example of this is Philips Consumer Electronics. They have classified product projects [Harlou et al. 2003] into peak products, optimised products, and platform-based products.

"Peak" products

- Products that include technology, which is still not mature enough to be included in a platform. These products are developed independently in order to not "damage" the platforms.

Optimised products

- Price competition is very hard on some markets, and in these cases products are often cost optimised independently of the platforms.

Platform-based products

- Products that are based on a platform, where one or more subsystems are reused across product families.

Figure 37. Classification of product development projects. The idea is to emphasise that all products are not and should not be platform-based [Harlou et al. 2003].

The idea is to separate platform development from product development, which is like separating the development process from the order-delivery process due to the difference of their nature. The separation can be performed for the following reasons:

1) To enable sufficient flexibility in product development; if they need to use standard elements only, the products will resemble each other. Flexibility also allows an optimal solution for one product only.
2) To develop products independently in order not to damage the platforms.

The challenge for companies is to manage several operational modes and communicate to the employees on how the company works in each case. One tool used for this purpose is process architecture.

5.6.3 Operational modes and process architecture

Process architecture describes the main processes used in the company and their relations with each other and possible combinations of sub processes if used in a more advanced manner. Harlou presents two process architectures; one is from B&O [Harlou 2006] and the other is from Philips [Harlou et al. 2003] [Harlou 2006]. In Figure 38, the three separate development processes at B&O are visualised:

1) Assortment/ family architecture development,
2) Standard design development, and
3) Product development.

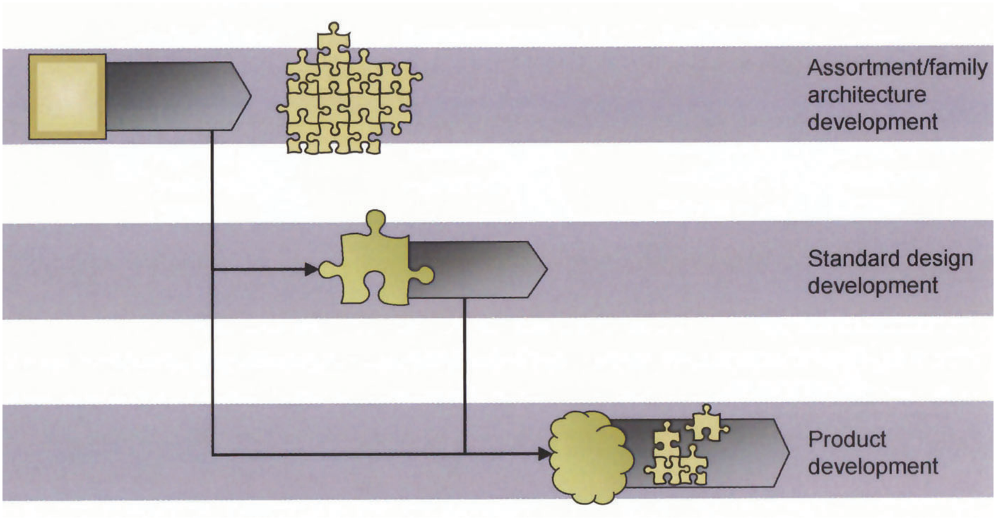


Figure 38. Three bands of development processes [Harlou 2006, page 136].

Each of the processes has its own design goals and success criteria set by the management. The first process is used in developing a family architecture; based on the results, standard design development is performed by using the corresponding process, as well as product development. The results of each process are presented in Figure 39.

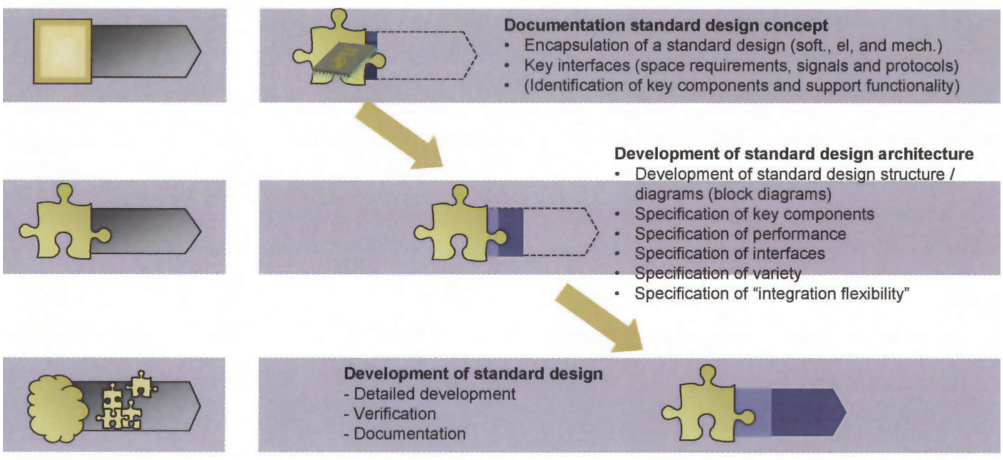


Figure 39. The gradual creation of standard designs [Harlou 2006, page 137].

In standard design development process the architecture for the standard design is specified and the actual detailed development and verification takes place in product development process. The Philips has managed to define process architecture enabling separate technology and platform development, as shown in Figure 40 [Harlou 2006].

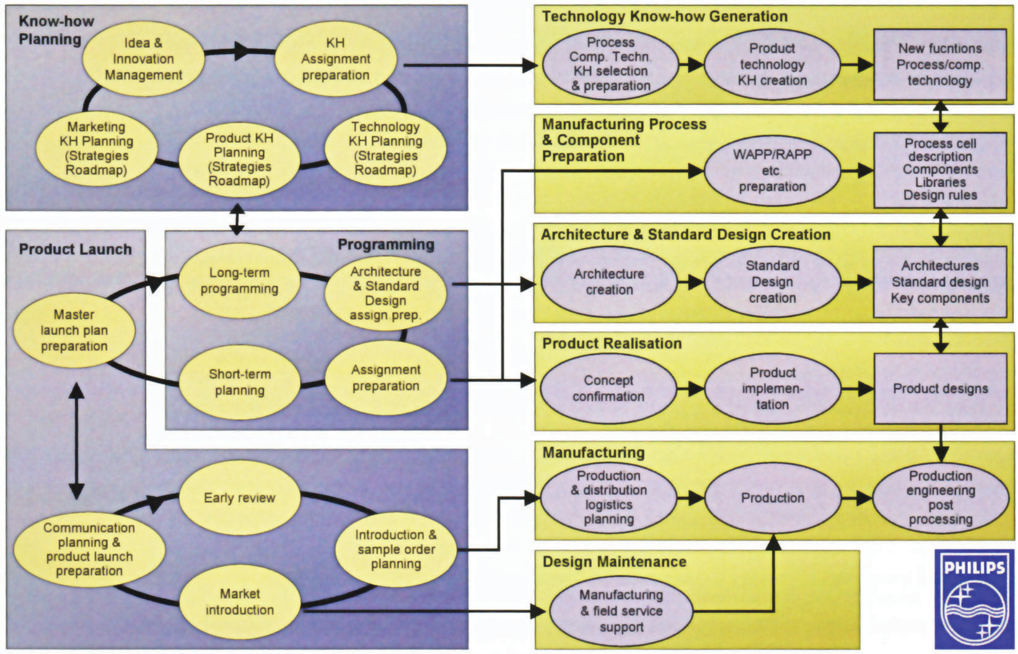


Figure 40. The Philips process architecture [Harlou 2006, page 47].

The activities on the left-hand side of the architecture are related to planning, while the activities on the right deal with development and realisation. Product development is carried out by a product realisation process, whereas architecture and standard design creation are implemented by using another process in the map.

5.6.4 Operational modes and organisation

Harlou reports that organisational changes at Philips were carried out according to the process architecture: *"Philips also changed their R&D organising accordingly. That is from being divided according to product type, e.g. Audio, Vision, Phones to being in divided according to project type, e.g. technology, platform, and product projects"* [Harlou et al. 2003].

A similar change took place at Bang & Olufsen: they changed the development organisation three times during the transformation [Harlou 2006]. The organisational change also demonstrates the changes in the roles and responsibilities within the development organisation. Platform projects are run so that the standard design is not available until the platform project has finished its work. *"The technology development is kept separate from the development of architectures and standard designs, as well as from the product projects"* [Harlou et al. 2003].

Contribution to the research questions

The Chapters 5.1, 5.3 and 5.4 contribute to the research question 1 by describing standardisation, modularity, and configurable product structures. The state of the art in Chapter 5.3 contributes to the research question 2 by describing Design Process needed for certain TS characteristics. The state of the art in Chapter 5.3 contributes to the research question 2 by describing Design Processes. The Chapter 5.6 contributes to the research question 2 by defining deliveries of the development of standard design architecture shown in Figure 39. The state of the art in Chapter 5.3 contributes to the research question 3 by describing design for re-use and design by re-use as a separate items to be managed. The Chapter 5.6 contributes to the research question by describing Design Management using multiple operational modes.

5.7 Research scoping based on the theories and state of the art

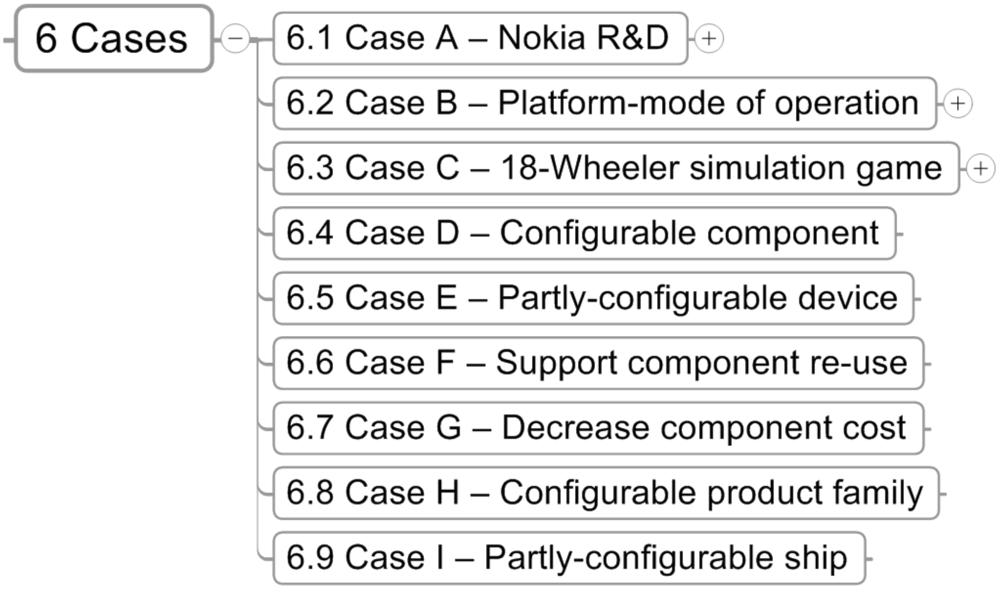
In this research the Technical System is a physical product consisting of electronics, mechanics, pneumatics, hydraulics, and software. The focus lies in the Design Management as part of the "Designing" Transformation system described by Hubka et al. [Hubka et al. 1988] in Chapter 4.1 and the part domain of Domain Theory described in Chapter 4.2).

The Design Process is a composition of product structuring activities carried out in an operative context. The operative context exposes us to the everyday work in an R&D organisation, i.e. to the world of deadlines, negotiations, and continuous reframing of the technical issue, for example. The detail level of design tasks is not in the scope of this research, and therefore the product models as such as well as the computer tools used for modelling fall outside the scope as well. This research will not provide a method applicable to partition any product architecture to meet the company needs as it is only one design task of the design process having many company specific optimisation criteria that are not generic to all companies.

This research deals with physical components and parts of a mechatronic product as well as the design processes and the management tasks. In summary, the scope of this research is:

1) characteristics of Technical System (TS) having effect on variability, commonality and product synthesis,
2) characteristics of Design Process (DP) having effect on Technical System characteristics as result of Design Process,
3) the dependency from TS to DP and vice versa,
4) the dependency of TS and design goals,
5) the management of design processes, and
6) the management tasks needed to improve R&D efficiency.

6 CASES



This chapter presents the data from different case studies. The data is captured by using the elements of Activity System (see Chapter 4.6). The Case B elaborates the platform mode of operations to provide for the reader an understanding on the different motives of Activity Systems, resulting in conflicts between Activity Systems within the operational mode. Then the data and data capture of the rest of Nokia cases are presented. The last case, Case I is from large R&D also and the same data capturing methods are used as in Nokia cases. At the end of this chapter conclusions are drawn on how the cases contribute to the research questions.

6.1 Case A – Nokia R&D

Case Nokia is described here from an external viewpoint into the Nokia R&D. The purpose is to define the organisation and the practices of the Nokia R&D for outsiders with no earlier knowledge of the platform mode of operation.

Nokia is a company specialising in communication technology. In the area of mobile devices, Nokia is the largest manufacturer in the world. At the end of 2007 Nokia had approximately 112 262 employees world-wide. Net sales of Nokia was 51 058 million Euros in 2007 [Nokia 2008a]. The researcher has analysed the material and has crafted an information package relevant to this research into this thesis.

6.1.1 The way of working

The main mode of operation in R&D is platform-based product development where external suppliers provide components that are re-used by Nokia in several products, thus yielding cost and standardisation benefits with economies of scale. Other modes of operation are spearhead products and ODM/OEM where the mobile device is developed and manufactured by suppliers and delivered similarly to a Nokia brand. Spearhead projects are rare and they do not follow the same rules and the same division of labour as platform-based product programs.

The Nokia R&D activities are divided into three sections from the design object/Technical System's point of view:

1) the development of components,
2) the development of platforms, and
3) the development of products and services.

The division of labour and power regulates all R&D activities. Components are mainly developed for re-use across multiple products, but in some cases, a component is developed for one product only. Platforms consist of components and they are re-used across multiple products. It happens very seldom that a platform is developed for a single product. The development of services and that of products are separate activities from component and platform development. Occasionally, a re-usable component is developed by the product program, but the product synthesis is optimised for the first product, not across multiple products. This is due to the time pressure and the primary motive of obtaining a product synthesis for the product, the secondary motive being commonality.

6.1.2 Motive(s)

The motive for the whole R&D is to create "beautiful products that change people's lives" [Öistämö 2008]. The Nokia-level motive is further decomposed into objectives so that each organisation and sub-organisation has goals derived, interpreted, and agreed upon from higher-level objectives. The motive for component development organisations is to *develop re-usable components enabling economies of scale*. The motive for platform organisation is to develop modular and configurable platforms for the various product families, while the motive for product and service creation is to *develop competitive products for particular customer segment* or segments. The segments are illustrated in Figure 41.

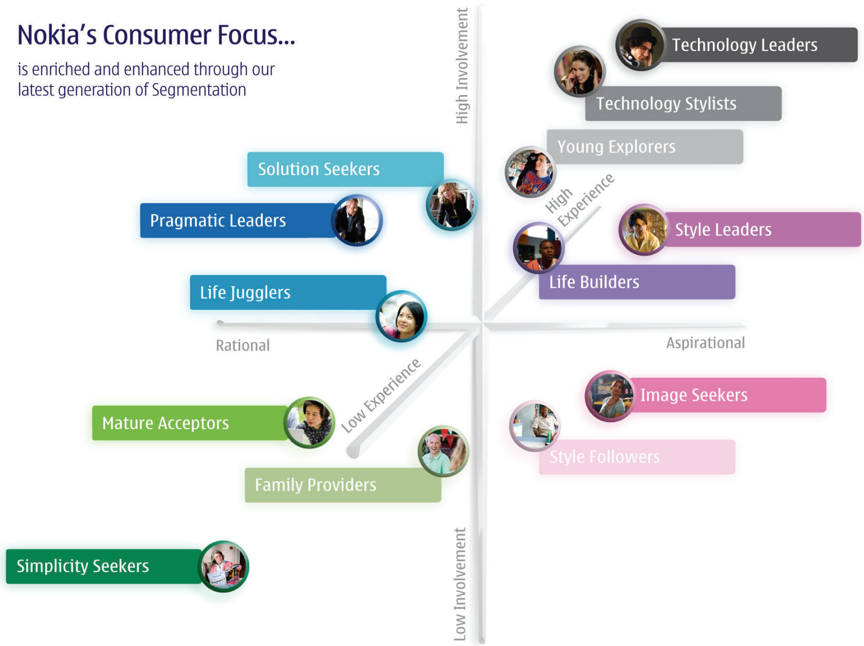


Figure 41. A consumer segmentation map. The design goals are derived from the preferences of particular consumer segment [Nokia 2008d].

6.1.3 Object

The design object comprises mobile device, software applications, and services [Nokia 2008b]. The broad scope of the design object is depicted in Figure 42.

Figure 42. A mobile device, software, and services as design objects. The solutions are systems of systems where mobile device, cellular network, internet, and content from service providers operate together [Nokia 2008b].

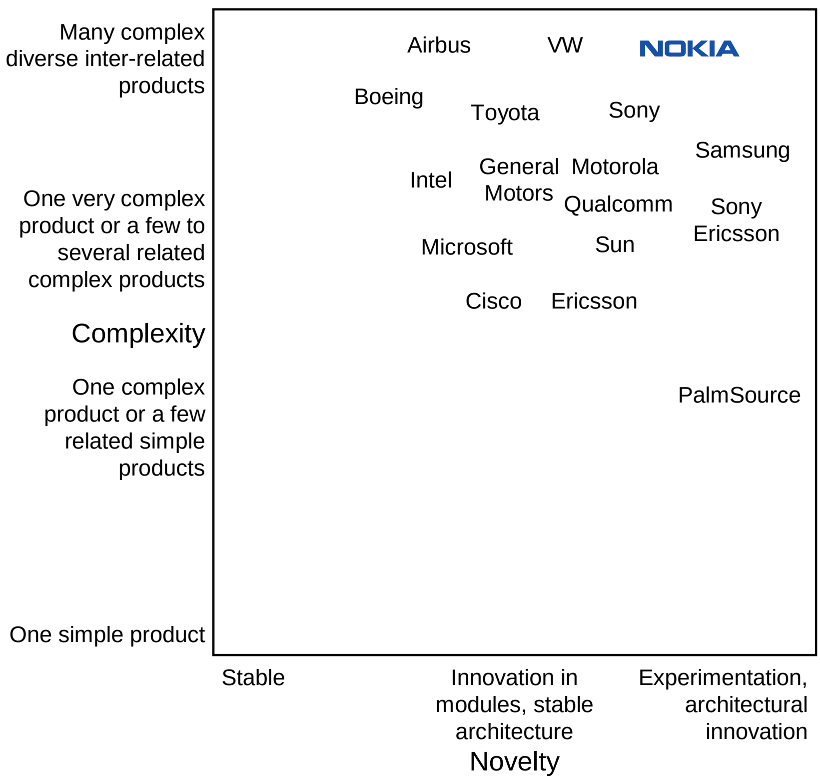


Figure 43. Comparison of the Nokia´s R&D context to other R&D´s. The complexity and inter-relation between products is a result of platform-based product development [Davis 2004].

The mobile device comprises electronics, software, and mechanics, and is further elaborated in Cases from D to H. The enabled services are e.g. music download, navigation with maps, sales configurator for salesperson etc. The services are not elaborated further as they do not fall within the scope of this research.

An outsider, consultant view on the Nokia R&D was: *"Over the last few years, Nokia's product creation has evolved so that it is now one of the largest and most complex, while also facing major rapid change."* [Davis 2004] His analysis of Nokia R&D via products developed is presented in Figure 43.

The Nokia R&D is placed on the upper right-hand corner, as it is based on architectural innovations and has a number of complex, diverse inter-related products. The complexity is a result of evolution. In 2000, a new organisation was formed with an emphasis on platforms. At that point, component re-use had already been performed for several years and the supply chain was capable of handling over 80 million devices per year. This enabled benefits from economies of scale, such as lower component prices and an improved negotiation power with the suppliers. At the same time, the business groups had several thousands of engineers with an orientation and motives in business and the product program.

6.1.4 Division of labour and power

Nokia consists of four Business Groups (BGs) [Nokia 2006a].

1) Mobile Phones (MP)
2) Multimedia (M)
3) Enterprise Solutions (ES)
4) Networks (NET)

and two Horizontal Groups (HGs)

1) Customer and Market Operations (CMO) including Sales & Marketing, Operations & Logistics incl. Customer Care, and Sourcing & Procurement for devices
2) Technology Platforms (TP) including Series 60 Platform, Symbian Product Platforms, Wireless Platforms, Product Technologies, and Product Process Services

R&D takes place both in Technology Platforms and in the Business Groups. Technology Platforms focuses on components and platforms, while the Business Groups focus on integrating products, services, or combinations of both. The matrix organisation is illustrated in Figure 44.

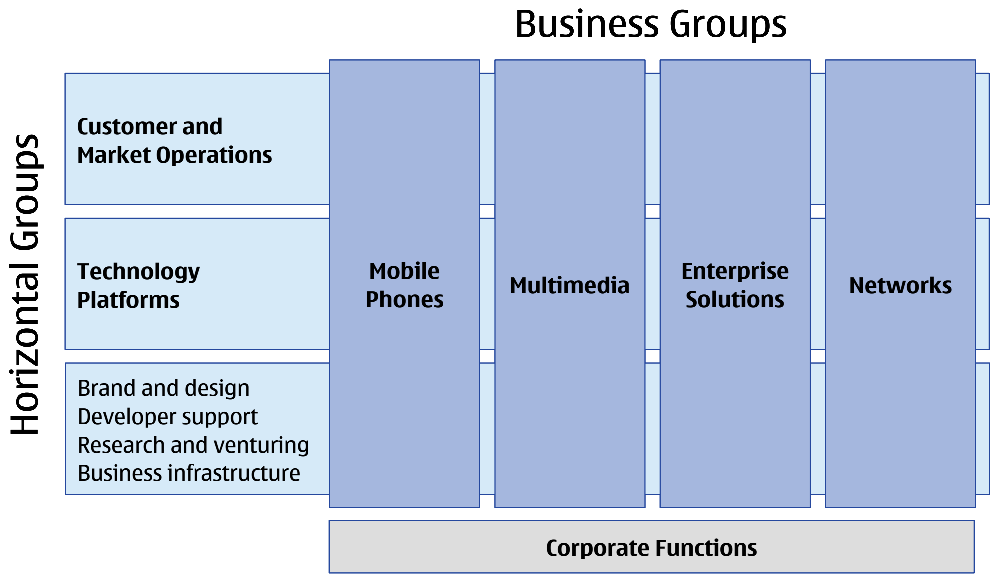
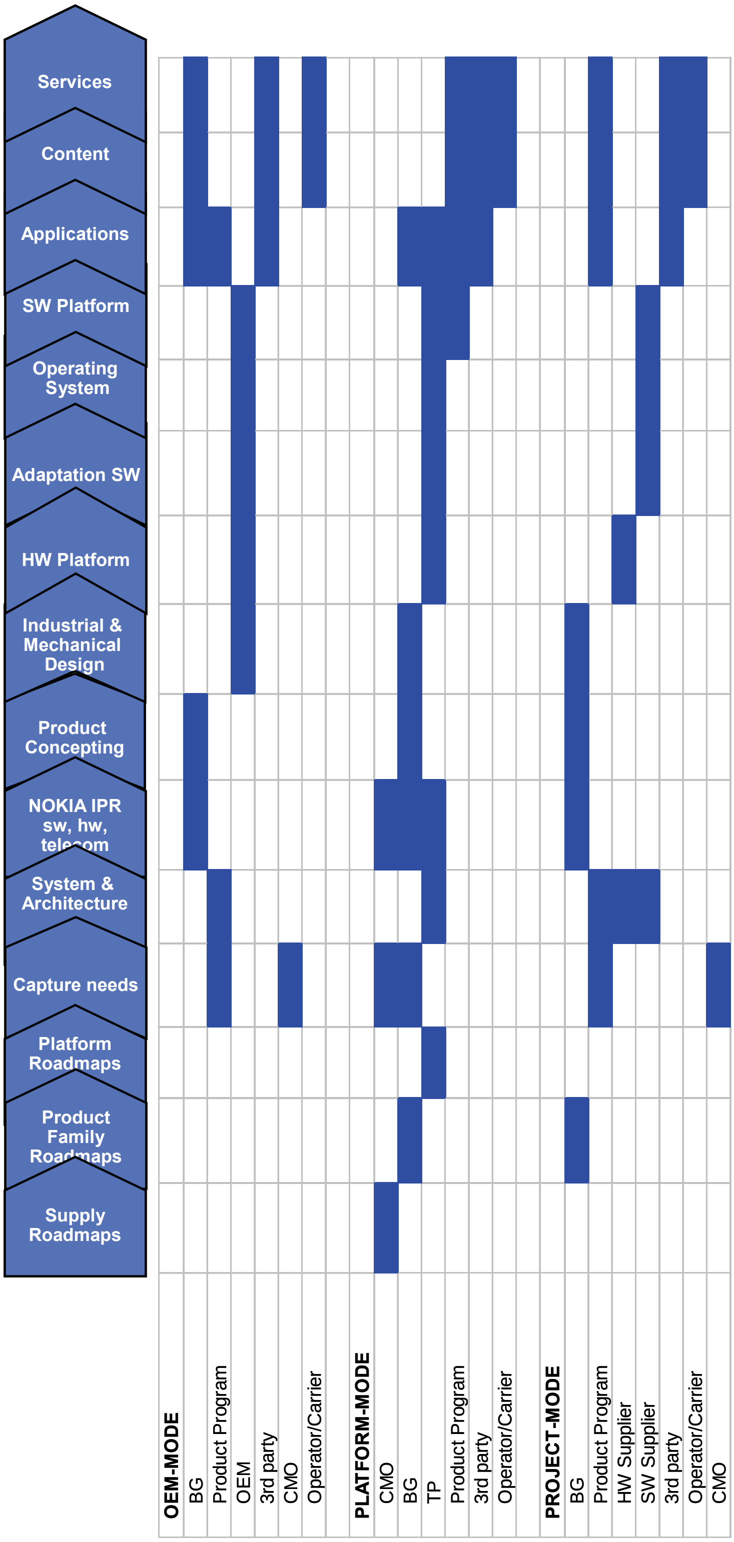


Figure 44. The Nokia matrix organisation as of 1 August, 2006 [Nokia 2006a].

The division of labour is defined in greater detail by listing value-adding activities in the value chain and marking which organisation does which activity. The operating modes and the division of labour are summarised in Table 2.

The product program has three main modes of operation and some room for modification in each of those modes. The division of labour depends on the mode in which new products are created in each case. The road mapping of suppliers, technologies, architectures, and product families are value-adding activities in the platform-mode of operation, as shown in Table 2

Table 2. Division of labour in different operational modes [Juuti 2008].



6.1.5 Rules

"Horizontal units drive and manage selected Nokia's strategic assets based on the corporate-wide and business strategies. Our business groups (BGs) have profit and loss responsibility and are therefore ultimately responsible for all business decisions impacting their profitability. Our horizontal groups (HGs) support the businesses, according to pre-agreed guidelines and cost levels, providing knowledge and expertise, as well as proactively proposing new solutions to fit business group needs and developing new business opportunities"[Nokia 2006a].

In a platform mode of operations, one guiding principle is that product programs re-use elements designed by platforms and do not change them. Another guiding principle is that re-usable elements are developed by the platform organisation, not by the product programs.

6.1.6 Instruments

The main instrument in Nokia is process architecture. It comprises the delivery process, the product creation process, and the customer engagement process [Nokia 2004a]. The process architecture describes the R&D processes used in Nokia, as illustrated in Figure 45.

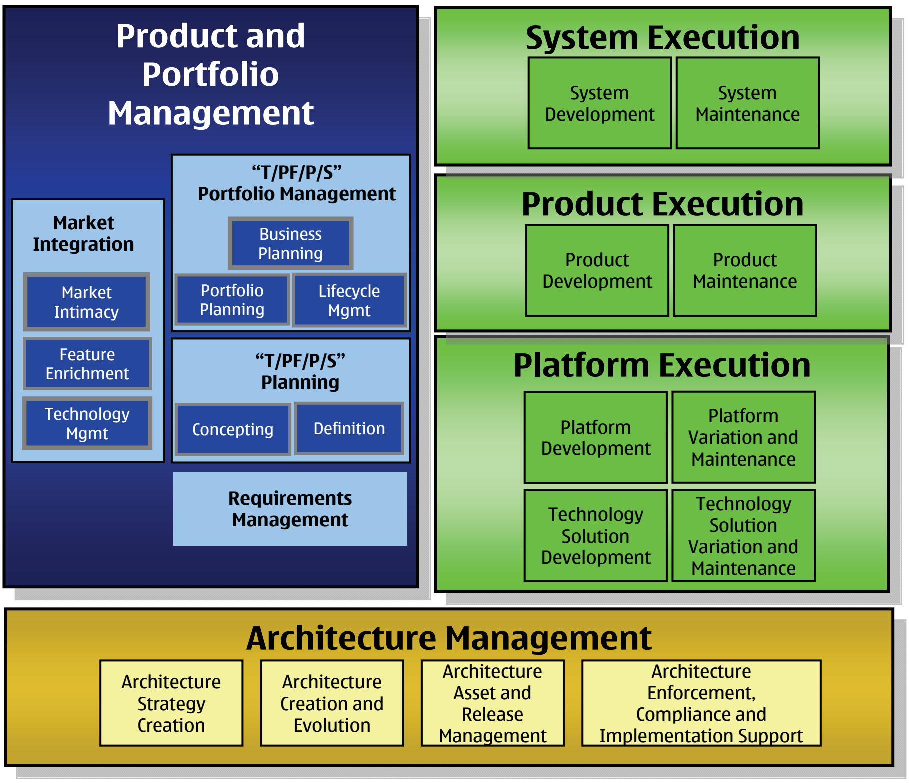


Figure 45. Product creation process architecture. The process architecture enables Design Process adaptation meeting the design goals and the type of product structure [Nokia 2004a].

The product creation process architecture has four main elements: portfolio management, architecture management, platform creation, and product creation. Portfolio management consists of Market Integration process, Portfolio management process, Planning process, and Requirements management process. Architecture management comprises Architecture strategy creation, Architecture creation and evolution, Architecture asset and release management, Architecture Enforcement, and Compliance and Implementation support. Platform execution consists of Platform development, Platform variation and maintenance, technology solution development, and Technology solution variation and maintenance. Product execution consists of product development and product maintenance. System execution consists of System development and system maintenance.

The Nokia process model which is used in all R&D projects consists of inputs, outputs, process phases, and milestones. In Nokia, a milestone is accepted if the design meets a list of pre-determined criteria defined by the management. If the milestone is rejected more design work is needed to fulfil the milestone criteria or, occasionally, the management is taking risks by accepting the milestone.

The instruments, division of labour and rules described in this Case are valid for the other Nokia Cases also, because the other Cases are sub-cases to this company-wide Case.

6.2 Case B – Platform-mode of operation

In 2001-2003, extra effort was put in Nokia R&D to increase the awareness and understanding of component re-use and modularity, known as the platform mode within Nokia. The effort comprises revised product creation process architecture, process descriptions, process trainings, and self-study material. The overall objective was formulated as "a stream of products and services [that] can be effectively developed and produced", adapted from Meyer & Lehnerd [Meyer et al. 1997]. The researcher has analysed the material and has crafted an information package relevant to this research into this thesis. The researcher has run several training sessions of the platform thinking and processes in Nokia R&D during 2001-2003.

Key elements in the mode were identified as shown in Figure 46:

1) Managing platforms with processes and a clear focus on what the platform is and what it is not,
2) Systems engineering for complex technical systems with architecture and well-defined and managed interfaces,
3) Modularity with components and enabling step-by-step evolution, and
4) Design re-use with a two-fold nature, design for re-use and design by re-use.

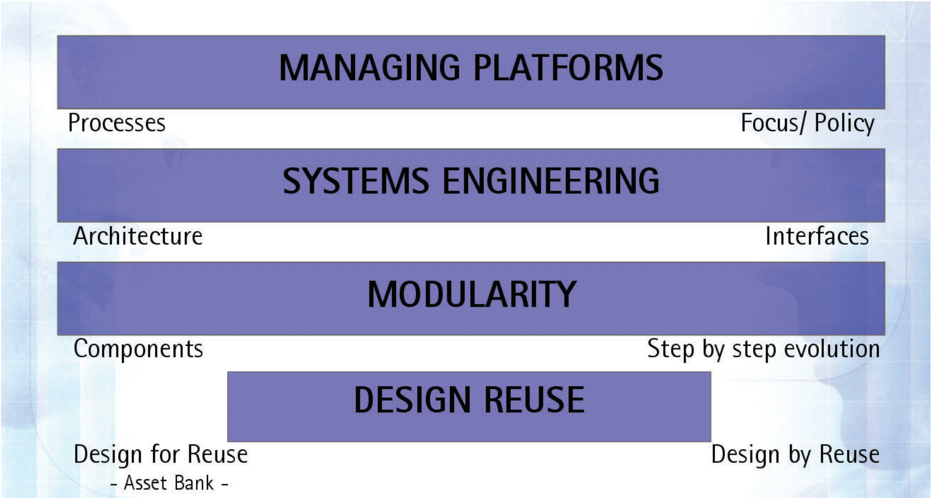


Figure 46. The objective and key elements in platform operations. The platform is based on Design re-use and managing is needed to determine the focus of the platform i.e. what belong to the platform and what is product specific design [Nokia 2003b].

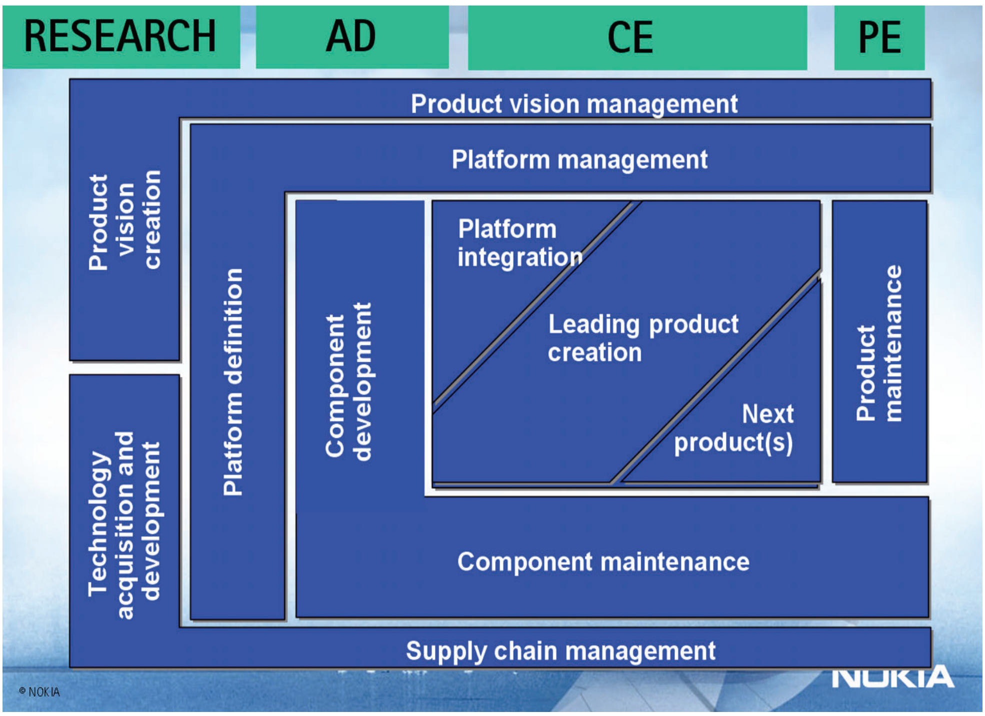


Figure 47. The older and newer product creation process architectures. The old process architecture does not recognise platforms as the new architecture describes only platform mode of operations [Nokia 2003b].

6.2.1 Product creation process architecture

The process architecture was heavily changed when transformed into platform-based product development. The old architecture (indicated in green in Figure 47) had only separate processes for research, advanced development (AD), concurrent engineering (CE), and product engineering (PE). Re-usable components were developed with the AD process and mobile devices with the CE process [Nokia 2003b], see Figure 47.

The new architecture (indicated in blue in Figure 47) had more processes and more thought through the roles and responsibilities between the processes. Platform definition, component development, and platform integration were separate processes and the life-cycle aspect was introduced to product vision, platforms, components, and the supply chain as a new issue to be managed. This was an attempt to implement a renewed division of labour between the technology platform and the product development organisations, and the critical role of design re-use. During the change, a number of tasks were removed from the CE process according to the new division of labour which changed the object of designing.

6.2.2 Process descriptions and Way of Working

The objectives of the new way of working were elaborated during the process trainings. The way of working was elaborated, for example, with the "delivery flow" starting from business needs and resulting in a device on market, as described in Figure 48.

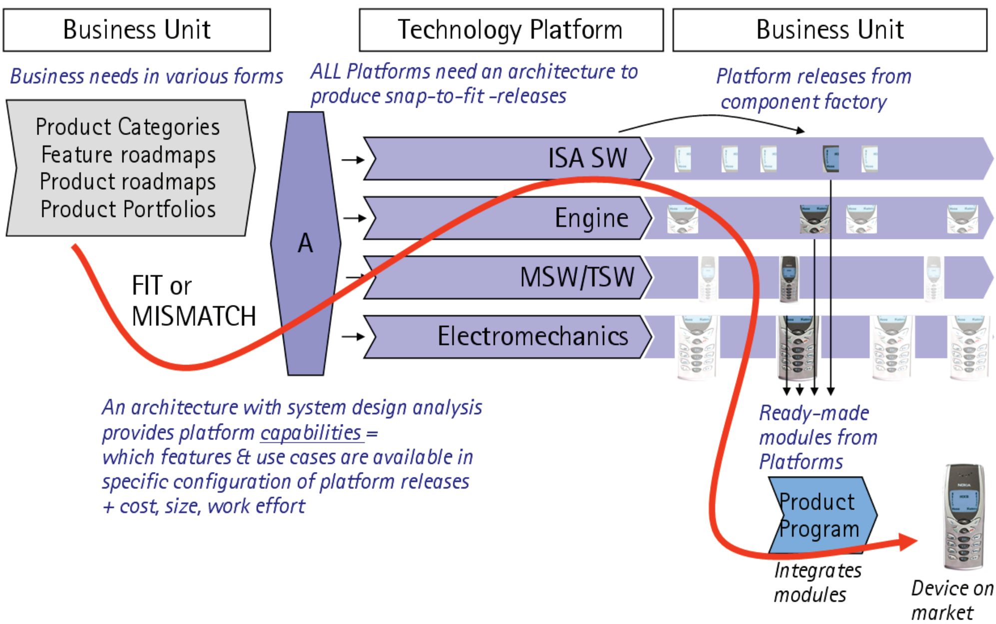


Figure 48. Platform-Based product creation operational mode. The development begins with Business needs capture, continues with architecture definition, and component development and ends to the product development program that integrates the product [Nokia 2004b].

The development starts from the various business needs and the assessment of the enabling technologies. As a result, the architecture (A) of the product family is specified. The architecture drives the development of subsystems, i.e. platforms (e.g. ISA SW). In this case, platforms are mainly mass-customised technical systems that enable e.g. configuration. Platforms consist of components which are developed separately, some in component factories that are entirely focused on the properties and the behaviour of particular components. The components are integrated to platform releases intended for product use. The product program uses concurrent engineering (CE) to integrate and verify the mobile device before launching it on the market.

6.2.3 Process trainings

Process trainings were held as part of the implementation of the "Blue Picture" (Figure 47). Learning was enhanced by developing two different simulation games; the team challenge in TP PRO was "How to design a platform?" while the other game, 18-Wheeler, focused on the challenge "How to re-use asset in a product development program?" The training as a simulation game was developed to highlight the tangible challenges in a platform mode of operations. The simulation was based on the Nokia operational mode and on the division of labour [Nokia 2004b]. 18-Wheeler is further described in Chapter 6.3. The properties of the simulation game are described in Table 3 [Nokia 2008e].

Table 3. Comparison of simulation games [Nokia 2008e].

Simulation	TP PRO	18-WHEELER
FOCUS::	*How to design a platform?*	*How to reuse asset in PD?*
Learning point 1	Platform capabilities	Business case optimization
Learning point 2	Architecture & interfaces	Continous planning
Learning point 3	Integration plan	Integration plan
Learning point 4	Communication	Communication
Learning point 5	Creative tension	Change management
Team size (persons)	10-30	8-16
Facilitators needed	1-2	1-2
Duration	7 hours	7 hours
CUSTOMER	Project people, line management	Project, line
solution type	lego	lego

In the end of the simulation, there was time reserved for discussion and reflecting upon the key findings. The participants shared their experiences in the discussion and told what the biggest challenges were during the simulation and how they managed to solve the issues. The facilitators also encouraged the participants to consider the biggest challenges in their work and what they can apply based on the issues learned during the simulation.

6.2.4 Self-study material – PCP Coach and introduction material

Self-study material was also created for people who had otherwise no opportunity to attend process training. The setting in the PCP Coach resembled a James Bond plot: the Blue Picture is stolen and Mr Smith needs to recover it. Process architecture was used as the layout of the city and each process element is hidden in a building. Mr Smith has to search through every building and collect the blue picture piece by piece by answering questions for each process. A picture from the PCP Coach is shown in Figure 49.

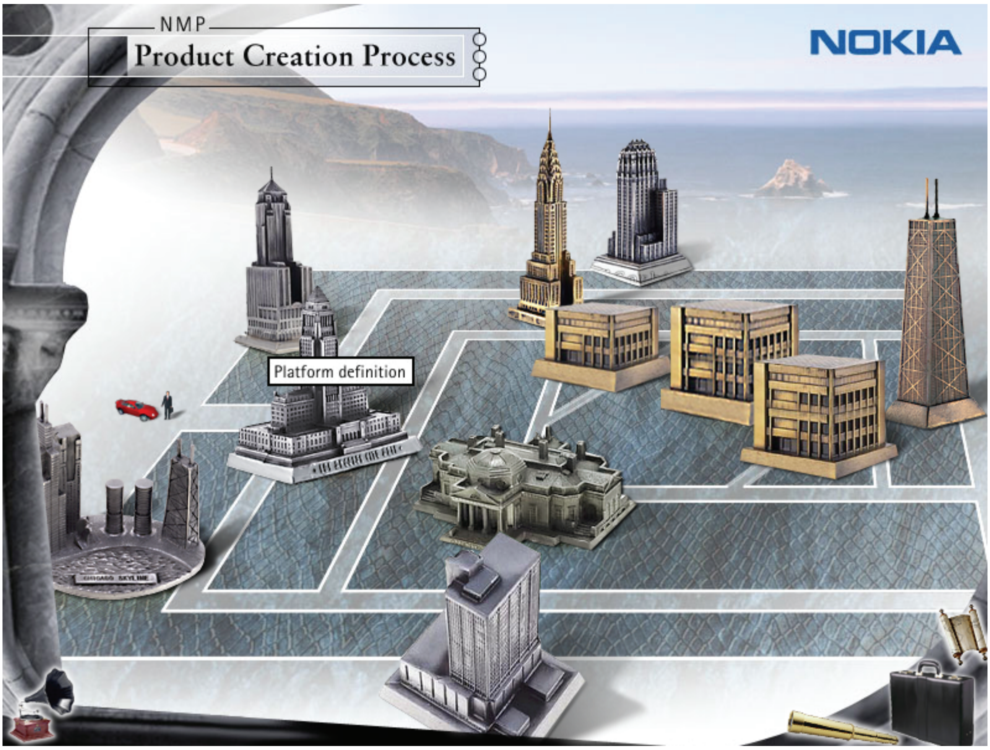


Figure 49. Mr Smith is entering the town to recover the pieces of process architecture. Every building contains one process module. The figure is a screenshot from PCP Coach [Nokia 2004c].

The self-study material also included terminology, process descriptions, and a questionnaire to ensure the learning of the key points. Process descriptions were defined for Platform Definition, Component Development and Maintenance, Platform Management, and Platform Integration. The lead product and the next products had a revised version of the CE process. The process flow of technology and the platform process are visualised in Figure 50 [Nokia 2004 c].

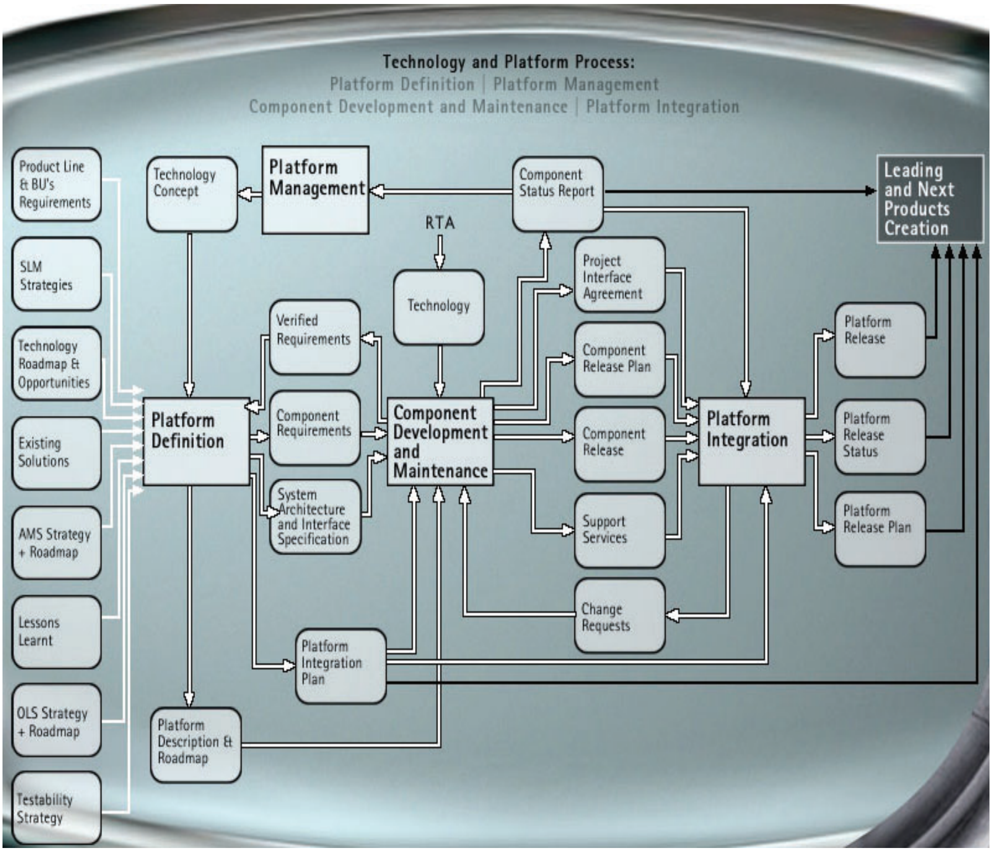


Figure 50. *The process flow of technology and platform process. Screenshot from PCP Coach [Nokia 2004c].*

The process flow mainly takes place by cascading from left to right, and quite a number of feedback loops are visualised. The platform definition and the component development processes are iterative in nature; thus a strict one-way flow was considered idealistic, not feasible, and hard-to-implement by the operative management.

The change was also extended to also covering the induction material for newcomers in the company, as well as the training material for both seasoned engineers and newcomers. Figure 51 is an example of how design re-use was described for newcomers.

Figure 51. A sample of the introduction material for newcomers to a platform organisation [Nokia 2005].

This is a summary of platform-based product development; the goals, the division of work, the design object, and the instruments used as part of the transformation process. After the reorganisation during the change, separate process descriptions were prepared for platform definition, and component development and the old CE process were modified to fit the new division of labour. The re-organisation was performed according to the type of design object described in Chapter 6.1.1. In this case, there is a dependency between the Technical System and the Design Process because the organisation uses a certain process developed for the particular design object.

In Chapter 6.2, a mode of operation was presented that is based on design re-use. During the re-organisation, the role and the motive of each organisation was clarified, and component or platform developing organisations now create design for re-use and product programs are Activity Systems using design by re-use. The delivery of several products following this set-up is clear evidence of an R&D organisation that enables product structuring for variability with commonality.

The data and findings in this case are valid for the Nokia Cases C, D, E, F, and G because they are done under the rules of platform mode of operation. This data and findings are not relevant to the Case H which was done under different mode of operation.

6.3 Case C – 18-Wheeler simulation game

6.3.1 Background and objectives

The simulation game 18-Wheeler was developed to provide concrete experience for product program people about the platform mode and the practical challenges it imposes on the product program. The scope of the simulation is illustrated in the red frame in Figure 52. The researcher contributes this case by developing the simulation game. The marketing of the learning opportunity is done by the researcher as well as the facilitation of 21 simulations. The researcher has analysed the material and has crafted an information package relevant to this research into this thesis.

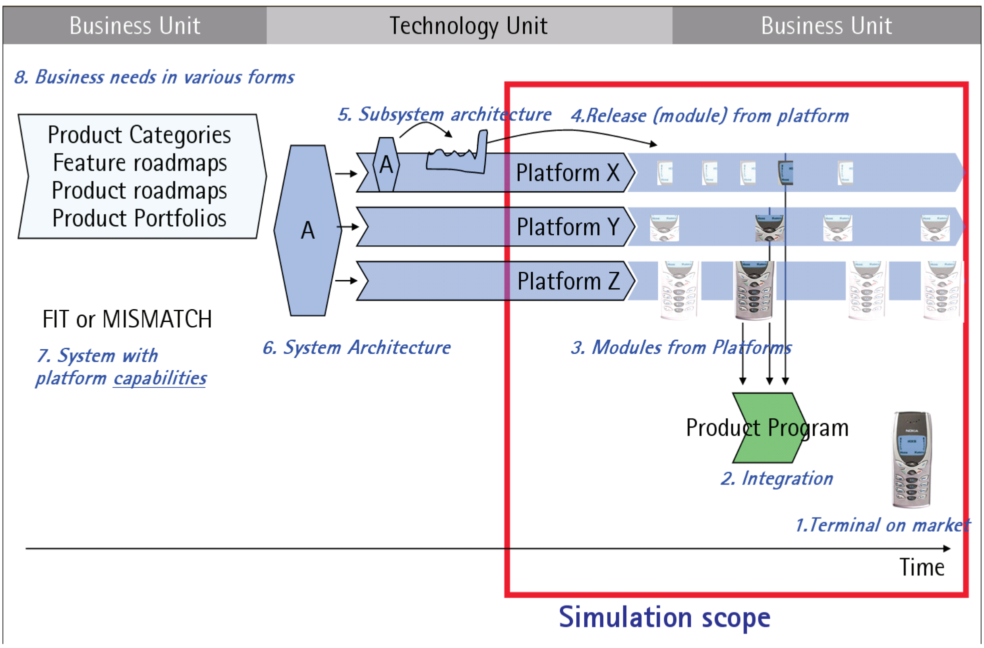


Figure 52. Simulation scope and process flow. The scope is indicated with a red box and the flow goes from left to right [Nokia 2004b].

Several factors affect the ways in which a company benefits from platform-based product development, and in this simulation the emphasis lies in human aspects. At Nokia R&D, human motives, attitudes, competencies, and skills are important enablers for harvesting the benefits. One example of the difference in motives is the case of a component development project and the product program. The development of an optimised ASIC (Application-Specific Integrated Circuit) for one product program only conflicts with the company-level objective, that is, to benefit from economies of scale. From the component project point of view, the question is whether the program people are willing and able to use ready-made solutions rather than create their own.

The ability to design by re-use is one significant enabler that requires an open mind. In creative organisations, the not-invented-here (NIH) phenomenon can easily undermine the reuse efforts. The capability to follow predefined product-level architecture and its constraints on subsystems, interfaces, and modules is another enabling factor. The product program needs to gain knowledge about which modules are needed from the platforms to create a fully functional product. This knowledge is also needed because some of the functionality and modules are implemented by the product program, not by the platform organisation.

Cooperation and collaboration skills are needed because of the high complexity and dependencies in and between the product programs and the technology platform projects. The time pressure in the telecommunications industry also has an impact: some platform deliveries are being developed to utilise the latest technology. Because of this, continuous planning and synchronisation between the platform projects and the product program are needed. The key learning points are summarised in Figure 53.

6.3.2 The simulation – step-by-step

The simulation is divided into five different sessions. The first one serves as introduction, the three in the middle are the actual game session, and the last one acts as an analysis session, as shown in Figure 54.

The objective of the team is to select modules that meet the customer preferences and integrate them into a fully functional truck constructed of LEGO© blocks. In addition, the team has to identify, design, plan, and implement some components. Information is mainly provided in the form of documents. The team receives a table of customer preferences and requirement sheets that the particular Business Unit has given to the technology unit. During the simulation, the information is further processed by the technology platform, and specifications per module are provided. Some time before the actual module is ready, interface specifications and integration notes become available. This follows the Nokia generic process flow and operational mode, as presented in Figure 55.

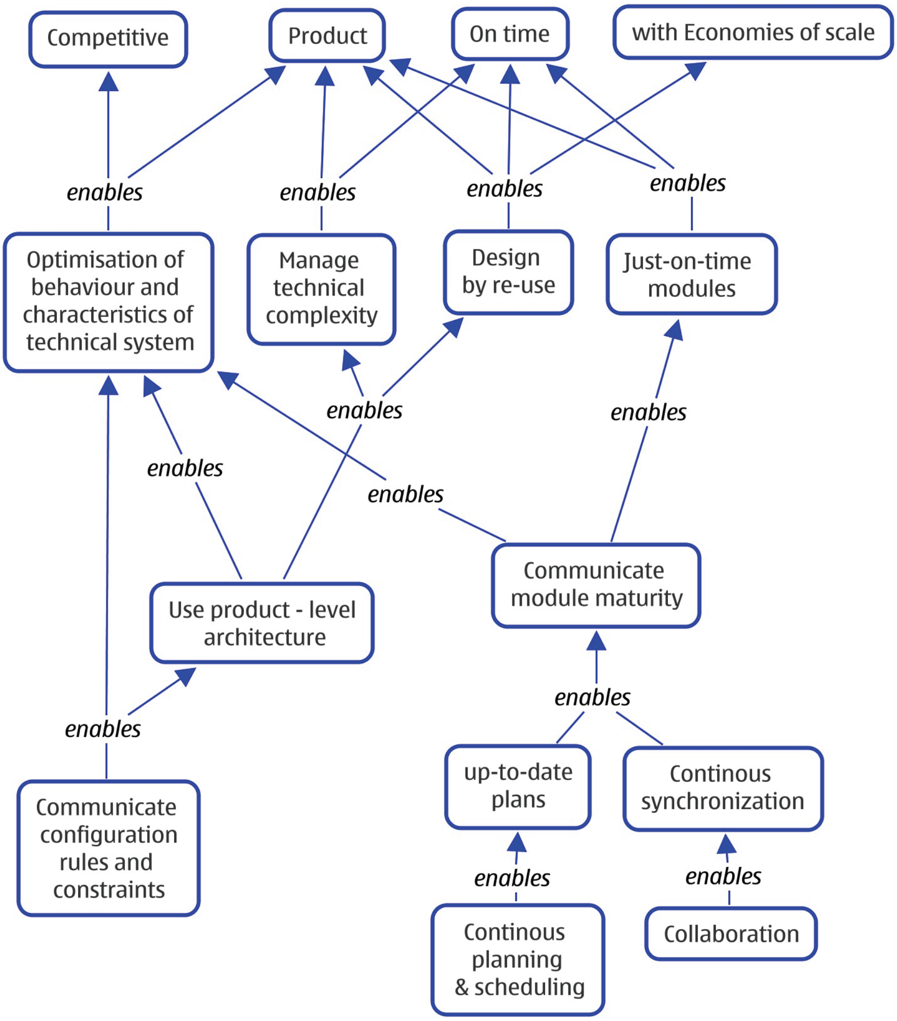


Figure 53. Key learning points of the 18-Wheeler simulation game [Nokia 2004b].

Figure 54. The simulation session breakdown [Nokia 2004b]. The Technic building blocks are demanding as such, and the platform-mode increases the challenge for the team even further.

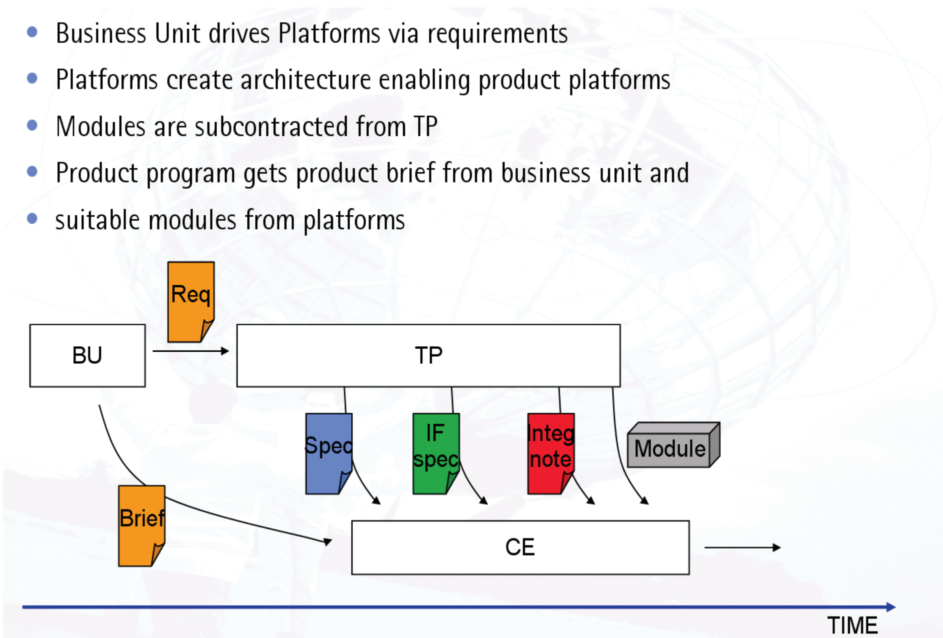


Figure 55. Platform-based operational mode - basis of the simulation game [Nokia 2004b].

The technology unit provides release plans that indicate time-wise when the specific module is available for integration purposes. Just like in reality, these plans change quite often. This has an impact on the product program; the people need to synchronise the plans and do some replanning when necessary. There are very few rules on how to play the simulation. The main rules are that modules are not allowed to be disassembled, the truck has to have an even number of wheels, the torque from the engine needs to be transferred to the rear wheels, and the implementation must not violate the architecture of the truck. This means that the truck needs to have a cabin, a body, front and rear suspension, an engine, a differential, and a driveline.

Introduction and briefing

The facilitator starts the simulation with a briefing. The key learning points—business case optimisation, continuous planning, communication, integration plan, and change management—are explained. The business environment in the truck business is described; the customers and their needs and preferences in particular are articulated. Several attribute scales are used to visualise the customer behaviour and preferences. The dimensions are the transport capacity, the power of the engine, and the agility i.e. engine power / total weight. Some artificial time pressure is applied with a bonus plan; the cheaper the truck is to the company and the faster it is delivered, the more money the team earns.

In this simulation, the facilitator ensures that all participants are aware of their task, follows the timetable, provides any information needed etc. In the product program, several roles can be identified. One person should concentrate on the continuous updating of the business case and informing the team members. One person takes care of the overall set-up, tries to capture the product level architecture, and assigns tasks to the other team members. There is also room for one person to take charge of the actual LEGO® brick building and integration efforts.

In the beginning, a number of questions are raised related to the constraints and dependencies between the various modules. A technology platform representative is then needed, preferably not the facilitator who is also quite busy in that phase. Some assistance is also needed in the integration. There are rules that modules are integrated in a separate place, and clear instructions are needed. The actual assembly is not performed by the product program.

Session 1: Product Architecture and Business case

The session inputs are the briefing material, the release plans, most of the requirement sheets, some module specification sheets, but no interface specifications. The session outcome is an optimised, scheduled, and planned business case. The biggest challenge for the team is to find out which modules are needed to fulfil the product-level architecture. The second challenge is to agree on the common terminology, i.e. to agree on the terms and the nicknames for the modules. In addition, the team needs to optimise the selection of modules they plan to use in terms of time, cost, and customer preferences. To be effective, they also need to agree on the roles and responsibilities.

Session 2: Detailed planning

In the beginning of this session, updated release plans are handed out. Usually, there is a need for some replanning and optimisation based on the newly-received facts. The team receives more specifications about the modules. In some modules, the specification differs from the requirements, which causes iteration in the decision-making. In this phase, the challenge is to identify what else is needed besides modules from the platforms. In the integration plan, it is very easy to test the level of product-level architecture knowledge. If the team wants to integrate rear suspension and a cabin, they have failed to understand the implementation of a typical truck.

Business-case optimisation is visualised by customer preferences and module properties. Module properties change as a function of time, and several optimal combinations are available. What makes the optimisation more complex is the fact that there are conflicts between the customer preferences and the cost of the truck, for example. The constantly changing release plans, properties of modules, and constraint in the product-level architecture forces the team to apply continuous planning. This is heavily affected by the quality and quantity of communication between the technology platform representative and the product program. Constraints and dependencies also appear in integration planning – in how to integrate the truck, what to do etc. as shown in Figure 56. Most of these issues require some sort of change management practices in place to manage the team activities in this complex and challenging environment.

Figure 56. The challenge; how to capture knowledge about architecture and subsystems? The picture is taken from a simulation arranged for academia.

Session 3: Integration

The integration of all the modules needed takes place during this session. The team receives yet another updated release plan, which forces them to change the configuration they already selected. Business-case optimisation is performed again, and the integration plan is updated. According to the integration plan, several builds take place where two modules are assembled according to the instructions from the team. In this phase, the team gets the actual LEGO® blocks and they can start to develop their own assemblies that are needed according to the product architecture. With good collaboration, planning, and some luck, the team manages to integrate a fully functional product, a truck with a profitable business case. An example of this is presented in Figure 57.

Feedback and de-briefing

In this session, the key learning points are summarised, and there is some time to reflect on the experiences. Based on the experiences, the people discuss in teams to identify the improvement opportunities in the project. Some improvement activities are then selected and actions are agreed upon. The owner of the simulation session monitors that the activities are carried out as planned. The effectiveness of this simulation depends on how many improvement opportunities the team can identify and how well those activities, if any, are carried out. Questionnaires are also filled in as feedback: to discover which issues in the simulation were found meaningful and to detect potential needs for improvement. In summary, the simulation is a simplification of the actual organisations but using the same division of labour and rules. The object, the modular truck, is also simple when compared to an actual mobile device. The motive, an end product by design by re-use with a profitable business case, is similar in both cases.

Simulation observations and contribution to the research

Simulations were run in Nokia for 200 engineers and at the university for 70 students. After twenty simulations, 270 persons had participated in the training. The feedback rating has ranged between 4 and 5 on a scale of 1 to 6, where 6 is the highest rating. There were 58 teams in total and they managed to integrate 40 trucks.

Most people start with the goal, a fully functional truck in their mind and they are very motivated to reach that goal. There have been many unhappy and disappointed people if the teams ran out of time. The lack of time is a result of several factors. For example, agreeing on the roles and responsibilities plays an important part in succeeding.

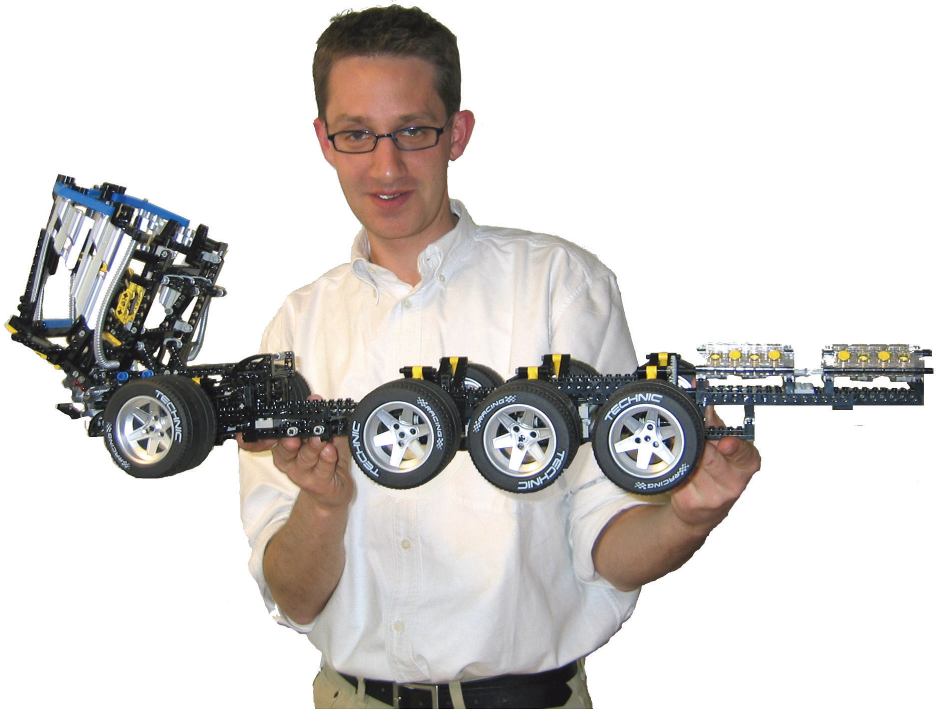


Figure 57. Optimised product as a result of the simulation game. The team managed to integrate rear wheels allowing rotation using the information from platforms. Some teams realised the flaw in the integration too late in the milestone review when the wheels were provided.

For successful integration, it is important to plan a feasible sequence of module integration. To succeed, communication and information-sharing are vital. The team needs to ask the host questions and capture knowledge of the platforms in order to understand which modules are needed and do embedded constraints exist. Architectural knowledge is needed for a feasible integration sequence. Those teams who collaborated with a platform expert were more successful in integration due to the good level of architectural understanding. Teams with little contact with a platform expert most often failed in the integration and the delivery of a fully functional truck before the deadline. This indicates that design by re-use requires gaining sufficient understanding of the synthesis reached by another party in order to apply a re-usable element in their own, larger synthesis.

The first simulation was carried out so that some of the modules were not ready and the platform experts had to take time to assemble the modules. They did not have time to share their knowledge with the product programs and due to this all teams failed; they did not manage to integrate the truck. This indicates that if the platform people use their time in development work and do not reserve time to share their knowledge, the product programs have difficulty in gaining sufficient understanding of the technical design.

One key learning point is about design by re-use. Some teams have decided not to take certain modules from the platform; they wish to design and assemble them by themselves instead. This is possible, but they ran out of time in the simulation. It took longer to design something from scratch rather than to use ready-made solutions. The argument voiced for this approach was that the module was not optimal for their purpose. In these cases, the overall optimisation was performed via emphasising the technical properties and neglecting the schedule.

The simulation makes team-level optimisation very attractive. The platform modules do not perfectly match the needs stated in the product brief. The product brief indicates the customer preferences, such as the torque of the engine or the transportation capacity. The modules look very simple at first, and it is easy to think "we can make a better one in no time". However, no team succeeded in building their own modules. Some teams had a different approach: they started negotiations with the platform expert. Their motive was to alter either the module properties or the platform release schedule, or both. This was a sign of initiative but against the simulation rules. The negotiations ended pretty soon without the desired results. This is an indication of conflicting motives between the Activity Systems.

It also increased the simulation credibility in modelling real-life situations at Nokia R&D. There are numerous examples in real-life projects at Nokia R&D in which the product programs, too, attempt to utilise the second approach. Depending on the management decisions, they even succeed from time to time. This indicates that even with a separation to platform development and product development, conflicts arise if the platform is not already released. These are potential cases to endanger the goals of the platform release to be used extensively in a product family. Management decisions sometimes lead to a sub-optimal solution for one product only.

6.4 Case D – Configurable component

There are many organisations in Technology Platforms that develop re-usable components. This case material describes the Activity System of such an organisation. The material is gathered with ethnography and from two Master of Science theses written during 2006-2007 by Antti Seppänen [Seppänen 2007] and Juho Niemi [Niemi 2007]. The researchers' contribution to this Case was to supervise the making of the two M.Sc. theses, analyse the material and craft an information package relevant to this research into this thesis.

The organisation **goal** is to create mass-customised components for re-use and share expert knowledge when those components are integrated into a single product by the product program. The design **object**, an Integrated Circuit, is modular and configurable [Niemi 2007] and belongs to a number of architectures. Modern mobile phone architectures can be divided into two categories, size and convergence architectures. In size architecture, the HW designer aims to minimise the total surface area and volume required by the electronics and electromechanical components [Seppänen 2008]. This requires minimising the usage of large ICs (Integrated Circuits) such as digital ASICs as shown in Figure 58. Therefore, size architecture is based on a single microprocessor which controls every function of the mobile phone. This single processor is responsible for running modem software, operating system, user interface, applications, peripheral drivers etc.

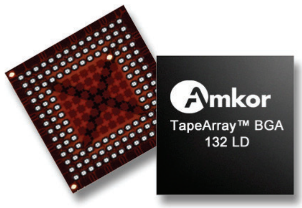


Figure 58. Picture of Integrated Circuit in resin package.

Limiting the amount of digital ASICs comes with the cost of calculating power. In a mobile phone hardware environment, a convergence architecture denotes a system which includes not only possibly the same digital ASIC as the size platform but also another powerful microprocessor called the Application Engine or APE. This second processor usually also contains e.g. a DSP (Digital Signal Processor), multimedia and graphics accelerators, and peripheral controllers. The number of microprocessors and other needs are derived from the business needs such as multiple cellular connectivity requirements (GSM, EDGE, WCDMA etc.) and multiple combinations of peripheral components, such as Bluetooth, FM radio, GPS, and WLAN.

The combination of microprocessors and peripheral components determines the potential mobile device functionality. Configurability is required because the peripherals are not the same in different product variants. For example, the GPIO (General Purpose Input/Output) pins may change due to the combination of peripheral components or the PWB layout of the mobile device [Seppänen 2008].

In Figure *59* Niemi [2007] presents a model which represents modularity and configurability of application engine part of a mobile phone based on convergence architecture. The modelling technique used here is based on Tiihonen et al. [Tiihonen et al. 1999]. Only the APE side of the mobile phone architecture is shown.

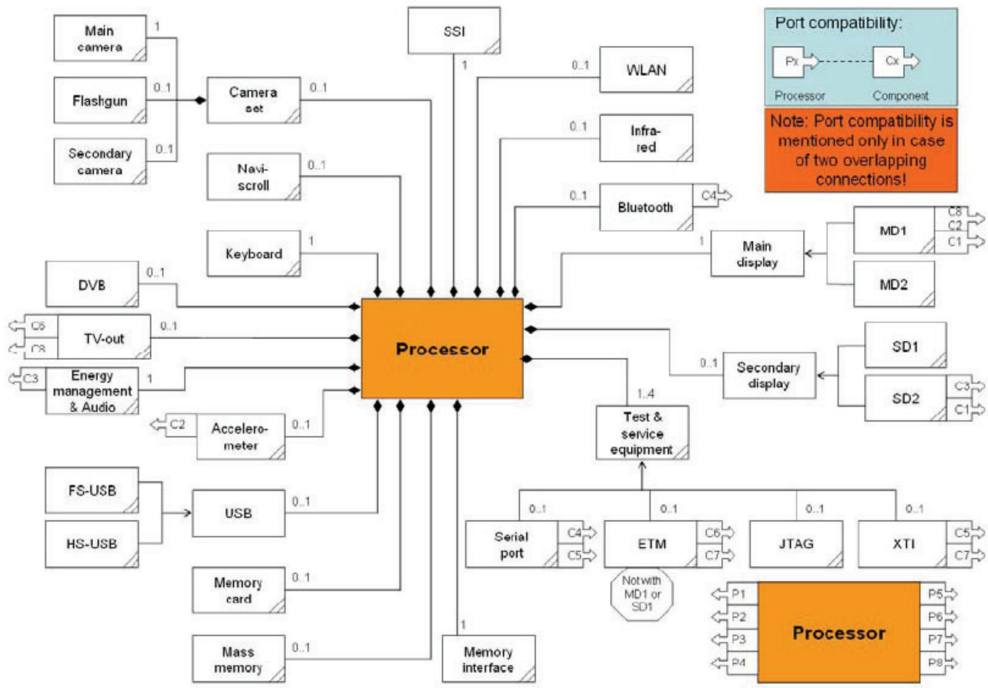


Figure 59. Configuration model of the hardware system [Niemi 2007]. The processor and the peripheral components are described and the configuration rules and constraints are modelled.

The model describes which components can be included in the same configuration. The key issue in the model is the modelling of the ports. The ports are used to model the terminal pins of the processor. The processor includes 124 GPIO (General Purpose Input/Output) pins. Each application component has a various number of terminal pins that need to be connected to the processor. The terminal pins in the processor represent the multiple properties. Thus, there exist restrictions of which processor's terminal pins are compatible with certain application component's terminal pins.

An essential element in the case of connections is also the software that guides the operation of the application components. When configuring the software, information about planned signals in certain pins are required. In other words, the information of which pin of a certain application component is connected with which pin of the processor. The terminal pins of the processor can be configured to be compatible with the application component's pins by the software. Still, this has to be performed within the limitations stated by the properties of the processor's pins. Thus, all the pins cannot be used for all purposes.

In the model, only the overlapping connection, i.e. the overlapping pins, are described. For example, Bluetooth and Serial port require the same terminal pin of the processor. Thus, these components cannot be included in the same configuration. Nevertheless, the components might be included in the same configuration with the help of software programming.

To summarise, a mass-customised component with relevant documentation is agreed to be the delivery content of this organisation. Product programs have service options from which to choose. The service options control what information, and how the knowledge of this organisation, is shared for the product program.

The **rules** follow the Nokia-level R&D strategy and the basic principle of platform-based product development: one entity performs design for re-use and another entity performs design by re-use, and therefore the division of labour takes place in the Nokia-level CHAS.

The **division of labour** & the division of power follow these rules: component development is performed in this organisation, and design by re-use is performed by the product program. The design tasks are known very well; only some new functionality or a new architecture may require new, yet unknown tasks. Service options can require some design tasks which are known beforehand. Decision-making is done based on the criteria provided by the milestones in the Design Process.

The **instruments** consist of processes, practices, methods, and tools used in this organisation. The component development process has evolved over time and is developed to ensure high-quality components to meet the configurability needs and enable efficient development work thus reducing R&D effort per component delivery. The component development process has particular tasks and criteria to ensure modularity and the desired configurability. For example, the desired combinations of peripherals around the processor are identified as much as possible. This is carried out with the help of critical use-cases that are identified, simulated, and verified. Critical use-cases are a combination of parallel activities performed by the user and they are critical for the system level in terms of processing power, the available peripherals etc. Some of the tasks and criteria are not documented but they are tacit knowledge of the community. For example, the following milestone criterion is used as an instrument increasing explicit knowledge at certain milestone: Are the configurability rules and constrains modelled and verified? This requires design task that defines the configuration model. Currently an Excel-spreadsheet is used to capture e.g. GP I/O configurations [Seppänen 2008].

Over two decades, the **community** in this organisation has learned to focus on the re-usability, mass production, and configurability needs therefore enabling economies of scale. The knowledge is partially explicit and takes place in the form of rules, norms, the division of labour, and instruments as described above.

During the evolution, the organisation has succeeded in resolving conflicts between the CHAS elements. Main conflicts arise when co-operating with other entities that have different motives. Typically, a conflict emerges when the product program would like to remove some component functions to speed up the development to be more suitable for their own time schedules. Another conflict emerges when multiple product programs have chosen the same component that is under development. The products have conflicting requirements concerning the functionality or the properties of the component. These issues are solved by executive management decision-making bodies. The data capture of this case is summarised and illustrated in Figure 60. The arrows model dependencies between elements identified in the case.

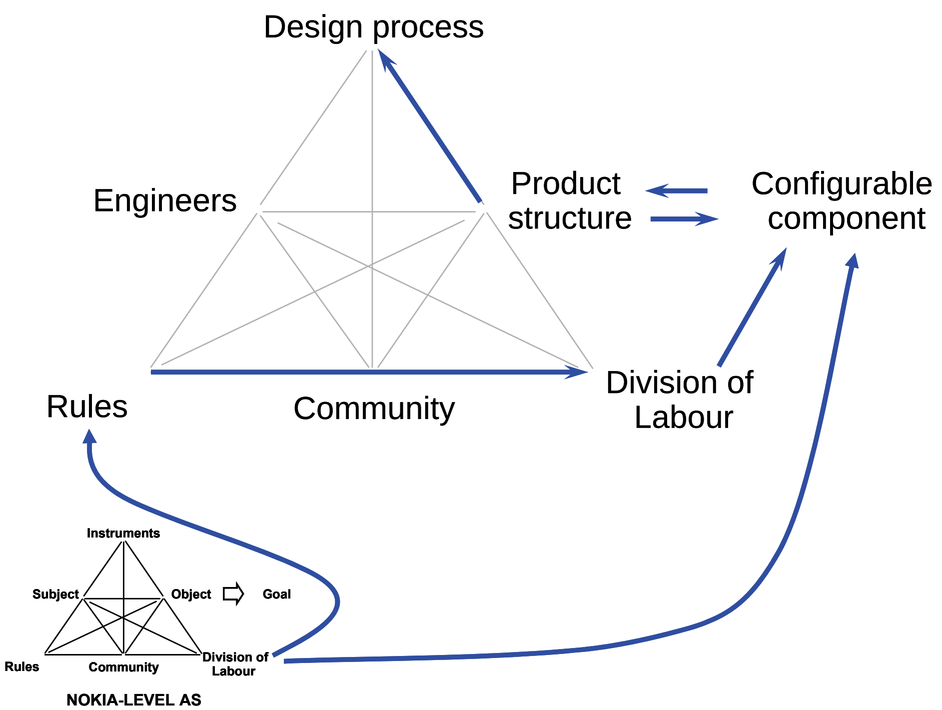


Figure 60. Data capture of Case D – a configurable component. The main dependencies are between Design Process, product structure, and configurable component as design goal. Nokia-level division of labour imposes rules and design goals to the Activity System.

In the Case D several versions of the IC was made along the time. In early versions there were minor changes in the IC design but later on, the major change was that the design work was transferred in a totally different organisation with people having very little background knowledge. This resulted in approximately 3 times more work effort needed per IC version. The receiving organisation created yet another version of the IC and their own, second version of the IC required approximately 1.5 times more work effort as the first one created by the source organisation. The reduction from almost 3 to 1.5 was because most of the required learning was already done (as an investment on capturing the ready-made synthesis) and the knowledge level was considerably higher. When the transfer was done, a considerable amount of work effort (approximately 5-10 percent of the total work effort) was put by the source organisation in training the receiving organisation. Thus the design by re-use imposed support effort to the organisation which did the design for re-use.

6.5 Case E – Partly-configurable device

This Case is based on the Activity System of an organisation which develops a new mobile device for the market. The material was gathered with ethnography during 2007-2008. The researchers' contribution to this Case was to analyse the material and craft an information package relevant to this research into this thesis. The organisation **motive** is to integrate standard, configurable, and one-of-a-kind components, both in hardware and in software, and to verify the behaviour and the properties of the mobile device. The delivery as **goal** and **object** is particularly designed to meet the requirements of a particular product concept. The delivery comprises some mass-customised components, some standard components, and some unique components for this program only. The data capture of this case is illustrated in Figure 61. The arrows model dependencies between elements identified in the Case.

The **division of labour** is such that engineers are part of the product program staff and their task is to design by re-using existing platform components. Some components are designed by the engineers, such as the plastic or metallic covers of the mobile device. Decision-making is based on the criteria provided by the milestones in the Design Process and the management process. The **rules** in this Case are derived from the motive. One guiding principle is to use the Concurrent Engineering process and to apply the agreed division of labour. The **instruments** Design Process to a particular CE-program way of operating guides the design and project management. From the designer's perspective, the **community** is the product program. The engineers have a home base in the line organisation.

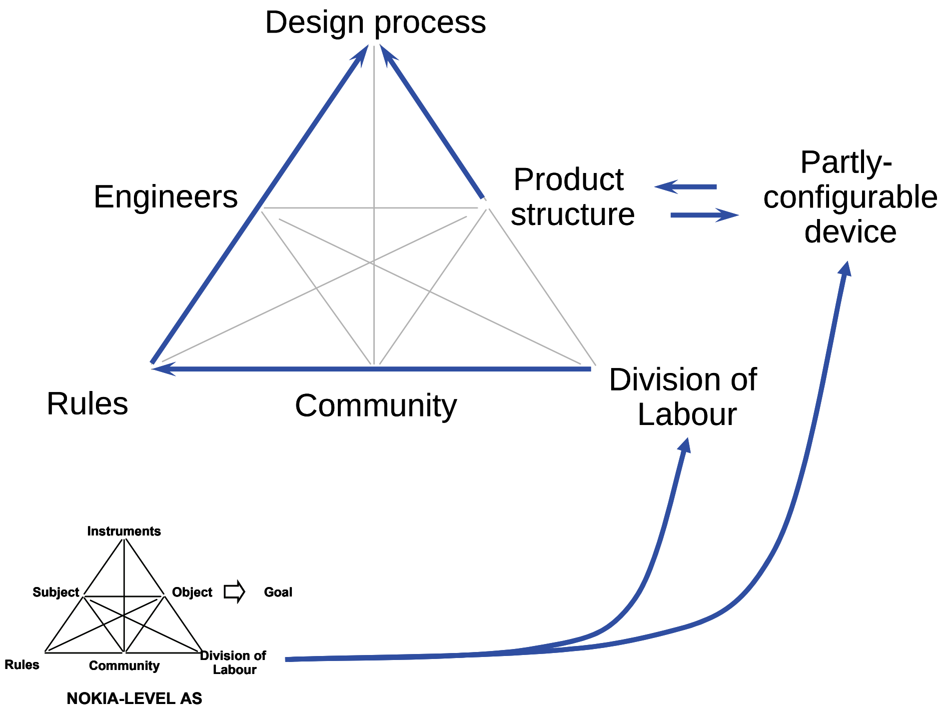


Figure 61. Data capture of the Case E – partly-configurable mobile device. The main dependencies are between Design Process, product structure and partly-configurable device as design goal. Nokia level division of labour imposes division of labour and design goals on the Activity System.

The goal conflict with the component development Activity System is illustrated in Figure 62. The two organisations have different goals, and when they need to co-operate due to the operational mode and the delivery flow, a conflict emerges. Managerial actions are needed to remove the conflict, or to minimise its effects. The arrows model dependencies between elements identified in the Case.

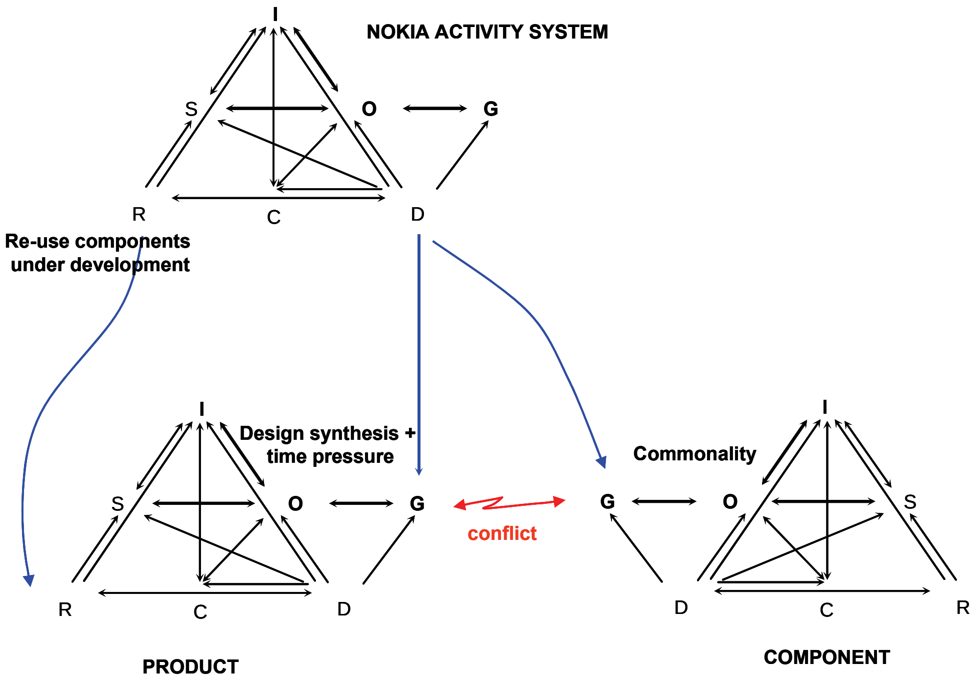


Figure 62. Goal conflict between two Activity Systems. The Nokia level division of labour imposes different design goals to the Activity Systems thus causing goal conflict between Activity Systems.

The mobile device consists of a configurable element, e.g. modem IC, and standardised elements, e.g. GPS- component. The classification of the delivery content is captured in Figure 63.

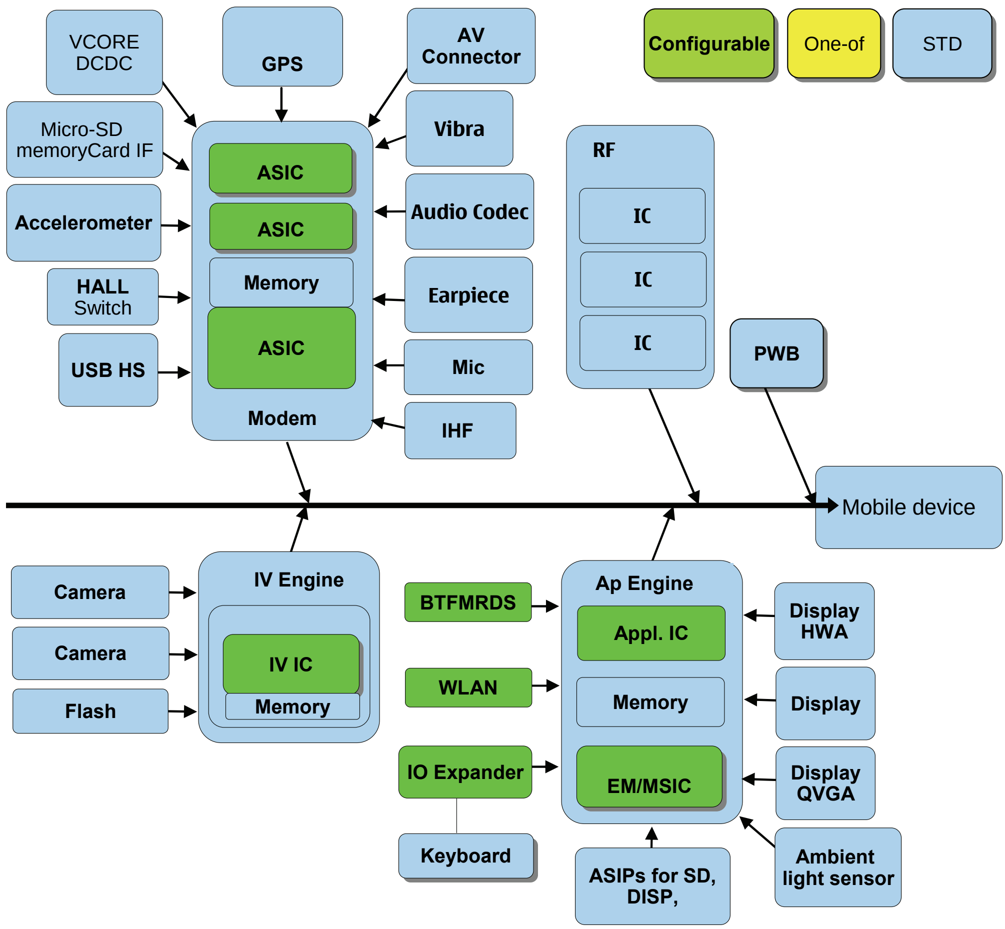


Figure 63. Delivery classification by PS-types in Case E. Mobile device consists of standard and configurable product structures.

6.6 Case F – Support component re-use

This Case material is based on the Activity System of an organisation that provides experts for integrating mass-customised components into a mobile device. The researchers' contribution to this Case was to analyse the material and craft an information package relevant to this research into this thesis. The experts have all the relevant knowledge needed during the integration and verification. The material was gathered with ethnography during 2007-2008. The organisation **motive** is to support mass-customised component design by re-use. The delivery **goal** is expert services necessary for enabling an efficient design of a particular product with particular components and for minimising the product program's time to market. The **division of labour** is such that the experts' time in this case is reserved for the product program, and technical consultation is provided whenever needed. Decision-making is based on the criteria provided by the milestones in the Design Process. The data capture of this Case is illustrated in Figure 64. The arrows model dependencies between elements identified in the Case.

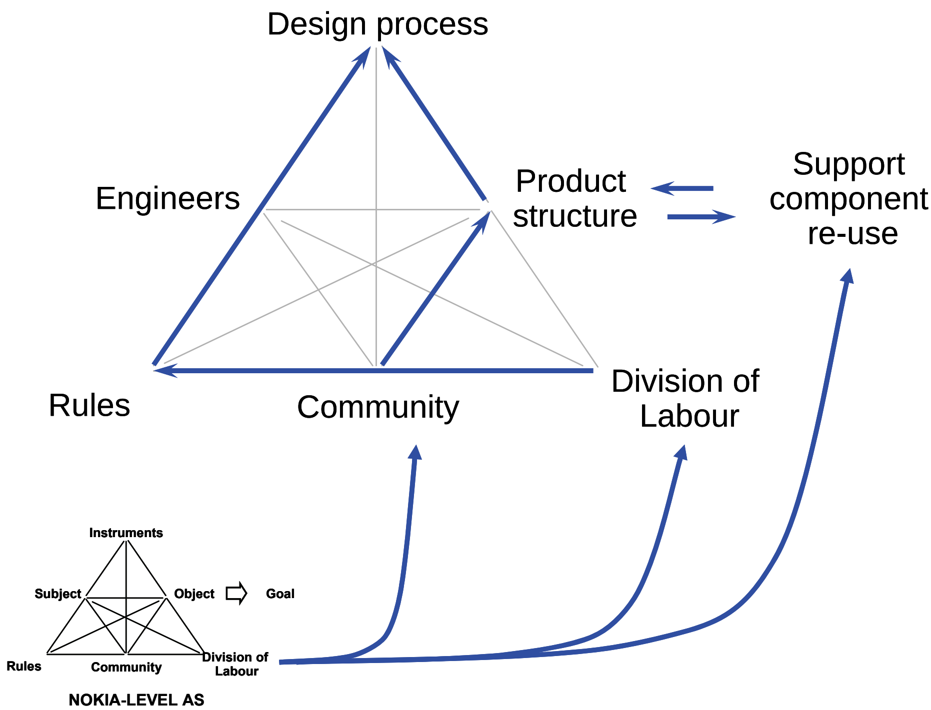


Figure 64. Data capture of the Case F - support component re-use. The main dependencies are between Design Process, product structure and component re-use design goal. Nokia-level division of labour imposes need to have technology experts in the community, division of labour that defines the needed roles and design for re-use as design goals.

The **rules** in this Case are derived from the motive. One guiding principle is to import the relevant criteria from the component Design Process to the product program CE process. This ensures that relevant verification is performed on the mass-customised component as a part of a larger system. Standard test cases are re-used as the **instruments**. The **community, the experts** have the internal goal of designing as much as possible by re-use, and meeting the needs of the product program.

6.7 Case G –Component cost reduction

The cost reduction of a component is very common across the Nokia R&D, and in the **community** there is a host of engineers who have performed such work. The researchers' contribution to this Case was to analyse the material and craft an information package relevant to this research into this thesis. The **motive** is to develop cheaper component versions with minimal R&D effort and to maximise design by re-use. The **goal** is a component with the same functionality as before but a smaller size, which requires less silicon and thus decreases costs. In these cases, the manufacturing process is changed, which enables a smaller pitch i.e. distance between two conductors in the IC design. In some cases, some new functionality is added and a new IC design is created. The **object**, the Technical System comprises IP blocks that are integrated into one IC. The IP blocks are re-used as much as possible. IP blocks are either standard elements or mass-customised elements. The **instrument,** the Design Process is optimised to ensure that the new manufacturing process creates components with high performance and reliability properties and is derived from the **motive. The division of labour** results in using only a few engineers in design by re-use and has an impact on the **object**. Decision-making is based on the criteria provided by the milestones in the Design Process. The data capture of this Case is depicted in Figure 65. The arrows model dependencies between elements identified in the Case.

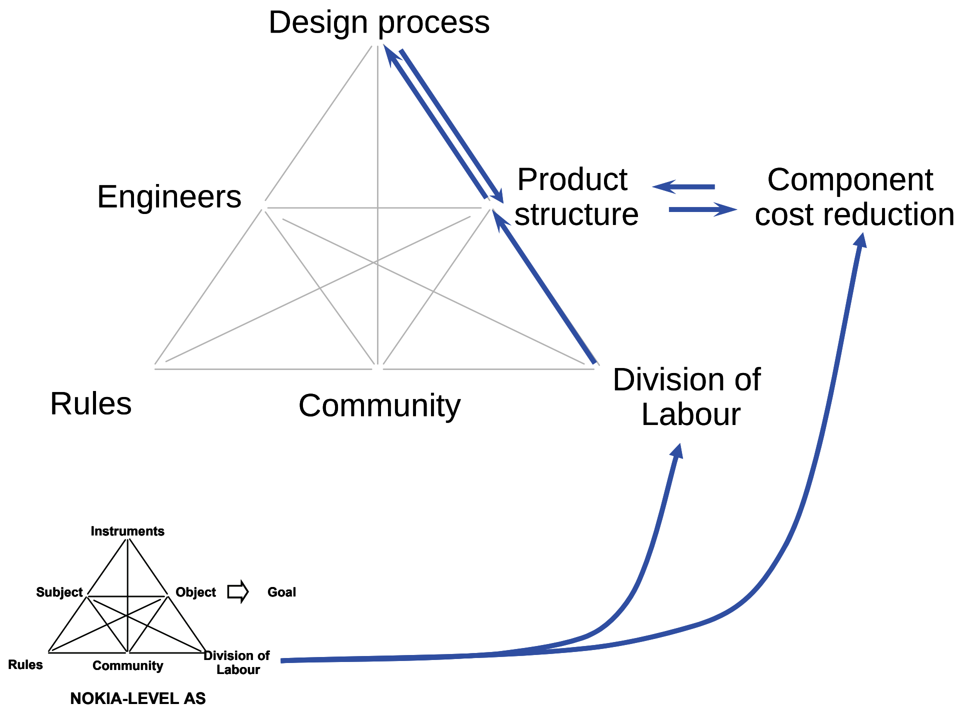


Figure 65. Data capture of the Case G – component cost-reduction. The main dependencies are between Design Process, product structure, and component re-use design goal. Nokia-level division of labour imposes division of labour that defines the role of this Activity System and component cost-reduction as design goals.

6.8 Case H – Configurable product family

In this case, there was a community that saw a new business opportunity. The researchers' contribution to this Case was to consult the concept generation for the new business opportunity, to teach the principles and design process of configurable products. The motive was to develop a configurable product family by enabling a new type of variability at various points of the order-delivery process. The motive was to change the current value-creation logic and to enable late-point differentiation, as illustrated in Figure 66.

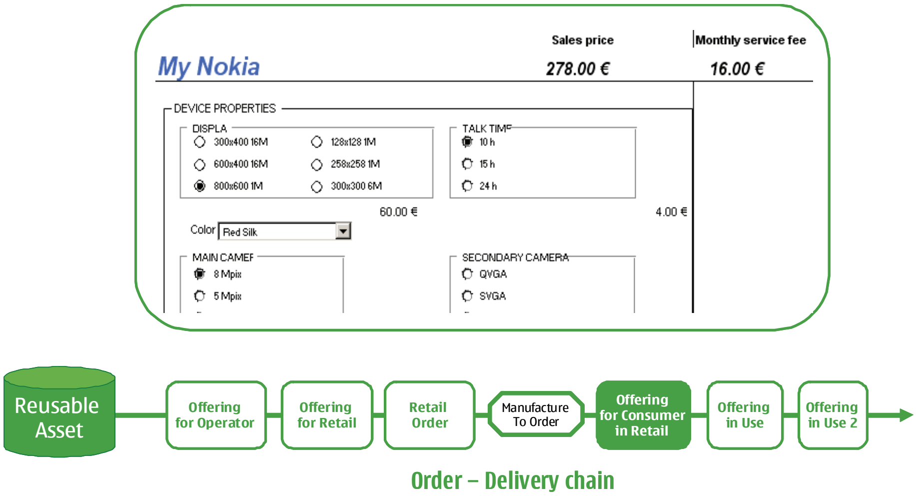


Figure 66. Late point differentiation in an order –delivery process. The picture visualises configuration options offered for consumer in retail shop e.g. display resolution, colour, and resolution of main camera.

Late-point differentiation means, for example, that the consumer can select from predefined options in the retail shop, and the final configuration will be assembled and programmed there. The **object**, a product structure for a configurable product family would enable these goals. The **instrument,** the Design Process was modified to enable visibility on the configurability needs per life phase. **The division of labour** differs from the traditional, as currently configuration is mainly performed by operators and retailers. This project was terminated due to conflicting design goal of other Activity Systems. For example this concept would have changed the logistics chain considerably. The arrows in Figure 67 model dependencies between elements identified in the Case.

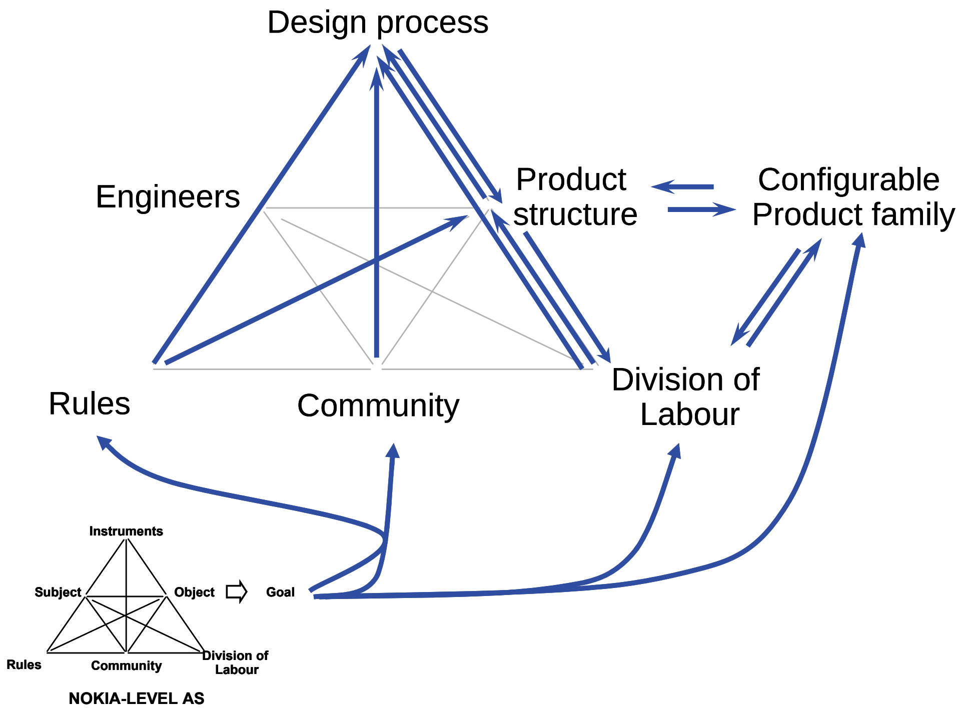


Figure 67. Data capture of the Case H - a configurable product family. The main dependencies are between Design Process, product structure, and configurable product family. Nokia-level goals impose rules e.g. customisation policy (see Figure 24), community and division of labour that re-defines design goals and causes iteration between these two elements.

6.9 Case I – Partly-configurable ship

Background

This research is made in co-operation with Finnish ship-building industry. The companies observed were two shipyards in Turku and Rauma owned by Norwegian Aker Yards ASA. In addition to the shipyards, nine other companies in the Finnish maritime supply network were studied. Four of them are design offices making contract designing of the ships and they are important partners of the shipyards. Three companies are suppliers of major interior and machinery elements of the ship. Two companies are delivering smaller building elements for shipyards. The most important product segments for these companies are cruise ferries and passenger ferries. The research was focused on deliveries of these types of ships [Lehtonen et al. 2007c].

The researcher's contribution to this Case is developing different operational modes with the research group and planning how the transformation from current mode of operation to desired mode can be done as a change project. The researcher has reviewed all the material of this Case and crafted an information package relevant to this research into this thesis.

Design object and division of labour

A passenger ship is a partly-configurable product type project delivery. Every ship is unique, but on the other hand most components or assemblies are re-used in many ship deliveries and some of the subsystems are configurable product structures. Therefore, there is great potential for design re-use by configuration and modularisation. The level of re-use differs from ship to ship. There is so called "prototype" ship-delivery, which is the first ship of its class. The re-use in these ships is rather low. Same ships of same class for the same customer are called "serial ships". The re-use in these kinds of ships is up to 70-90 % (depending on the calculation method) [Lehtonen et al. 2007b].

The customer requirements from ship operators are naturally the most important source of variation, but there is also another source of making changes in deliveries from ship to ship. The design tasks on a ship can be more or less given to the supply network depending how skilful contractors are available for this particular ship delivery. Outsourcing is a popular way of working in the design tasks, as well as in component manufacturing and assembly tasks. In the design, even a part of the conceptual design is from the design offices. A big amount of the embodiment design (called "basic design" in this area) is made outside the shipyards and subcontractors make practically all of the detailed design. The way in which the division of work between the shipyard itself and the subcontractors is made, is the main element for defining different ways of delivering the ship. It is chosen as it changes the Design Process significantly [Lehtonen et al. 2007b].

Rules and division of labour

The way of building passenger and cruise ships in Finnish yards is changing. There are three main factors causing this change. The first one is moving away from "one big company" policy where the shipyard makes everything by itself and has all the personnel needed. The second factor is the change in the "shipbuilding philosophy" originated from changing cost structure. The third is an urgent need of changing from the craftsmanship paradigm to the industrial manufacturing paradigm. There are many underlying reasons for these changes as discussed later. One reason is however above all other: Increasing size of the ships. As shown in the Figure 68, the cruise ship "Genesis" which is under construction now is almost twice as big as "Voyager of the Seas" that was built less than ten years ago. Yet the building time has not doubled nor the size of the shipyard. New, more efficient ways of working are the only possibility to make profit and survive in this business [Lehtonen et al. 2007c].

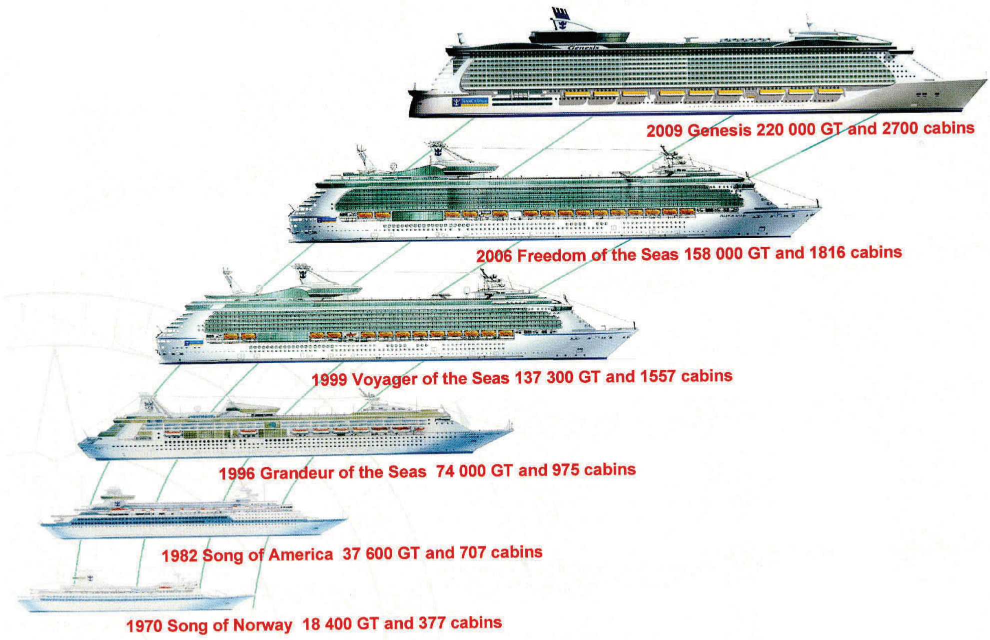


Figure 68. The evolution of the cruising vessel. The demands to the network of Activity Systems have increased as the size of the vessel has increased [Picture and data: Aker Yards].

Very few shipyards in the world build the whole ship by themselves. As mentioned earlier, the supply network is particularly wide and important in the Finnish marine industry. Not only actual work is subcontracted but also responsibility of design work and process control is increasingly going to be the responsibility of the subcontractor. There are four different complexity levels concerning the work bought from the subcontractors:

1) Work according the instructions,
2) One physical area of the ship made complete,
3) One functionality of the ship project made complete, and
4) One functionality of the ship developed and maintained

The traditional way of regarding the building of the hull as the most important task in shipbuilding is not feasible when building cruise ships and passenger ferries. The amount of investments on interior and equipment are far bigger than the investments on the hull. Thus, there no longer is business logic in constructing the ship by the terms of building the hull. Neither there no longer exist technical reasons for designing and building the hull first. This leads to changes in "shipbuilding philosophy". The standardisation and efficient production of these parts of passenger vessels is required [Lehtonen et al. 2007c].

Building of cargo ships in Far East is very efficient enabled by standardising the work. The ships made there are very much alike. The problem is that there is no "standard luxury cruise vessel". In the cruise ships business, it is a value in itself that every ship is an individual. The more the demanding travellers are among the ships passengers, the more important are the ship specific solutions also in the passenger ferry business. Thus there is an urgent need of building different ships by using same parts. The obvious solution is modularising the ship and encapsulating the variance inside the modules. This again supports the division of the contract to the "module experts" in the network [Lehtonen et al. 2007b].

There is also need to change the industrial paradigm. The profit margins in the ship building can not support traditional craftsmanship. Approaches that are more industrial are needed. According to the visionary ideas presented in this research and development projects with European shipyards, shipbuilding should become more like assembly work than actual building and manufacturing.

These trends are the reasons for a change which has lead to the different delivery processes. There are no two ships exactly alike when observing the building process. And there are no two ships with similar product structure when one considers "as delivered" -structures. However, four generic processes can be found. The actual ship delivery is a combination of these generic processes.

Operational modes as instruments

The empirical research revealed that there are four operational modes of how the ship delivery can be done: [Lehtonen et al. 2007b]

1) Conventional main contractor centred project delivery. The shipyard coordinates all the design work and the actual design. Component manufacturing and final assembly onboard of the ship can be divided into different sub-suppliers. This is the traditional way of working in the ship-building industry. However, this is nowadays largely considered to be ineffective and inflexible causing higher costs and longer delivery times.

2) Dividing the ship in spatial areas, which are then made by turn-key type deliveries by a team of sub-contractors. A team normally consists of a partner who is responsible of the design and another partner responsible of the physical realisation of the delivered area. At the moment, this way of working is increasingly wide-spread. The co-operation within network becomes more efficient. When constructing the ship of turnkey deliveries, the importance of general architecture and the definition of interfaces will become important. The building blocks of the ship are not functional but defined on the spatial terms by the layout.

3) The third way of making the ship delivery is to start using modular structures and configurable product paradigm. In this model the sub-contractors are not selling their work effort for building a ship, but instead they have modules that are building blocks for the delivery. These modules are not necessarily physical assemblies, but so called process modules are also used. This kind of module can include, for example design and coordination of certain process phase. This is an emerging way of working. The main motivation is the possibility to convert hand-made single parts to industrially-made products with the benefits of serial industrialised production. This approach should be utilised from the very start of negotiations with customer to make sure that modules available could be used in the ship. If a ship can be sold as a modular product, this enables a lot of re-use of design. The goal conflict emerges when subcontractor is offering their standard modules or configurable modules, but the modules do not fit in the partly-configurable product structure designed to meet customer needs. The subcontractor is not able to cover investments for the ready-made design.
4) The fourth way of making delivery is more of a concept than reality, but it is considered to be a strategic goal of tomorrow. The aim is to develop the sub-supplier network to an Extended Enterprise. The idea is that strongest partners in the network could come to the level of the shipyard to share the responsibilities and rewards. This requires that part of the value chain is transferred from the shipyard to the first tier partners. The common opinion is that this kind of network would be very agile and could achieve very high cost efficiency without compromising the end product quality.

The fit between the design goals, product structure and Design Process

The ways of working in the ship building industry have changed within the last 20 years. The products delivered are increasingly becoming collections of assemblies produced by different companies in the supplying network. From the partition of the product emerges also the need of the division of the design tasks. In earlier research the dependencies between product structure and the order-delivery process were found. Dependency originates from the requirement that product structure and Design Process need to support same design goals. In this case the research group wants to check that the proposed processes also have corresponding product structuring strategies supporting the same goals as the order-delivery process [Lehtonen et al. 2007c].

In the first way of making ship delivery, the design goal is to maintain flexibility so that ship could be made up with any possible team of sub-contractors consisting of individuals of any skill level. In this kind of a situation, a strict product structure is more of a nuisance than an asset, because the product structure in this case comes from the restrictions from the part structure and requirements from the functional structure. The conclusion is that the way of working is mainly unstructured and thus no special product structure is required. Also the Design Process for developing one-of- a- kind product structure is appropriate in terms of R&D efficiency.

In the second way of making the delivery, the process requires spatial division. The ship is welded up from ready-made steel blocks. The design goal is to handle the interior the same way. In this case, the product structure is the division of sub-assemblies according to the spatial structure. This could be called "industrial assembly-based modularisation". The word "modularisation" must be put in parenthesis, because the division has connection to functionality only by chance, not by intention. Thus, these are no modules, for example according to references [Pahl et al. 1996] [Ulrich et al. 1991]. The Design Process for developing standardised and modular elements is most suitable in terms of R&D efficiency.

In the third way the product structuring paradigm is actually mentioned. The design goal is to use functional based product modularity and, in addition to accept some kind of mixtures of product and process; process modules and the Design Process for configurable elements, also process elements, is most suitable in terms of R&D efficiency.

In the fourth way the corresponding product structuring methodology is more obscure. The design goal is connected to the life-cycle management of the product offering. Because this way of working is only at the planning stage, the actual product structuring method cannot be pointed out. Currently, the Design Process for partly-configurable elements is seen most suitable in terms of R&D efficiency.

Observations and contribution to this research

Mode of operation
The shipyard is responsible for the delivery to a customer, for example, Caribbean cruise lines. The shipyard prepares an offer for the shipping company that includes suppliers, and the suppliers are selected when the shipping company has approved the offer. The division of work is free, allowing modifications in the product structure from ship to ship. Cost-efficiency is a very dominant driver for the shipyard; subsequently, the purchasing organisation also receives offers from competing suppliers. The shipyard owns all design and materials of the delivery project [Taneli 2007].

The **goal** of the shipyard is to create a cruise vessel and an operating mode that enables decreased costs, an improved time-to-market, and decreased R&D effort per ship. The **object** is a cruise vessel. The ship is divided into sections according to the general arrangement of the ship with separate sections to prevent fire and flood. In addition, the sub-deliveries include systems such as electricity, fresh water, grey water etc. Some parts of the ship are delivered as modules, such as sections of the hull and the engine department. The ship comprises crafted elements such as the hull, interior decorations in the restaurant etc. [Taneli 2007].

The project delivery is organised in such a way that in every delivery the suppliers are requested for quotation and the **division of labour** is agreed upon individually for each case, as it is a result of which suppliers win the price competition. The chosen combination of suppliers has an impact on the Technical System, as each supplier has different technical implementations to meet the same requirements. This causes goal conflicts and is a result of different motives of different companies. The division of labour also has an impact on the **instruments** in the Design Process, as the criteria differ according to implementation. Currently the design of operational mode in each case seems to take considerable amount of managerial effort to agree upon ways of working and processes to be used. Some documents e.g. quality manuals are used as instruments. Decision-making is based on the criteria provided by the milestones in the Design Process. The main **rule** is to optimally meet the shipyard's needs in this particular delivery [Lehtonen et al. 2007c].

It appears that certain Design Process is most efficient in producing a product structure with certain properties. There is also a clear link from design goals to certain product structure and Design Process. The design goals have dependency to the selected operational mode as discussed earlier [Lehtonen et al. 2007b].

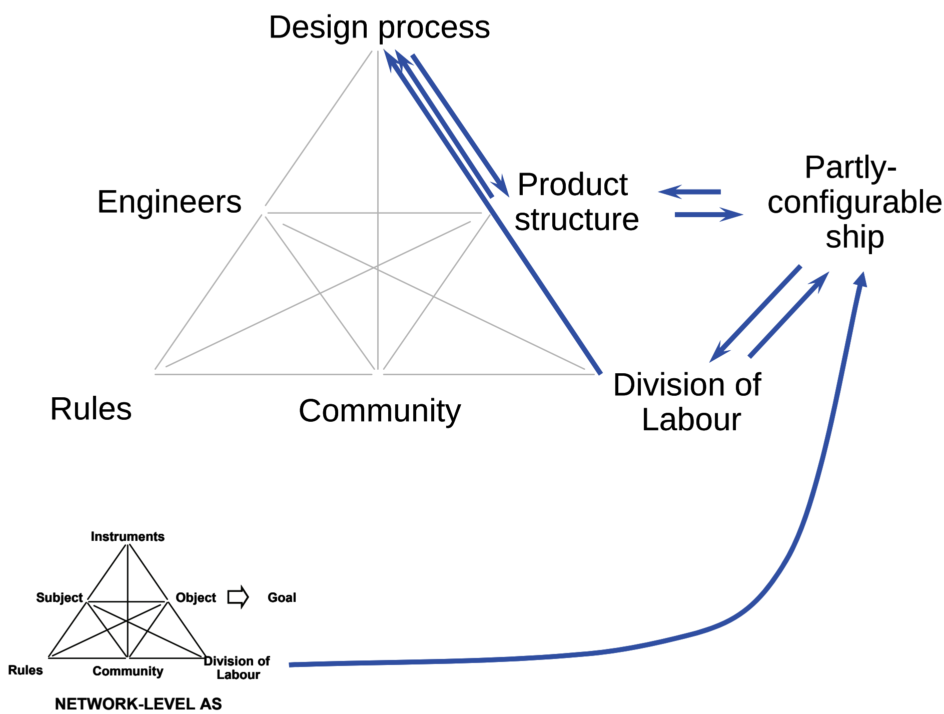


Figure 69. Data capture of the Case I – a partly-configurable ship. The main dependencies lie between Design Process, product structure, and partly-configurable ship. Network-level division of labour imposes division of labour that partly re-defines design goals and causes iteration between these two elements.

Design by re-use is possible for engineering companies, but the component and system suppliers have a limited opportunity due to the change of product structure depending on the combination of suppliers. Design for re-use is possible but not economically feasible for the suppliers because of the case-by-case selection process thus inducing a high risk. The ship consists of standard product structures (valves, pumps, pipes), one-of-a-kind structures (restaurants, bars, shops, a movie theatre, a concert hall), configurable structures (e.g. control systems), and partly-configurable structures (a power plant). This supports the classification of product structures. The data capture of this Case is illustrated in Figure 69. The arrows model dependencies between elements identified in the Case.

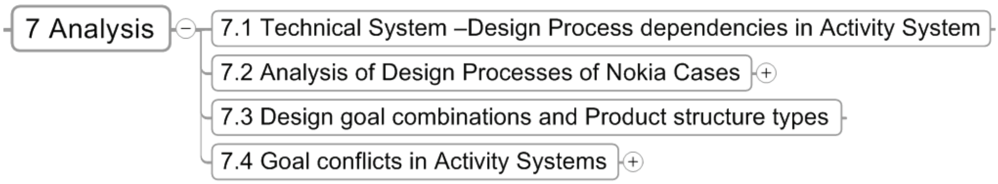
Contribution to the research questions

The Cases D – "Configurable component", Case E – "Create new product" and Case I – "Partly-configurable ship" contribute to the research question 1 by indicating characteristics of Technical Systems that are investigated in this research to give focus to the "how" research questions. Agreed interfaces and behaviour of the element enable product synthesis when unique elements are fitted together with standard, unique, or configurable elements.

The Cases D, E, F, G, H and I contribute to the research question 2 by indicating the need of Design Process and the dependency between Technical System and Design Process. The Nokia Cases, especially Cases A – "Nokia" and B –"Platform mode of operation" contribute to the research question 2 by describing The Nokia process model that consists of inputs, outputs, process, and milestones. The use of similar process model with milestones was observed in all Nokia Cases (excluding the Case A and B as Nokia organisation is not developed with process and the operational mode is not developed with process). Within Nokia, milestone is accepted if the design meets list of predetermined criteria defined by the management. If the milestone is rejected more design work is needed to fulfil the milestone criteria or, occasionally the management is taking risks by accepting the milestone. Also the milestone criteria and design tasks are adapted every time when new project is started. This indicated that fit between Technical System and Design Process does not happen automatically or by itself. The observations in the Cases D to G indicate that the fit needs to be designed.

The Cases C, D, E and I contribute to the research question 3 by indicating the difference between motives and design goals of several Activity Systems. The Case A – "Nokia" and Case I – "Partly-configurable ship" contribute to the research question 3 by describing different operational modes for Activity System networks. The Case F – "Support component re-use" and Case I – "Partly-configurable ship" contribute to the research question 3 by describing conflicts of several Activity Systems on motive level.

7 ANALYSIS



This chapter consists of an analysis of the dependencies between Technical System and Design Process, the difference between Design Processes in Nokia, the Design Process goal combinations, and the goal conflicts in Activity Systems. It concludes how these contribute to the research questions in the end of the chapter.

7.1 Technical System –Design Process dependencies in Activity System

The analysis is done by taking the data from industrial cases, based on which the matrix is created. In the matrix, as presented in Table 4, the Activity System elements appear both in columns and rows, and in addition, dependency from an upper (e.g. Nokia) and lower (e.g. external supplier) Activity System is included. The cell contains the letter of the Case in which the dependency is found.

Table 4. Summary of Activity System dependencies based on the Cases.

	Motive	Subject	Object	Instrument	Rules	Community	Division of labor & power	**Goal**	Subject	Object	Instrument	Rules	Community	Division of labor & power	**Goal**	Subject	Object	Instrument	Rules	Community	Division of labor & power
	One level upwards							**On the same level**							**One level downwards**						
Motive															a,b,d,e,i						
Goal	b									d,e,f,g,h,i				h,i							
Subject										d,e,f,g,h,i											
Object			b,d,f,g					d,e,f,g,h,i			d,e,f,g,h,i			h			b,g,i				
Instrument				b					c	d,e,f,g,h,i			b,c	c				a,b,i			
Rules					a,b			h		h	e,f,h			d					a,b,i		
Community										f	h										
Division of labor								d,h,i		g	h,i	e,f			d,e,f,g,h,i				a,h	f,h	e,f,g,h,i

a Case - Nokia R&D Introduction
b Case - Platform-mode of operation
c Case - 18 Wheeler simulation game
d Case - Configurable component
e Case - Partly configurable device
f Case - Support component re-use
g Case - Component cost reduction
h Case - Create new configurable product family
i Case - Create partly configurable ship

The results of Table 4 show that a dependency was found between the object (Product Structure) and the instrument (Design Process) in all Cases. The results are visualised in the picture of an Activity System where arrow thickness represents the extent of dependency, as depicted in Figure 70.

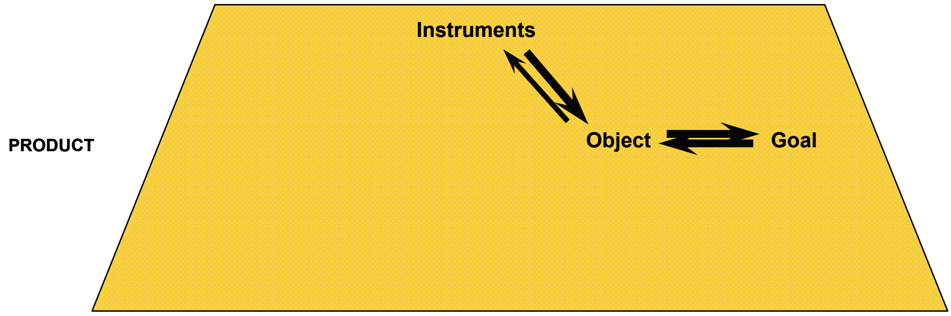


Figure 70. The dependency between Technical System and Design Process within Activity System. The arrow thickness describes the intensity of dependency of the Cases.

The result follows Hubka's alignment:*" The essential knowledge applicable for method must originate from the technical system, the object being designed"* [Hubka 1996, p.133.]. Based on this evidence, it is valid statement that there is a dependency between the Technical System (TS) and the Design Process (DP). The results also show other dependency chains between the object and the instruments. Some TS-DP dependencies did not occur directly via the object, i.e. the product structure, but via a longer route. These cause-effect chains are visualised in Figure 71.

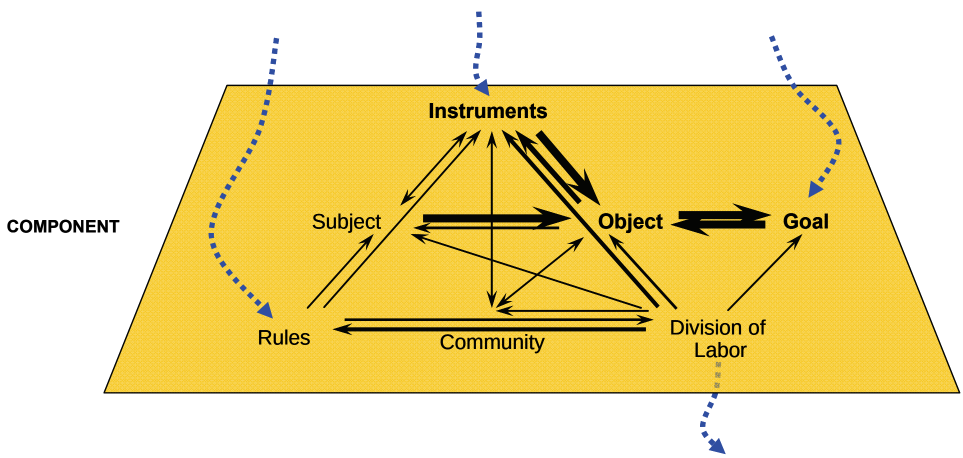


Figure 71. The cause-effect chains from other Activity Systems and elements. The analysis reveals that other Activity Systems impose goals, rules, and instruments on the target Activity System.

Some dependencies in the data occurred from the company-level down to the component level CHAS and had an impact on the TS or the DP. When different levels of Activity Systems and dependencies between the Activity Systems are included, one can obtain a view on a holistic network of dependencies with an impact on the Design Process and Product Structure, as illustrated in Figure 72.

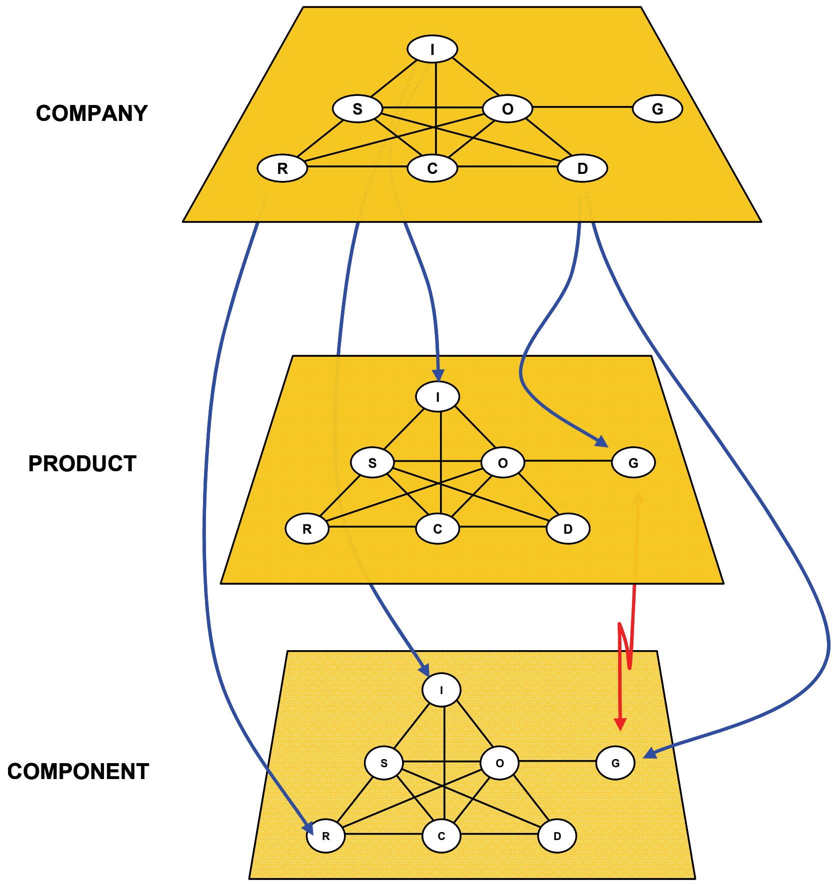


Figure 72. The holistic picture on cause-effect chains in the network of three Activity Systems. The goal conflict between product and subsystem due to company-level division of labour is indicated with red arrow.

The Figure 72 is a simplified picture only visualising the dependencies within Activity Systems and between three Activity Systems. There are numerous cause-effect chains that have an impact on the instruments, the object, and the goal on the product level in the network of Activity Systems. In Nokia, typically over 10 Activity Systems are necessary for new product development; in the Case I, there were dozens of subcontractors, i.e. more than 20 networked Activity Systems. This implies an intense network of dependencies (and potential conflicts) in the companies' operative context.

7.2 Analysis of Design Processes of Nokia Cases

This data is gathered from the Nokia Cases with a detailed analysis of the instruments in use, both documented and undocumented processes and practices. The objective is to focus on the delta between the Design Processes for different TS types in the Nokia Cases. These are compared in Tables 5, 6 and 7. The process phases are presented as they are used in Nokia R&D to simplify the mapping of results. In general, the Design Process at Nokia consists of five phases:

1) Identify needs,
2) Define architecture,
3) Specify components,
4) Manufacture, and
5) Integrate and verify

7.2.1 Identify needs

The Identify needs phase begins by gathering the requirements from all the relevant stakeholders in all the relevant product phases. Typical stakeholders include consumers, mobile cellular network operators, marketing, R&D, manufacturing, operations, logistics, sourcing, and after sales. The life-phases of a product are creation, launch, usage, and recycling. Table 5 shows the identification needs for the design tasks in various Design Processes.

Table 5. Design Process tasks in identify needs-phase.

GOAL	Commonality via standard element.	Variability with commonality via standard elements and configurable elements.
OBJECT/ FOCUS	How to identify parameter values for standard component?	How to identify variation parameters and potential values of each parameter? How to define needed parameter combinations?
INSTRUMENT	Synthesis resulting in parameter values.	List of design parameters with desired values. E.g. conjoint analysis, pair wise comparison
DESIGN TASK	Identify needs and derive requirements for standard component	Identify needs and derive requirements for configurable component.

Each Design Process in each case has emphasis on particular design challenges. In practice the biggest challenge is to derive requirements for a configurable component because the component design depends on the combinations of parametric values. The IC design cannot enable all possible parameter combinations.

Another challenge is that requirements are captured differently for different type of component, and if the requirement capturing method is incorrect the design is lacking of relevant information in next phase. For example, if the goal is configurable component the needs captured as average values do not define configuration parameters nor desired combinations of parameter values. The impact of this dependency is that knowledge of the product-level architecture is needed i.e. the component type before needs capture in order to be able to choose correct needs capturing method for particular component.

7.2.2 Define architecture

This phase uses derived requirements as input and results in description of architecture. In this phase the designer proposes components and the goal of each component i.e. whether the component is one-of-a-kind, standard, configurable, or partly-configurable component. This is presented in Table 6.

Table 6. Design Process tasks in define architecture-phase.

GOAL	Commonality via standard element.	Variability with commonality via standard elements and configurable elements. Re-usable component which is modified with parametric values (see cut-to-fit modularity Chapter 5.3).
OBJECT/ FOCUS	How to specify functionality and interfaces for standard components /IP-blocks? How to partition functional and non-functional requirements to the technical system?	How to specify the components and which combinations of components are allowed and what are the corresponding properties and behaviour of the technical system?
INSTRUMENT	Performance estimations	Configuration model, several models of the architecture
DESIGN TASK	Partition functionality and allocate requirements to standard components	Partition functionality and allocate requirements to components. Specify modularity and configurability needed.

In this phase, the different nature of the Design Process of a standard component and a configurable one is evident. The Design Process of a standard component follows the model proposed by Hubka [. The Design Process of a configurable component requires some additional tasks [Lehtonen 2007a], e.g. the creation of a configuration model. There exist several methods for doing this, but the challenge related to the maintainability of a rule-based or a constraint-based configuration model still needs to be resolved.

7.2.3 Specify components

Specify/select – Nokia has a possibility to define own proprietary components for Nokia use only. This is emphasised in Design Process because selecting ready-made component is clear-cut and no process exists for that, only quality and supply criteria. The Table 7 describes the design task difference when component is specified. Usually the component has internal architecture and similar design tasks are needed as described in previous chapter.

Table 7. Design Process tasks in specify components-phase.

GOAL	Commonality via standard element.	Variability with commonality via standard elements and configurable elements.
OBJECT/ FOCUS	Synthesis	Synthesis
INSTRUMENT	List of Design parameters with desired values	List of Design parameters with desired values per each parameter.
DESIGN TASK	Specify standard element. Specify internal architecture of the standard element (see previous phase).	Specify configurable element. Specify internal architecture of the configurable element (see previous phase).

7.2.4 Integrate & verify

The manufacturing of both component types is done similarly so there is no difference in tasks except the task of verifying. The verification takes place in many levels and in each level there is difference how the verification is carried out. The standard component is verified with verification environment and the interfaces, functionality, performance and reliability is tested with several test methods. With configurable component the difference is the vast amount of test cases needed to cover all possible parameter combinations of the IC. The verification space can be calculated: if there are 10 interfaces, each of which has 10 pins and each of which can have 3 different functions the total test cases reach 10*10*3=300 test cases. In practice, the IC has some 300 pins, over 1000 adjustable parameters and millions of potential combinations. This imposes verification challenge because it is practically impossible to verify all combinations. The design tasks do not differ as such except for regarding verifying configurable or partly-configurable element as discussed above.

7.2.5 Dependencies in the design tasks of the various Design Process –types

The dependencies of design tasks are captured in a matrix. The matrix covers only the first three parts of the Design Process, due to the lack of dependency data for the latter parts of the process. The activities indicated in the rows need input from the columns if their intersection is blue. These dependencies can increase iteration in the Design Process.

For example, if the needs are captured for a standard PS type (column) but the design task is specify architecture of a partly-configured PS type (row), the needs capturing must be performed again. The matrix indicates that it is not feasible to use the information of a standard PS type for a partly-configurable PS type. In practice, this means that one must have a good understanding of the PS type before any Design Process activities are carried out. As this is impossible by definition, the other solution is to use iterative process models to analyse and synthesise the product structure.

One observation is that one is able to specify the architecture for a partly-configurable product only if the needs capture is performed for the same Product Structure type. When specifying the architecture for a standard product, the designer is able to use the requirements captured for a configurable or a partly-configurable product. The results indicate that the complexity increases and the nature of information changes from a Design Process for a unique product towards a Design Process for a partly-configurable product.

Table 8. Dependencies between different design tasks of Design Process types.

	Capture needs	one-of-a-kind	standard	configurable	partly-configurable	**Specify architecture**	one-of-a-kind	standard	configurable	partly-configurable
Capture needs	o									
one-of-a-kind		o					p			
standard			o					p		
configurable				o					p	
partly-configurable					o					p
Specify architecture						o				
one-of-a-kind		x	x	x	x		o			
standard			x	x	x			o		
configurable				x	x				o	
partly-configurable					x					o
Specify component										
one-of-a-kind							x	x	x	x
standard								x	x	x
configurable									x	x
partly-configurable										x

The results in Table 8 also indicate a need with blue box and potential need (indicated with the letter p) for iteration from the Specify Component phase to the Specify Architecture phase, and from the Specify Architecture phase to the Capture Needs phase. The conclusion is that it is important to perform the requirements capture task with an appropriate focus as well as performing the Specify Architecture having the Product Structure type in mind. This was indicated in the Nokia cases and in literature. This can decrease the iterations needed during the development.

7.3 Design goal combinations and Product structure types

The analysis is performed for goals relevant to variability and commonality. The data indicates that design for re-use and design by re-use are crucial in the industry. The potential goal combinations with a corresponding Product Structure type are illustrated in Figure 73. Only some goal combinations are rational and benefit the industry, others are possible but they make little or no sense with regard to the industrial objectives. Figure 73 is interpreted from left to right. In every junction, one goal is added to the design task. For example: *Engineering in OD process AND Design for re-use AND Design by re-use AND Variability AND Commonality* → this goal combination leads to Case A – a configurable PS-type. These goal combinations are useful for target-setting and understanding the targets as shown in Figure 73.

Table 9 is a summary of the different goal combinations with a practical example and comments on the reasoning of that particular combination to the company. It lists the combinations and proposes such combinations that are to be used with Design Processes. Some of the goal combinations are in contradiction and those need to be avoided. The table can be used when considering the appropriate design goals for the project.

Table 9. Evaluation of goal combinations.

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	

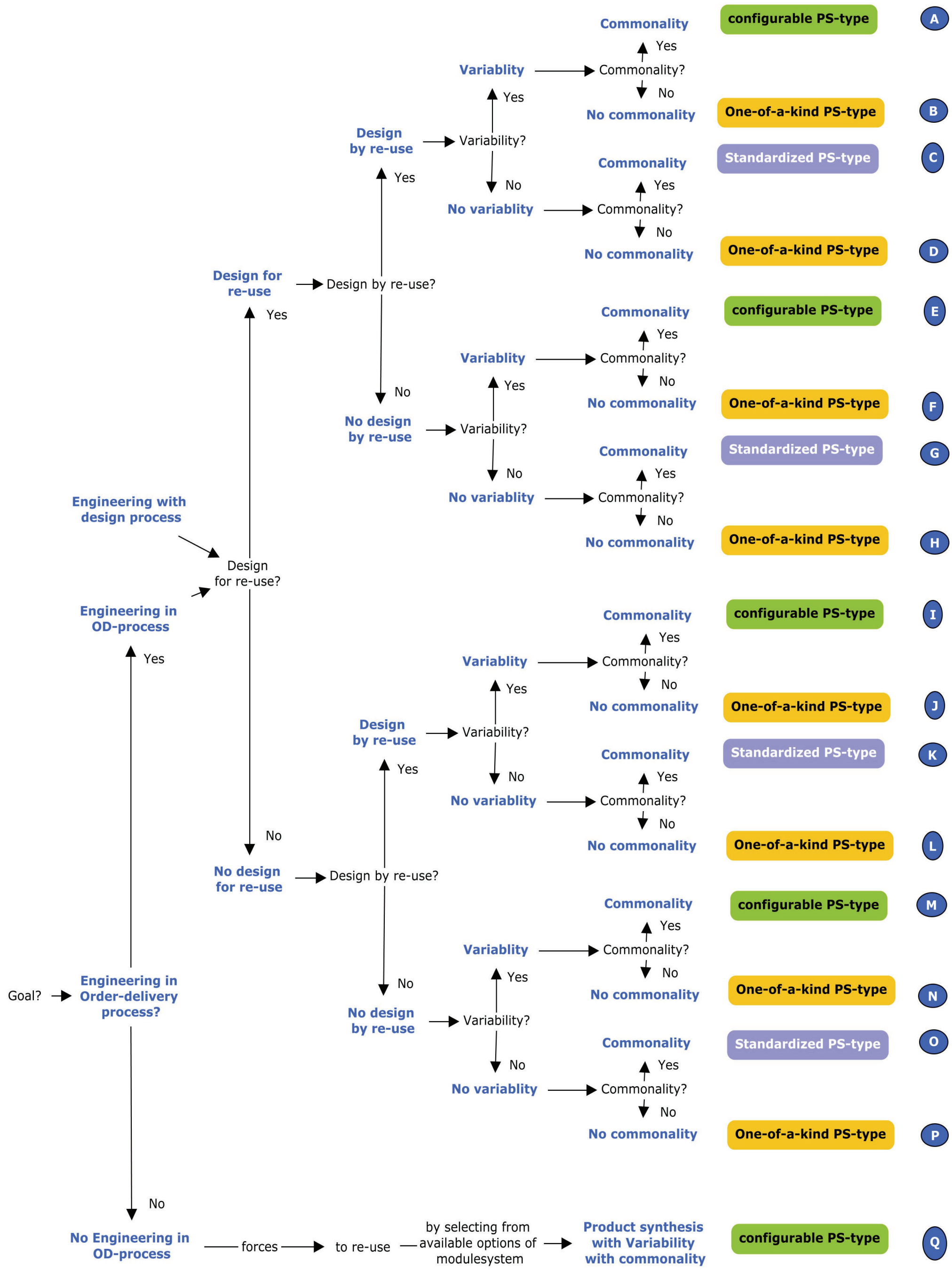


Figure 73. Goal combinations and corresponding PS-types. Goal combination I is an example of waste work because work effort is invested for configurable product structure and the goal is not to re-use it (Design for re-use? – No.). Goal combination J is appropriate in this case as the one-of-a-kind product structure requires less work effort.

7.4 Goal conflicts in Activity Systems

The data from Cases C and E imply that some goals are contradictory in an operational context. Conflicts were detected between one-of-a-kind vs. design for re-use and one-of-a-kind vs. design by re-use; rule conflicts also occurred. There are a number of conflicts between the various elements; conflicts related to design goals, Product Structure, or the Design Process.

7.4.1 One of a kind vs. Design for re-use

In Case E, the goal for $AS_{component}$ is to develop an element for design re-use. The $AS_{product}$ aims at a product synthesis thus expecting a one-of-a-kind solution from $AS_{component}$. This creates a conflict between Activity Systems. Should the latter goal win, the product synthesis is improved but benefits, e.g. from economies of scale are not available. If design for re-use wins, it may undermine the product synthesis e.g. in terms of competitiveness.

7.4.2 One of vs. Design by re-use

This goal conflict occurs between the subjects, i.e. the designer and the object and the goal. The conflict was observed in a number of Cases, and no single explanation was found for it. Unless the conflict is resolved, the company fails to benefit from the re-usable asset, and the extra design work effort will result in delays in the project, undermine economies of scale, increase the risks, and potentially decrease the quality of the product.

7.4.3 Rule conflict

When analysing an Activity System with project delivery and transforming towards configurable delivery, one clear rule conflict emerges. In a project-delivery company, the practice is to capture the needs for a particular delivery. Companies with configurable products apply an entirely opposite approach: the customer is made to select from the existing options and cannot set any requirements for the product.

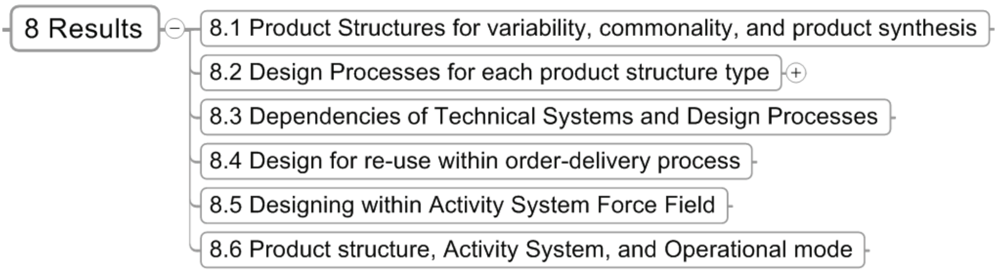
Contribution to the research questions

The analysis in Chapters 7.1, 7.2 and 7.3 contribute to the research question 2 by indicating that fit between TS and DP is needed.

The analysis in Chapter 7.1 contributes to the research question 2 by addressing the role of tools, methods, design guidelines, and checklists as instruments of CHAS having an effect on design tasks. Chapter 7.2 contributes to the research question 2 by describing the differences between design tasks and the fit needed of design tasks to different product structures.

The analysis of Case C and Case D contributes to the research question 3 by describing phenomenon “capturing ready-made synthesis” that decrease R&D efficiency. The design by re-use increases R&D efficiency but the capturing of ready-made synthesis requires work effort due to the learning needed thus decreasing R&D efficiency. The analysis in Chapter 7.3 and 7.4 contribute to the research question 3 by describing desired goal combinations and the result of conflicting design goals of two different Activity Systems. The analysis in Chapters 7.1 and 7.4 contribute to the research question 3 by describing the dependences and goal conflicts between Activity Systems.

8 RESULTS



This chapter comprises the results of this research; a classification of Product Structure types, a process model for different Product Structure types, the dependencies between Technical Systems and Design Processes, the aspect of design for re-use and design by re-use, the treatment of product structuring within the Activity System Force Field, the identification of operational mode dependency to Product Structure and Activity System, and concludes how these results contribute to the research questions.

8.1 Product Structures for variability, commonality, and product synthesis

Based on empirical data, several product structure types were found. The classification is influenced by and shares a similar philosophy with the design paradigms proposed by Victor et al. [Victor et al. 1998]. Technical System consists of standardised, configurable, one-of-a-kind product structures and combinations of those. In practice, this division can be found in a product that consists of parts that are initially separate. The classes are characteristics of the Technical System. A mechatronic product consists of one of following product structures:

1. The One-of-a-kind PS type has one goal: **a unique** synthesis that meets the needs. It is designed for a particular solution, and the objective is to achieve a technical system that meets the needs. This type can contain unique parts and standardised parts. The unique parts do not fit mass production, i.e. it may be possible to manufacture unique parts using the existing equipment but the efficiency and costs are not on the mass-production level. The standardised parts fit to mass production.

2. The Standard PS type has two goals: mass production and product synthesis. The goals for standardisation can be re-use within one product, re-use across products within the company, or re-use in multiple industries and value chains. The synthesis may have various sub-goals: a product synthesis or a component synthesis. The difference is in the goal of the optimisation: when developing a re-usable component, the goal is on the component synthesis which may have a negative impact on the product synthesis, which is acceptable. Standardisation is not an explicit term, and this research has identified three different scopes for standardisation. The goals are:

1) Re-use within one product,
2) Re-use across products within the company, and
3) Re-use in multiple industries and value chains.

The different scopes into a standardised product structure have an impact on the Design Process. For example, the requirements differ from each other. The capturing of requirements for an element re-usable within one product involves fewer stakeholders than the capturing of requirements for an element re-usable in multiple industries and value chains. Merely this task in the Design Process is different and thus requires a different analysis and synthesis task along the process. The standard PS type contains standardised parts.

3. **The Configurable PS type** is a product structure with three goals:

1) Variety by modularisation or configuring,
2) Commonality by re-use, and
3) Product synthesis.

It consists of standard and configurable parts. Variability is achieved via configurations: re-using a particular combination of standard 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 also involves a sub-goal: no engineering design is needed in the order-delivery process.

4. The Partly-Configurable PS type has three goals:

1) Product-level synthesis,
2) Commonality by re-use, and
3) Variety by configuring or modularisation.

The goal for the product synthesis can be on the product level or the element level (which can be a separate product itself). It may contain standard parts, configurable parts, one-of-a-kind parts, and partly-configurable parts. It is a combination of the other product structures defined above. This also follows the findings of Pulkkinen [Pulkkinen 2007].

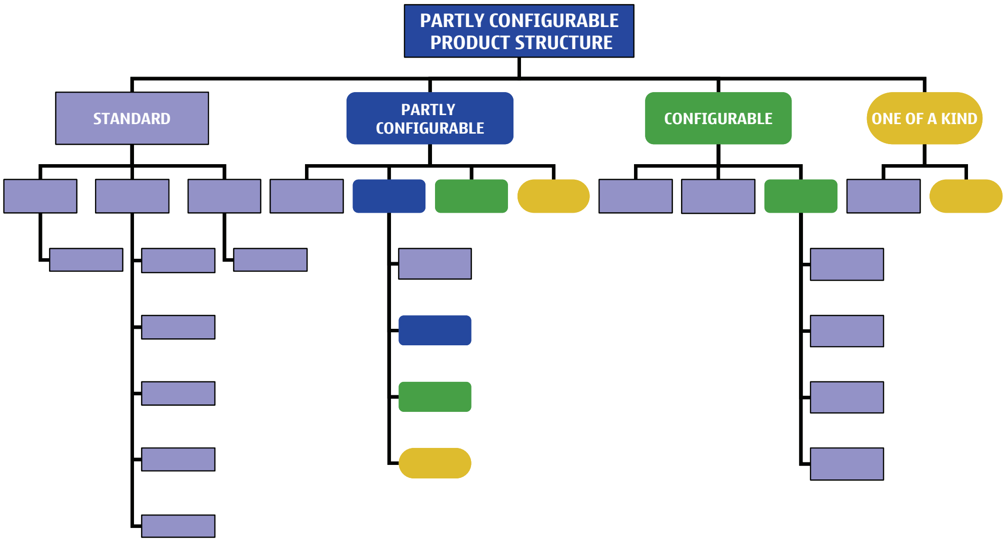


Figure 74. *The classification of product structures [Juuti et al. 2006].*

In the example in Figure 74, the product structure type is partly-configurable and consists of standard parts, partly-configurable parts, configurable parts, and one-of-a-kind parts. The product breakdown structure shows the recursive nature of the product structures. For example, the configurable element can contain configurable sub-elements. In the Case I, all these PS types were found. There, the objective of the shipyard was to decrease costs by having less one-of-a-kind and partly-configurable elements and more standard and configurable elements because they are based on mass production and thus enable a lower bill of materials. The product structure types are similar to module drivers proposed by Erixson [Erixson 1998]. The standardised product structure type corresponds to module drivers “Carry over” and “Common unit”. The configurable and one-of-a-kind product structure type corresponds to module driver “Technical specification” and “Styling”. The design goals and design tactics are summarised in Figure 75.

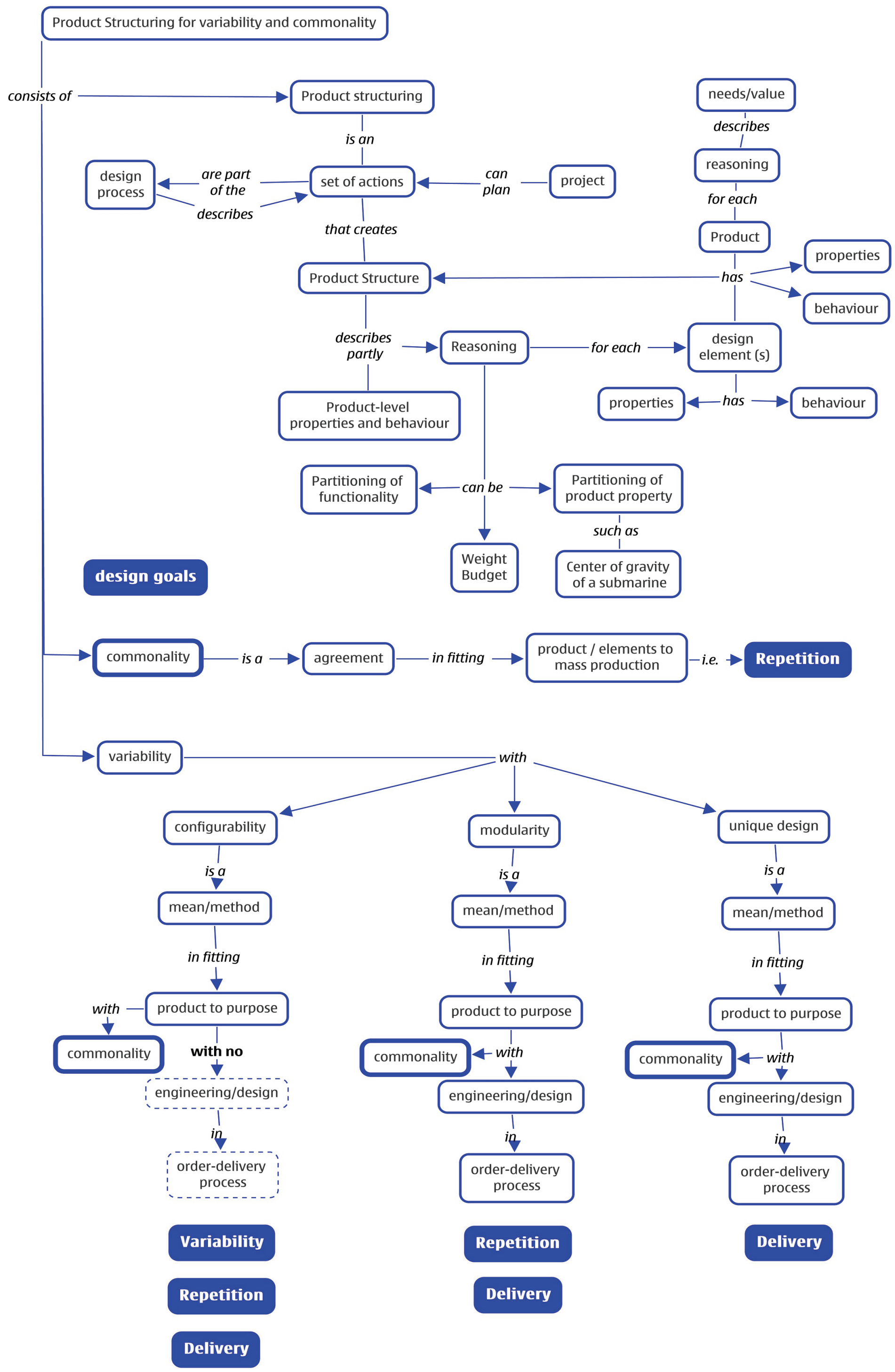


Figure 75. The summary of design goals (marked with blue background) and design methods. Configurability aims to variability and repetition and delivery (synthesis) as the unique design aims to delivery only. This explains the difficulty when designing configurable products.

The underlying product structuring idea found in the industry is to allocate particular product properties to a certain part. In Nokia´s case, for example, variability was allocated mainly on one configurable hardware component enabling mass production and late-point differentiation with software settings. The use of standard components enabled high production volumes and a low bill of materials. On the general level, the product structure types can be analysed with a triangle, each tip representing a 100% composition of one PS type, as depicted in Figure 76.

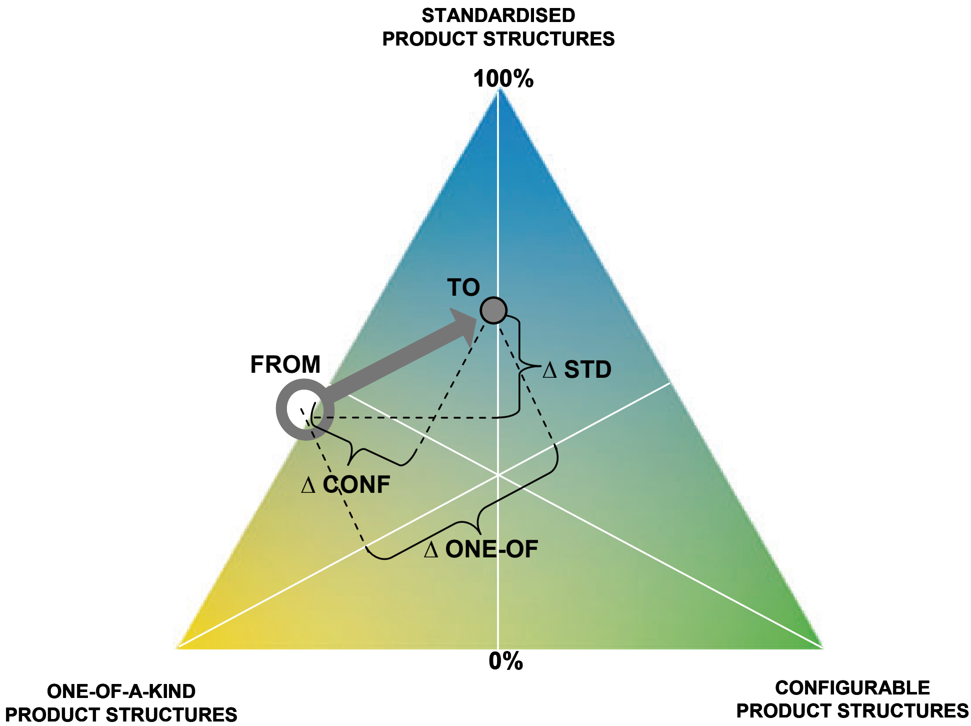


Figure 76. General- level target-setting for Product Structuring. The idea is to set targets to the product structure in terms of product structure types. In this example the target is to decrease the amount of One-of-a-kind structures (from 70% to 30%) and increase the amount of standard structures (from 50% to 70%) and configurable structures (from 0% to 20%).

With this approach, the company can choose in which direction to improve the Product Structure. In this case, the product consists of standardised and one-of-a-kind elements only, and the objective is to decrease the amount of one-of-a-kind product structures by 40%, to increase the amount of standardised product structures by 20%, and to increase the amount of mass-customised product structures by 20%.

8.2 Design Processes for each product structure type

The analysis of the empirical data indicated that a certain PS type was designed using a particular Design Process. It also indicated a dependency from the PS type to the Design Process. This research found differences between the Design Processes and built a process model based on that. The intention of the model is to differentiate four Design Processes for the different PS types. This is not fully aligned with the empirical results, as some activities between the different processes are the same even if the PS goal is different. For example, the activities in the manufacturing and integration phase are similar between standard and configurable product structures.

The purpose of the model is to highlight that a different product structure either requires different design tasks and/or the design tasks are to be performed differently for different product structures. For example, the "specify architecture" for a standard PS type and a configurable PS type differ considerably; the capturing of the configuration rules and constraints is a design task for a configurable PS type but not applicable for a standard PS type.

The phases of the model are based on system engineering practise. The mapping of the data from Nokia Case was more accurate to these phases than Design Processes proposed by Hubka, Ulrich or VDI2221. Concepting is not visible as it was observed only on product level but not on component/part level. This model visualises the most important phases where difference on design tasks was observed. The difference between tasks is analysed in Chapter 7.2.

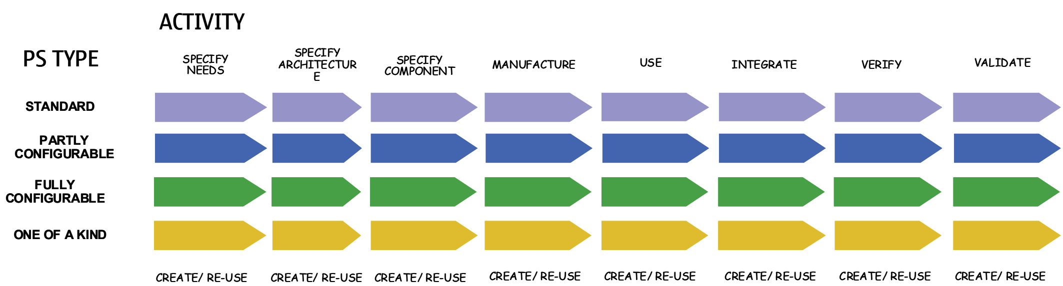


Figure 77. Model for different Design Processes. Note: The activities are not on timeline.

In Figure 77, each PS type has its own horizontal process flow where the time goes from left to right. If the goal is a standard PS type, the designer will first use the horizontal set of activities and carry out those activities as specified for that phase. The "Use" phase is added to highlight that all components are not re-designed, but they are re-used.

Figure 78 provides an example of a product. It is a snapshot immediately following the "Specify architecture" phase when information exists on the architecture of the product and the allocation of PS types to product elements. The PS type is partly-configurable, and the elements that need to be designed are marked with the "new" sign. The rest of the elements are re-used.

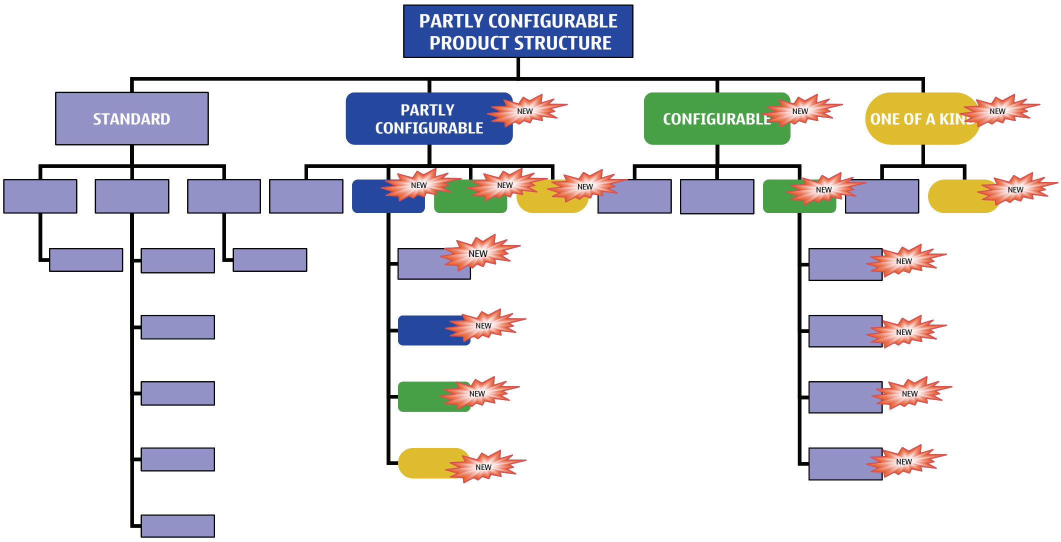


Figure 78. Product Structure decomposition of the case example.

Now the Technical System is defined on high level and one can plan which process elements are needed. The needed elements are visualised in Figure 79.

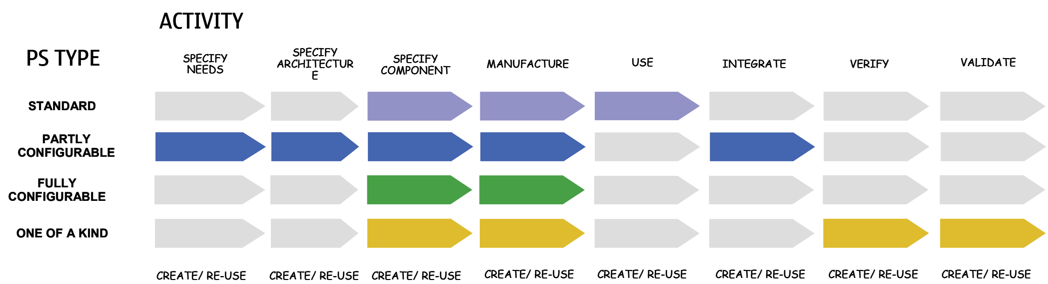


Figure 79. The process elements needed by the Technical System to be developed.

All unnecessary elements are indicated in grey. The project manager can now pick all the relevant process elements for each PS element marked with the "new" sign. When the work effort per each element is estimated and resource allocation is in place, the project manager is able to write a project schedule based on this information.

8.3 Dependencies of Technical Systems and Design Processes

In the Domain Theory and in the Theory of Technical Systems, a system can be decomposed to smaller entities or subsystems. When they are combined it with TS-DP dependencies and the dependencies between process activities, there is a full view of the dependencies. The chain of dependencies is shown in Figure 80

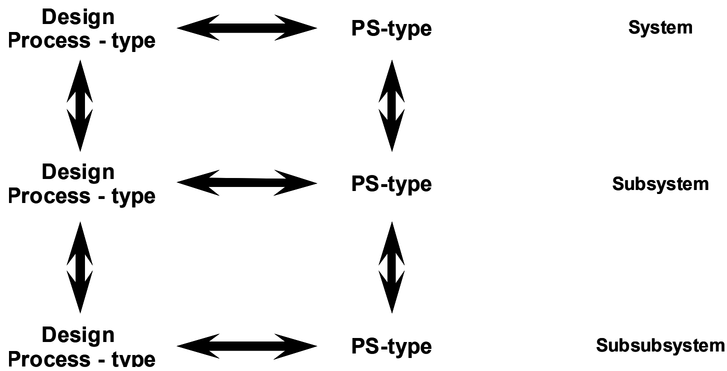


Figure 80. Dependencies of Technical System and Design Processes. A change in subsubsystem´s Design Process type can result in changes on the product structure synthesis on system level.

The dependencies between the different levels of a Technical System are shown on the right-hand side as proposed in the Domain Theory and the TTS. The results presented in this work indicate dependencies between the Technical System and the Design Process. Further analysis of the design activities in the previous chapter implies that the Design Process types on the various TS levels also contain dependencies. These dependencies result in a dynamic setup; if the TS architecture changes on any abstraction level, it has a potential impact on the other levels of the Technical System and the Design Process type.

To improve R&D efficiency, one is tempted to organise and match the PS types and the Design Process types during the R&D project. This is aligned with Hubka´s general procedural plan [Eder 1995]. The fit between organisation, design process, and modularised product is also proposed by Holmqvist et al. [Holmqvist et al. 2004]. He proposes that *"… the existing organisation and the product development process also have to be adapted to better suite modularization and to be suitable for the development of modularized products".* This improves the R&D efficiency due to less wasted work on wrong processes and less iterations needed. However, the dynamics between the levels and the Design Process and the TS set a considerable challenge for planning and managing the use of correct process elements for a particular PS type.

Another challenge is that the designer seldom follows the Design Process exactly as intended. This diminishes the value of planning and configuring the Design Process to meet the Technical System and the PS types on various abstraction levels.

8.4 Design for re-use within order-delivery process

The delivery flow is an operative element that has an impact on product structuring. It describes which organisation or company delivers their part of the technical system to whom. The delivery flow can be internal, within the company, or operate through the company. An order-delivery process is a typical delivery flow, starting from the customer order and ending in the delivery of the product to the customer. An order-delivery process can contain R&D activities if the product is one-of-a-kind or partly-configurable. The standard PS type and the configurable PS type do not require engineering in an order-delivery process.

When the company has decided to utilise design re-use, they set up separate projects or an organisational entity that focuses on design for re-use, as at Nokia, Philips, and VAG Corporation. If design is performed in the order-delivery process, the goal is different; the aim is to deliver a product synthesis on time. The time pressure can deviate the PS type e.g. from a standard type to a one-of-a-kind PS type. This was observed in the Case of Nokia and has been the reasoning behind separating the Design Process and the order-delivery process from each other. Different order-delivery processes are illustrated in Figure 81.

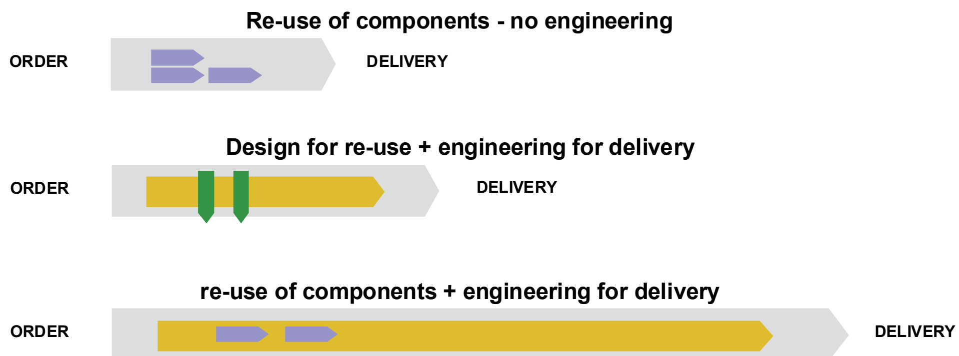


Figure 81. Different order-delivery processes. The direction of arrows indicates the different design goals. In the second case the green arrows indicating projects designing for re-use and the yellow arrow indicating the delivery project have conflicting design goals.

The colour blue indicates the re-use of components, orange the engineering effort, and green a design for re-use effort. The rest of the activities in the process are indicated in grey. The mixing up of design for re-use and engineering for delivery is complicated, as the goal of design for re-use is in a number of products, not only for this particular delivery. These goal conflicts were identified in cases where the Design Process for a standard PS and a configurable PS was part of the order-delivery process.

Design by re-use has an impact on the synthesis in having constraints from the parts structure early on. Design by re-use has an impact on how the synthesis is created, as visualised in the Domain Theory by Andreasen in Figure 13 [Andreasen et al.1997]. This is also mentioned by Hubka: *"For instance many design characteristics are already defined for an individual branch at the start of a Design Process i.e. designing begins from the organ structure or even only within the component structure. This…has not up to now been clearly and explicitly expressed in the theory"* [Hubka & Eder 1998].

The conclusion, based on the analysis and CHAT, is that different operational modes require different CHAS-networks for improved R&D efficiency. The concepts and their connections are presented in Figure 82.

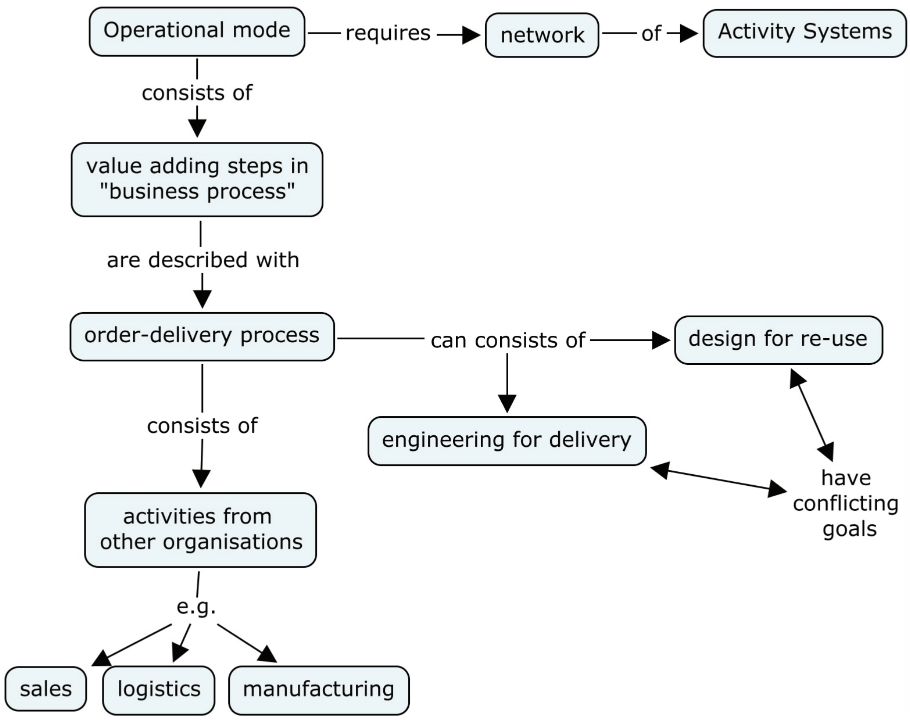


Figure 82. Concept map describing the dependency between operational mode, Activity System, and order-delivery process.

The order-delivery process is a result of the chosen operational mode in R&D and with R&D and an example of division of labour of the CHAS. The operational mode drives particular CHAS networks and dependencies in the network.

8.5 Designing within Activity System Force Field

The Design Process within an Activity System has a number of dependencies, as analysed in Chapter 7. As this research treats these dependencies as force vectors and takes into account all the forces having an impact on the Design Process, the statement that product structuring takes place within the Activity System Force Field can be made. The Force Field is visualised in Figure 83 using Hubka's model of the Design Process. The whole transformation system takes place within a Force Field and the Force Field can manipulate the design management, the working means, design tasks etc. It can e.g. deviate the project from designing re-usable element to design a one-of-a-kind element which was discussed in Chapter 8.4. The recognised forces are originated from the motives and goals of Activity System and are visible in the analysis in Chapter 7.1. See Table 4.

The different PS processes are inserted inside. The colour yellow indicates the Force Field that has an impact on the design activities. The picture aims to visualise the difficulty of following the Design Process for a configurable element all the way from left to right if the designing is part of an order-delivery project with tight schedules and conflicting goals. The TS and Design Process are now in an operational context.

Another viewpoint to the same phenomenon can be illustrated by having Activity Systems on different levels of the Technical System and mapping the dependencies there. The company-level Activity System has dependencies on several levels, and in some cases, conflicts in the goals, rules, division of labour, and other CHAS elements occur. Product Structuring with a Design Process takes place within the Force Field generated by one or multiple Activity Systems. The network of different Activity Systems (see Figure 72) within the Force Field provides fruitful grounds for various conflicts to emerge during the Design Process, as analysed in Chapter 7. If the Activity System goal is well aligned with the Technical System goal, the delivery meets the needs. In other cases, the delivery meets the needs of the Activity Systems involved and the added value for the customer will suffer.

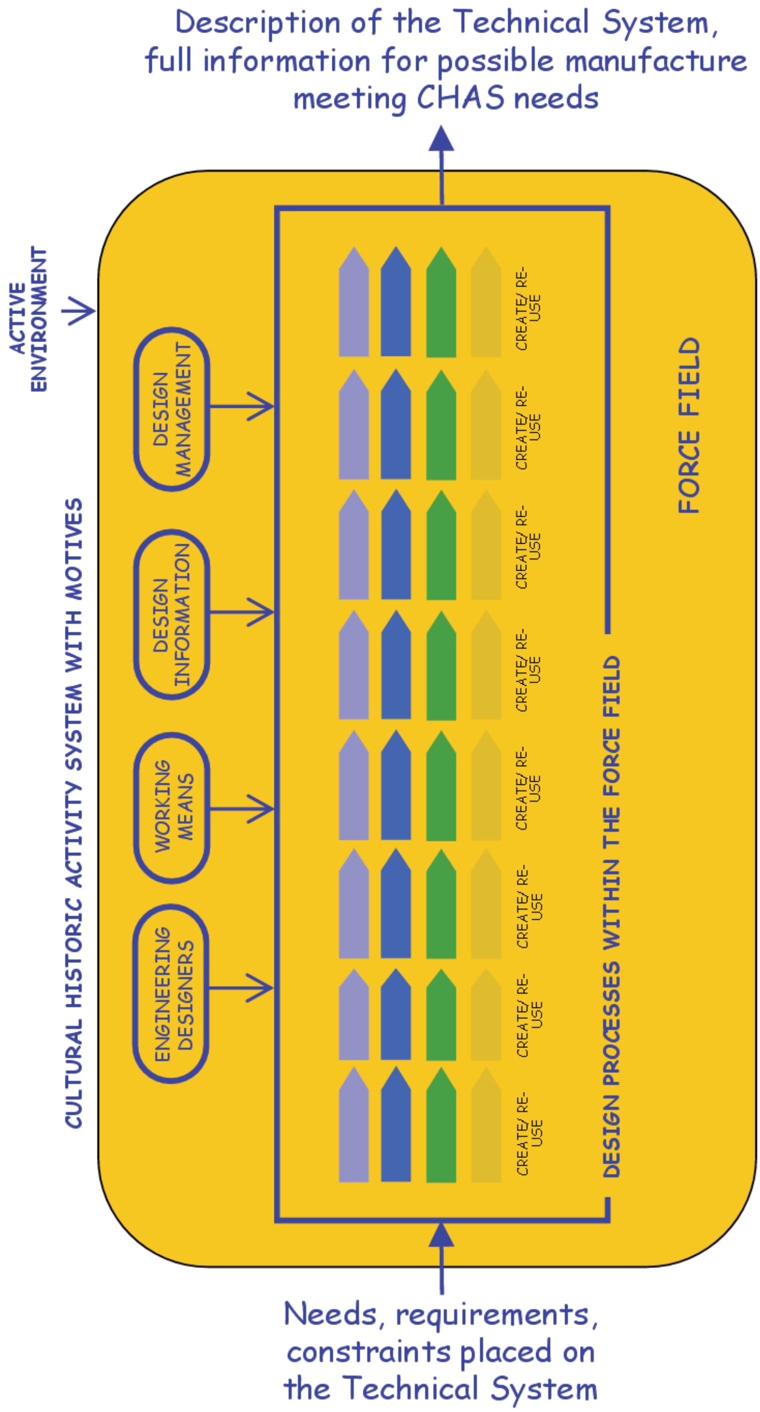


Figure 83. Designing within a Force Field. The Design Process and design tasks are continuously exposed to forces originating from the Activity System(s).

8.6 Product structure, Activity System, and Operational mode

The observations in previous studies [Juuti et al. 2006] gives evidence that there are different types or classes of structural elements. A variety of Product Structure types were found in industry and no research results were found to be in contradiction of the statement. The analysis of the correlation of PS types and the combination of design goals was performed in Chapter 7.3. The analysis proved this statement to be a true. Research on modular methods in Chapter 5.3 does not contradict with this.

Differences between the Design Processes were analysed in Chapter 7.2, and the results support the statement. An analysis using the Cultural Historic Activity Theory was also used in Chapter 7.1, and the results support the statement, as well as the research results presented in Chapter 8. The research results indicate that Product Structure and Activity System need to be aligned with the operational mode. This is also supported by the findings in Chapter 5.6.2 and 5.6.4.

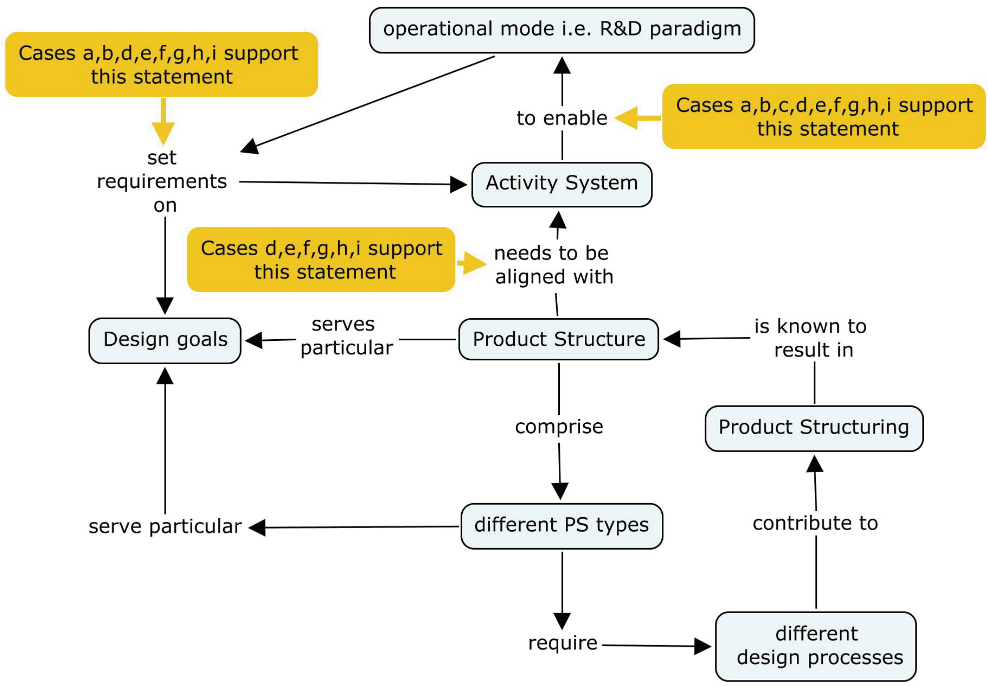


Figure 84. The role of Product Structure and Activity System in particular operational mode. The product structure needs to be aligned with Activity System to enable and to gain the benefits of particular operational mode.

The overview of the synthesis is visualised in Figure 84. The operational mode is enabled by aligning the Product Structure and the Activity System. If the Activity System or network of Activity Systems is not aligned with the Product Structure and the Operational mode, the efficiency and the quality of the deliveries are negatively affected.

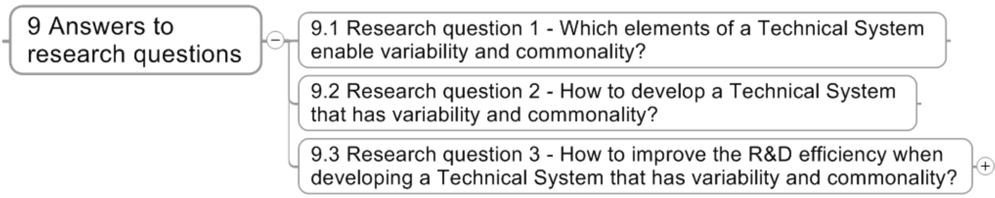
Contribution to the research questions

The results in Chapter 8.1 contribute to the research question 1 by proving that commonality is achieved with standardisation of behaviour and properties of product element. It also contributes by describing the other Product Structure types as elements enabling commonality, variability and product synthesis.

The results of Chapter 8.2 and 8.3 contribute to the research question 2 by proving that certain product structure is developed with corresponding Design Process and design tasks. For example, configurable product structure requires design tasks that define the configuration model consisting of configurability rules and/or constrains. The results in Chapter 8.2 contribute to the research question 2 by proving the Design Process that uses appropriate design tasks delivers product structures that enable variability, commonality, and product synthesis. The delivery is verified by using milestone criteria, and redesign is needed if criteria are not met. Such milestone criteria for Design Process, derived from design goals, that requires standardisation, modularisation or configurability enable variability, commonality, and product synthesis because the delivery is evaluated against milestone criteria.

The result of Chapter 8.5 contributes to the research question 3 by describing the Designing within Force Field and how the Force Field can deviate from original design goals and/or Design Process thus not meeting the milestone criteria or criteria of other Activity Systems. The result in Chapter 8.6 contributes to the research question 3 by describing the dependency between Product Structure, Activity System and operational mode as solution in aligning motives of several Activity Systems.

9 ANSWERS TO RESEARCH QUESTIONS



This chapter covers the answers to the research questions.

9.1 Research question 1 - Which elements of a Technical System enable variability and commonality?

The elements of Technical System enabling variability and commonality are Standard, Configurable, One-of-a-kind and Partly-configurable Product Structures.

The study on the theory basis, state of the art and empirical study is done in two companies to identify the elements and characteristics of the elements. The Product Structuring models in Chapter 4.3 contribute to the research question 1 by describing characteristics of product family architecture that serves as module system for configurable product. The Chapters 5.1, 5.3 and 5.4 contribute to the research question 1 by describing standardisation, modularity, and configurable product structures.

The Cases D – "Configurable component", Case E – "Create new product" and Case I – "Partly-configurable ship" contribute to the research question by indicating characteristics of Technical Systems that are investigated in this research to give focus to the "how" research questions. Agreed interfaces and behaviour of the element enable product synthesis when unique elements are fitted together with standard, unique or configurable elements. The results in Chapter 8.1 contribute to the research question 1 by proving that commonality is achieved with standardisation of behaviour and properties of product element. This enables modularity which enables configurability serving variability.

The characteristics of the elements are (see Chapter 8.1):

1) The One-of-a-kind Product Structure enables one goal: a unique synthesis that meets the needs. It can contain unique parts and standardised parts.

2) The Standard Product Structure enables two goals: mass production and product synthesis. The standard Product Structure type contains standardised parts.
3) The Configurable Product Structure is a product structure enabling three goals: Variety by modularisation or configuring, Commonality by re-use, and Product synthesis. It consists of standard parts and configurable parts.
4) The Partly-configurable Product Structure enables three goals: Product-level synthesis, Commonality by re-use, and Variety by configuring or modularisation. It can contain standard parts, configurable parts, one-of-a-kind parts, and partly-configurable parts.

9.2 Research question 2 - How to develop a Technical System that has variability and commonality?

The development of Technical System that has variability and commonality needs:

1) **Design Process for each Product Structure type,**
2) **The fit between Product Structure type and Design Process type, and**
3) **The fit between Design Process and Project Management Process**

The study on the theory basis, state of the art and empirical study is done in two companies to identify how to manage the development. The Activity System Theory discussed in Chapter 4.6 contributes to the research question by indicating fit needed between Technical System and Design Process. The state of the art in Chapter 5.3 contributes to the research question by describing Design Process needed for certain TS characteristics. The Cases D, E, F, G, H and I (see Chapter 6.) contribute to the research question by indicating the need of Design Process and the dependency between Technical System and Design Process.

The analysis in Chapters 7.1, 7.2 and 7.3 contribute to the research question by indicating that fit between TS and DP is needed. The results of Chapter 8.2 and 8.3 contribute to the research question by proofing that certain product structure is developed with corresponding Design Process and design tasks. For example, configurable product structure requires design tasks that define the configuration model consisting of configurability rules and/or constrains. It proves that certain product structure is developed with corresponding Design Process. In other words; certain product structures require certain design tasks.

The partial answer to the research question 2 is that certain product structure is developed with corresponding Design Process and that certain product structure requires particular design tasks. Therefore, the conclusion is that the development of Technical System that has variability and commonality is developed in such a manner that each product element with particular Product Structure type (see Chapter 8.1) is developed using appropriate Design Process type (see Chapter 8.2). Thus, Design Process for each Product Structure type is needed.

The Design Science in Chapter 4.1 contributes to the research question by presenting the design management as one element having impact on the Design Process by setting acceptance criteria on the design, as depicted in Figure 8. The Chapter 4.4 contributes to the research question 2 by defining framework for Design Coordination. Activity System Theory in Chapter 4.6 contributes to the research question by indicating the dependency between Technical System and Design Process. The state of the art in Chapter 5.3 contributes to the research question by describing Design Process and the fit needed between Technical System and Design Process. The Chapter 5.6 contributes to the research question by defining deliveries of the development of standard design architecture presented in Figure 39.

The Nokia Cases, especially Cases A – "Nokia" and B –"Platform mode of operation" contribute to the research question 2 by describing The Nokia process model that consists of inputs, outputs, process, and milestones. The use of similar process model with milestones was observed in all Nokia Cases (excluding the Case A and B as Nokia organisation is not developed with process and the operational mode is not developed with process). In Nokia, the milestone is accepted if the design meets a list of pre-determined criteria defined by the management. Should the milestone be rejected more design work is needed to fulfil the milestone criteria or, occasionally the management is taking risks by accepting the milestone. Also the milestone criteria and design tasks are adopted every time when new project is started. This indicated that fit between Technical System and Design Process does not happen automatically or by itself. The observations in the Cases D to G indicate that the fit needs to be designed.

The analysis in Chapter 7.1 contributes to the research question by addressing the role of tools, methods, design guidelines, and checklists as instruments of CHAS having an effect on design tasks. Chapter 7.2 contributes to the research question by describing the differences between design tasks and the fit of design tasks to different product structures.

The results in Chapter 8.2 contribute to the research question by proving the Design Process that uses appropriate design tasks delivers product structures that enable variability, commonality, and product synthesis. The delivery is verified using milestone criteria and redesign is needed if criteria are not met. Such milestone criteria for Design Process, derived from design goals, that requires standardisation, modularisation or configurability enable variability, commonality and product synthesis because the delivery is evaluated against milestone criteria.

The partial answer to the research question is: The Design Process delivers desired product structure type when there is fit between design tasks and milestone criteria and when there is fit between design goal and milestone criteria. This research considers design tasks as part of Design Process and design goals and milestone criteria as part of Project Management Process. **Thus the conclusion can be reformulated: The Design Process delivers desired product structure type when there is a fit between Design Process and Project Management Process.**

9.3 Research question 3 - How to improve the R&D efficiency when developing a Technical System that has variability and commonality?

The R&D efficiency can be improved when developing a Technical System that has variability and commonality by:

1) **Managing the fit between Product Structure and Design Process,**
2) **Managing the fit between Design Process and Project Management Process,**
3) **Decreasing work effort needed for capturing ready-made synthesis,**
4) **Managing the designing within Force Field, and**
5) **Managing the distributed design activities in many organisations using operational modes.**

This research uses the answers to the research question 2 as a starting point to provide answers to this research question. The misfit of Product Structure and Design Process creates unnecessary work effort that is waste thus reducing R&D efficiency. Therefore, managing the fit between Product Structure and Design Process improves R&D efficiency.

Similarly the misfit between Design Process and Project Management Process creates unnecessary work effort that is waste thus reducing R&D efficiency. Therefore managing the fit between Design Process and Project Management Process improves the R&D efficiency.

This research identifies two phenomena and one best practice was found having effect on R&D efficiency:

1) Capturing of ready-made synthesis
2) Designing within Force Field
3) Design management using operational modes

9.3.1 Capturing of ready-made synthesis

This research discusses the design for re-use and design by re-use. Very little evidence is shown in related research what actually enhances or facilitates design by re-use. The NIH – Not Invented Here –phenomena is well-known and referred but that is not the only phenomena that decrease R&D efficiency in practise. This research introduces the phenomenon “Work effort needed for capturing ready-made synthesis”. The phenomenon exists when designer is aiming a synthesis of Technical System and one needs to re-use ready-made design (i.e. capture sub synthesis and optimise it with the new synthesis).

The Activity System Theory in Chapter 4.6 contributes to the research question 3 by indicating learning needs when the Activity System desires to deliver more advanced and complex technical systems. The state of the art in Chapter 5.3 contributes to the research question 3 by describing design for re-use and design by re-use as a separate items to be managed.

The analysis of Case C and D contributes to the research question 3 by describing phenomenon "capturing ready-made synthesis" that decrease R&D efficiency. The design by re-use increases R&D efficiency but the capturing of ready-made synthesis requires work effort due to the learning needed thus decreasing R&D efficiency. The result contributes on research question 3 by proofing the Design Reuse - capturing the synthesis done by someone else requires work effort. Logically, the overall synthesis is more difficult when combining several readymade sub-synthesis from other persons into a one larger synthesis as if the sub-synthesis would be result of one's own thinking.

The conclusion is that the design by re-use increases R&D efficiency and the capturing of ready-made synthesis decreases R&D efficiency because it requires work effort due to the learning needed. Therefore, decreasing the work effort needed for capturing ready-made synthesis is an important goal for management tasks. This research concludes that the capturing of ready-made synthesis is a phenomenon that calls for more research on how to decrease the capturing effort and how to speed up the learning needed.

9.3.2 Designing within Force Field

This research introduces the issue of conflicting goals in the field of Design Management. Conflicts emerge when several Activity Systems are needed to develop a product and some of the Activity Systems have different design goals. This conflict is very well observable in cases where new, reusable elements are created within project that is operating in order-delivery process thus having tight time pressure on the schedule and deadlines.

The Activity System theory basis in Chapter 4.5 and 4.6 contribute to the research question 3 by indicating potential conflicts needing resolving thus consuming work effort. Cases D and E contribute to the research question by indicating the difference between motives and design goals.

The analysis in Chapter 7.4 contributes to the research question 3 by describing the result of conflicting design goals of two different Activity Systems. The results of Chapter 8.4 contributes to the research question 3 by proving the Management needs to manage conflicts when design for re-use is done within order-delivery process to ensure the product structure meets the criteria for design for re-use.

One conclusion is that there is need to manage goal conflicts when design for re-use is done within order-delivery process to ensure the product structure meets the criteria for design for re-use.

However, this is only one example of the bigger issue – Designing within the Force Field. Designing within Force Field can deviate from the original design goals and/or Design Process during the development thus not meeting the milestone criteria or criteria of other Activity Systems. The iteration and rework needed decreases R&D efficiency.

The Design Science in Chapter 4.1 contributes to the research by providing a model where to place the Force Field. The Cases C, D, E, and I contribute to the research question by indicating the difference between motives and design goals of several Activity Systems.

The analysis in Chapter 7.3 and 7.4 contribute to the research question 3 by describing desired goal combinations and the result of conflicting design goals of two different Activity Systems. The result of Chapter 8.5 contributes to the research question 3 by describing the Designing within Force Field, and how the Force Field can deviate the project from design goals and/or Design Process thus not meeting the milestone criteria or criteria of other Activity Systems.

The conclusion is that the Force Field can deviate the project from the design goals and/or Design Process during development thus causing the product structure not to meet the milestone criteria or criteria of other Activity Systems. This causes iteration and rework thus decreasing R&D efficiency. Therefore, the managing of the designing within Force Field can increase R&D efficiency.

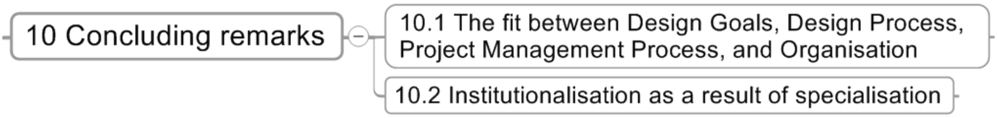
9.3.3 Design management using operational modes

One challenge for Design Management is to deal with goal conflicts and different motive as discussed in previous research questions. One industrial best practise was found that is used in several companies. It is called operational mode and it describes different ways of how the development of new product is made depending on the main design goals of the product.

The theory basis presented in Chapters 4.5 and 4.6 contributes to the research question 3 by indicating the need of aligning the motives of several Activity Systems thus minimising conflicts consuming work effort. The state of the art in Chapter 5.6 contributes to the research question 3 by describing multiple operational modes enabling alignment of several Activity System motives. The Case A – "Nokia" and Case I – "Partly-configurable ship" contribute to the research question 3 by describing different operational modes for Activity System networks. The Case F – "Support component re-use" and Case I – "Maritime industry" contribute to the research question 3 by describing conflicts of several Activity Systems on motive level.

The analyses in Chapters 7.1 and 7.4 contribute to the research question 3 by describing the dependences and goal conflicts between Activity Systems. The result in Chapter 8.6 contributes to the research question 3 by describing the dependency between Product Structure, Activity System and operational mode as solution in aligning motives of several Activity Systems. The conclusion is that managing the dependency between Product Structure, Activity System and operational mode is one solution in aligning the motives of several Activity Systems thus increasing R&D efficiency.

10 CONCLUDING REMARKS



This chapter consists of remarks of the researcher to the research results.

10.1 The fit between Design Goals, Design Process, Project Management Process, and Organisation

The fit between Design goals, Design Processes and product structures needs to be planned simultaneously although the CHAT does not enable this kind of modelling directly. Baxter et al. present model having process model data, design task data, and product model data interconnected via process logic engine [Baxter et al. 2007], which is aligned with the conclusions of this research.

The fit between Design goals, Design Processes, project management process, product structures, and organisation as elements do not have intelligence or capability to act on their own. Therefore, the fit between them does not take place without help and it needs to be designed by a human. The misfit between the elements waste work effort as discussed above. Thus the conclusion is that the R&D efficiency is increased when the fit of the above-mentioned elements is successfully designed because less waste effort is used in design and in management. Therefore the R&D efficiency is increased when the optimisation of above mentioned elements is successful.

During the research and interviews for the cases only subsets of these elements were presented or discussed demonstrating lack of awareness on the dependencies between these elements and the benefits the successful fit provides. Erixson states that *"every product reflects the organisation and the development process that developed it"* [Erixson 1998], and it is supported with the findings in this research as well as results by Holmqvist et al. [Holmqvist et al. 2004].

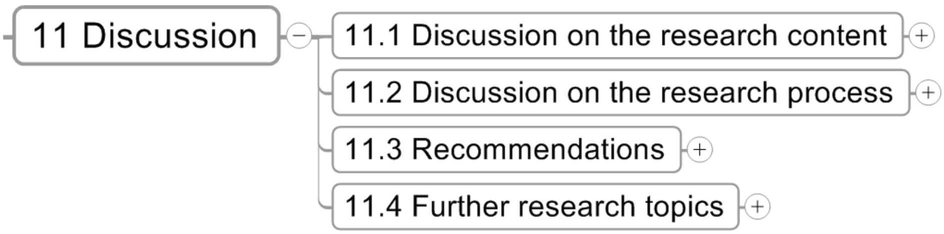
10.2 Institutionalisation as a result of specialisation

The impact of repetition in large R&D can lead to specialisation of individuals and Activity Systems to particular synthesis. The adaptation of Design Processes, rules, division of labour etc. is not needed if the Activity System develops only certain type of product structure. The specialisation of the Activity System increases R&D efficiency as the effort needed for learning new technologies and solutions is not needed, and the management effort required for adjusting Design Process and planning is also unnecessary.

In large R&D the smaller organisations and teams are driven to specialise in particular problem solving and synthesis because it is more efficient. The specialisation is possible as tens or hundreds of products are developed over the years requiring particular specialisation. The specialisation takes place when required investments for maintaining specialisation can be financed by the company. If the efficiency is the only measure it will lead the organisation to produce similar synthesis project after project regardless of initial design goals or available new technology. The "new goals" or "new technologies" are avoided because they increase work effort and the main driver is to minimise the work effort needed. This is one of the forces in the Force Field discussed in Chapter 9.3.2. If the specialisation force is too powerful, it can deviate the Activity system from creating competitive solutions meeting customer needs. The stronger the specialisation force, the bigger the probability that the Activity System turns into institution.

In this context the institution carries the meaning that institution exists primarily to serve its own needs and secondarily the needs of other Activity Systems (such as the company, customers etc.) as discussed in Chapter 9.3.2 resulting in poor product competitiveness. The researcher sees that the specialisation force is a result of maximising the R&D efficiency. Therefore, the conclusion is that product competitiveness will decrease in the long run resulting in reduction of profit if efficiency is used as the only measure for R&D.

11 DISCUSSION



This chapter covers the discussion on the research content, research process, recommendations to the question "How to design variability and commonality to Technical System efficiently?" and elaborates the improvement ideas on three levels: in the Elements of Activity System, in the Activity System, and across Activity Systems. After this, further research topics are introduced.

11.1 Discussion on the research content

11.1.1 Research question 1

The data from Case D to Case I and the related literature validate that products consist of product structures for variability, commonality, and product synthesis. Harlou, Pulkkinen, and Lehtonen have proposed standard elements and design elements [Harlou 2006], partly-configurable product [Pulkkinen 2007] but none of them propose this classification. Thus the classification is considered to be novel. The validity is acquired by proving the existence of the elements in mechatronical products. The classification does not have internal discrepancy thus being consistent. The technology used in case products can set limitations to this research because products consisting of e.g. software may need to have different product structures.

The companies face the following challenge: how to know what to standardise and what to modularise? What to have as one-of-a-kind product structure? These questions emerged when the research Cases were observed. They do not fall within the scope of this research and thus call for more research to find solutions to the questions.

11.1.2 Research question 2

The data analysis in Chapter 7 validates the need for a certain Design Process type for certain Product Structure type. It is aligned with Hubka´s proposal how to derive procedural plan from general procedural plan [Eder 1995]. The novel item is the definition of the difference between same design tasks when it is part of different Design Process, as analysed in Chapter 7.2. The limitation can be that the process model is applicable with mechatronic products only.

The analysis in Chapter 7.2.5 implies that the traditional linear representation of a Design Process does not always suit the context. Some process models currently address the iteration, but the evidence from the Cases indicates that iteration is common. This calls for more research on Design Processes and methods minimising the iteration loops during the development. The limitation in this issue is that how to foresee which design task types are appropriate in new project developing new solutions? In early phase the decomposition is not done yet thus knowing the product structure type at that stage is not possible.

11.1.3 Research question 3

This research proves the dependencies within Activity Systems as carriers for changes in the Product Structure, the Design Process, and the Design Goals. It also discovered the dynamic nature of a Design Process as a procedure. When these are combined together with the Designing transformation system in Figure 8, the conclusion is that designing takes place within the Force Field. This viable synthesis explains, for example, why it is difficult to keep the goals unchanged during the development. Case E – Partly-configurable device" in Chapter 6 demonstrates a situation where the original design goal of a configurable component is dominated by the design goal of the product program, i.e., to design a standard component. Thus the Force Field is considered as a novel concept for Design Science in the context of a Management & Goal system and valid as the people discussed in Nokia recognised and understood that they had several experiences of this issue.

The use of the Cultural Historic Activity System has increased the researchers' awareness of historical and cultural issues in the companies. The purpose of the Activity System is to optimally carry out the central activities; and in order to do that, the Activity System continuously tries to resolve conflicts between the elements. After some period of time, the Activity System has a vocabulary of its own, as well as tools, and methods that are used as instruments when solving complex design issues. This can decrease the benefits of documenting synthesis using modelling methods because each Activity System can have their own models that are not compatible with the models of other Activity Systems. In the worst case each individual has a vocabulary, tools, and methods of ones own, which are used as instruments for synthesis.

This can lead to a situation where the Activity System has very little exposure to external information, thus enforcing introvert behaviour. Now, if some new product requirements are captured by this Activity System, the interpretation and the understanding of goals and the potential technical solution can be much polarised and meet the needs of the Activity System, not the customer. This can be the result of a lack of vocabulary and the dominance of "good, known solutions", for example.

The "Power of CHAS" is seen as a potential explanation to why some companies fail to develop competitive products and some others succeed in this. The more permanent organisational and operative structures and instruments there are, the higher the probability of failing in new product development. This phenomenon calls for more research in this aspect.

During this research, the data analysis indicates the role of the Activity System and the Product Structure in an organisation. Further analyses of Design Goal conflicts lead us to the concepts of 'delivery flow' and 'operational mode'. The researcher identified the operational mode as the top-level concept explaining the logic of the company R&D; the rules and the division of labour, and power when developing new products. The operational mode dictates which projects and organisations need to co-operate and co-create, thus creating operational structures that provide fertile grounds for potential Activity System conflicts. These results are considered relevant and novel for Design Science.

The researcher also considers the operational mode a common nominator for causing dynamics in the Design Process during product development, as it creates dependencies between the Product Structures, the Design Goals, and the Design Processes. In this world of constant change, the General procedural plan does not serve the needs of companies. The dependencies require new aspects on how to adapt the Design Process to the particular design task.

If the company has multiple operational modes and the Activity System contributes to a number of operational modes, the probability of conflicts is even higher. This is due to the numerous networked Activity Systems, Product Structures, and Design Processes. They intertwine tightly and thus make the management of R&D a very complex task. This calls for more research on the area of operational modes, Product Structures, Design Processes, and on how to manage this type of complexity. This issue is considered valid by using triangulation; the people discussed in Nokia recognised this issue, Harlou reports similar issues from Philips and B&O [Harlou 2006] and Andreasen describes similar issue, as depicted in Figure 31.

11.2 Discussion on the research process

Discussion on the research process is carried out by identifying issues in each process step that can disturb the research and produce obscure results.

11.2.1 Formulate research question

The research questions are formulated with an emphasis on the industry needs. Mass customisation is increasing, and an increasing number of companies need information on how to create products with variability and commonality enabling more profits and increase in R&D efficiency. It is known that Design Processes are used to create new products and thus the research questions focus on Design Processes and how to manage using Design Processes.

11.2.2 Formulate research strategy

The strategy is to use relevant theory basis, state-of-the-art references and empirical data from industrial cases. The selected theories and state of the art contributes to the research questions, as noted in the end of the Chapter 4 and Chapter 5. The answers to the research question and the work effort needed for carrying out this research indicate the research strategy is successful.

11.2.3 Select relevant theory basis

The objective of this research is to use Design Science as a basis and create novel viewpoints using the Cultural Historic Activity Theory. Both of these models are generally accepted. Later research results on design coordination were studied and theory basis was expanded with Design Coordination. The selected theory basis is able to explain the phenomena under investigation simply and elegantly thus following the principle of Occam´s razor known in philosophy of research [Niiniluoto 1997]

11.2.4 Selection of research methods for the research question

The research strategy narrowed down the number of applicable research methods. Ethnography using facilitation (see next chapter) together with the CHAT provided sufficient and valid data relevant for the research questions. The research methods proved to be useful and serve answering the research questions well.

11.2.5 Data gathering

The data was gathered with the CHAT from the material provided by the companies and researchers, using literature and the meeting material of the researchers. The data gathered from multiple sources is considered valid and relevant for the research question. The issue in data gathering with the CHAT is that how the information is modelled by the researcher. There were times when the researcher needed to describe dependencies between Goal and Subject and Goal and Instrument but those were not aligned with the CHAT. This issue is stated in the concluding remarks in Chapter 10.

In the case of Nokia, the platform mode of operations is elaborated in detail to provide an understanding of the different motives of Activity Systems resulting in conflicts between Activity Systems inside the operational mode. The data and the summary of each Case are presented. The Case A and B are treated as individual cases as they contribute to the research questions alone. The Cases from C to H are in a way "sub cases" as they take place within Case A because the projects operate within Nokia R&D and within Case B because the projects operate within platform mode of operation. The "sub-cases" are used to provide further insight and knowledge to the research questions.

The researchers' role in Nokia can be described as participatory observant. During the sessions several facilitation methods are used and solutions to the items are created, planned, and scheduled. The fact that facilitator manages the process has an impact on the results of the session. There are multiple ways to resolve the items and each path lead to a bit different conclusions. Nevertheless, the conclusions of the workshops are verified with the participants and when the participants validate the conclusions the importance of the path is decreased from the research point of view.

Facilitation is a promising way of doing research in the field. It helps in data gathering and in the same time the researcher has smaller effect on the results when comparing to interviews, for example. The group processes problems, discusses the root causes and possible solutions, and the facilitator records the results on the flipchart, visible to participants. This enables instant verification that discussion is captured correctly thus reducing the error for misinterpretations. The findings are documented using Activity System model (see Chapter 4.6) and using field notes, a collection of observations during 1999 – 2008. The field notes are the origin to the models presented in Chapters 7 and 8 and primary source when the simulation game was developed and key learning points were defined. Part of the field notes remain unpublished due to confidentiality issues but the conclusion is that it does not harm the research results in terms of novelty, consistency, validity nor limitations as the Cases represent the issues relevant to the research questions in a holistic manner.

11.2.6 Data analysis

The data analysis is transparent and logical so that other researchers are able to point out any flaws in the analysis or the logic. The analysis and the results are considered to be valid and relevant for the research questions as they are used to give answers to the research questions.

11.2.7 Results

The synthesis is based on logical conclusions on the theory basis, the state of the art and the data analysis. The synthesis provides novel aspects on the research questions and the models describing the phenomena relevant to research questions.

11.2.8 Conclusions

The results were concluded based on the theories, state of the art, and analysis of empirical findings. The results were discussed with people from the Cases and the results were accepted as an accurate description of what is happening and why. Thus the verification of the results is considered valid. The results are not applicable to companies that do not see the need to manage R&D and the Design Processes. Another limitation is that the technologies used in the case companies are for mechatronic products. This may result in situations where the results are not applicable to product with other technologies. Regarding the research question 3 the discussion suffers from the lack of relevant research results in this field because the conclusions are novel such research does not exist. This research is considered to widen the field of Design Science to the research fields earlier been proprietary to management science, organisation science and social sciences such as social psychology.

11.3 Recommendations

The recommendations are based on the fundamental approach of the alignment in and between elements and systems in the Cultural Historic Activity Theory. The logic is that the more coherence there is in and between the Activity System elements, the more aligned the thinking and the work in an organisation are. This improves organisational efficiency and the quality of the outcome. Another fundamental assumption involves organisational learning. The assumption is that the Activity System learns by developing new instruments and resolves conflicts between elements. The renewed instruments and elements enable more culturally advanced central activity (see Figure 19). The recommendations are a collection of the best practices in the industry and the results of this research, and they enable the Activity Systems to be more successful in delivering products with variability and commonality. The goal is the same as in the research question, and these recommendations are not applicable if the goals in a case are different.

11.3.1 Example -How to design variability and commonality to Technical System?

The answer to the question using the following elements of this research results is:

1) Classification of Product Structure types (Chapter 8.1)
2) Process model for different Product Structure types (Chapter 8.2)
3) Design for re-use (Chapter 8.4)
4) Product structuring within Activity System Force Field (Chapter 8.5)

Let us begin by using Activity Systems and Activity System networks, and the approach is top-down. It is important to understand the delivery flow and whether the designing takes place as part of the order-delivery process. In this case, the proposal is that only one of the Activity Systems is part of the order-delivery process. This is to minimise the goal conflicts between the Activity Systems. In practice, to design variability with commonality means that the product synthesis is a configurable or partly-configurable Product Structure type.

There needs to be an Activity System that delivers the product synthesis with a configurable or partly-configurable Product Structure type. This means that the architecture needs to enable the development and re-use of those Product Structure types. One-of-a-kind elements are developed if needed. This Activity System needs to utilise design by re-use to be successful and meet the goal, and the network of Activity Systems needs to enable this. There needs to be existing re-usable standard or configurable elements, or Activity Systems that will deliver the standard or configurable elements needed. Yet these Activity Systems must not have excessive time pressure schedule-wise from any other Activity Systems such as Activity System A.

Now let us proceed with the answering by using the proposed Design Process model, and list the activities needed phase by phase, assuming for the sake of simplicity that no changes or iteration are needed.

Activities for the Activity System:

1) Capture the needs using the configurable or partly-configurable Design Process type,
2) Specify the Architecture and allocate Product Structure types to components/elements using the configurable or partly-configurable Design Process type,
3) Specify the components using Design Process types meeting the Product Structure type of each component,
4) Manufacture the components, and
5) Integrate and verify using the configurable, partly-configurable, or one-of-a-kind Design Process type. (One-of-a-kind is proposed as some verification methods do not address configurability. In such a case, the verification needs to be performed on one configuration at a time, which is very inefficient.)

By using the Product Structure types and the corresponding Design Process types, one can design products for other goal combinations, as well. In this case, the goal combination was variability & commonality & product synthesis for a configurable product, and product synthesis & variability & commonality for a partly- configurable product. The goal combinations related to each Product Structure type are described in Chapter 8.1.

These activities require a synthesis with design by re-use on several abstraction levels, and the proposal is that they are carried out as described in Design Science or in the Domain Theory.

11.3.2 How to improve each element of an Activity System?

AS element – Goal

The improvements of the goal consist of two aspects: clear target-setting and managing the targets during the Design Process. The accuracy of the goals and the target-setting, or actually, the lack thereof, was a main discovery in this research. Target-setting can be improved by specifying the goals using the Product Structure types and the design goal combinations, as described in Chapter 7.3.

Another improvement aspect is related to managing the Product Structure type during the Design Process. The Force Field influences the designing, and the intense dynamics in the technical systems architecture on a number of abstraction levels may alter the Product Structure type. The management task is to ensure that the Product Structure type remains the same during the development; otherwise the company will lack re-usable elements for a host of products thus having implications on the other product development projects as well.

Design by re-use can be increased by adding time pressure on the synthesis. It forces the engineer to re-use rather than to design from scratch due to the lack of time. Time pressure should not be used when designing for re-use because it forces hasty decisions which are particularly harmful with standardised and configurable elements

AS element – Subject

The engineer can increase the commonality of products by re-using parts/subsystems. When the parts are complex, the organisation should provide support & knowledge to facilitate the re-use of parts. Different views on the product structure and access to the reasoning of the re-usable elements enable the engineer to learn and internalise the previous optimisations and offer a better opportunity to evaluate how to integrate "old parts" to the new synthesis. The variability of the product is improved by increasing the design skill of the engineer. The engineer should have advanced knowledge of how to design variability into a product and what kind of product structures enable variability.

AS element – Object

The understanding of the design object can be increased by having several views on the Technical System based on the same information and architecture as proposed in the Domain Theory. Understanding the Product Structure type is vital: otherwise the processes and methods are misused, which results in poor design and flaws in the architecture with fatal dispositions.

AS element – Instrument

In the Cultural Historic Activity Theory, all representations of the object, Technical System in this case, are part of the Instruments category. The instruments are mediating artefacts for the engineer who performs the analysis and reaches the synthesis. The descriptions of the Product Structure are instruments that enable purposeful design activities and synthesis. In addition, all kinds of descriptions of the Design Process are useful for the designer. Therefore, the company should provide the designer with refined Design Processes for each Product Structure type.

These instruments are also useful from the management viewpoint. The Product Structure type descriptions and the corresponding Design Processes enable clear target-setting and managing the targets during the Design Process. When design and management are carried out elegantly, a minimum amount of iteration is needed in the Design Process and a better R&D efficiency is achieved. Design methods and tools are also parts of instruments, and very valuable tools in complex design optimisation tasks. Therefore, the company should analyse which methods and tools serve the various design tasks and invest in training and a further development of tools to meet the needs of designers and managers.

AS element – Rules

The Activity System can have rules that increase design by re-use. At Philips, there is a clear rule of not to mix product development and platform development. The rule enables the isolation of projects on design for re-use and product development projects. Rules can also be set for the use of standard components and interfaces so that modification is not allowed.

AS element – Community

The community of designers and managers have values, norms, and underlying assumptions about what to design and how to design it. Commonality and variability are improved when the community prefers design re-use and good knowledge of the market needs and of what kind of variation is needed now and in the future.

AS element – Division of Labour and Power

The benefits from variability and mass customisation can be improved with a couple of rules: one is to offer pre-designed configurations only. This way, no design effort is needed in the order-delivery process and the company can benefit from mass-customisation. The practical change is to make the customer choose from options rather than to capture the needs and requirements from the customer. The latter method radically decreases the use of pre-designed elements; as the requirements are likely to cause changes in the product architecture and the elements and in addition to require additional design work.

11.3.3 How to improve the whole Activity System?

Improving the Activity System mainly refers to the internal aligning of the AS elements and the aligning between the AS elements. The alignment of the Product Structure type and the goal combination is the main conclusion of this research work. Another important alignment takes place between the Product Structure type and the Design Process type. The management should put in effort in minimising the Force Field (see Chapter 8.5) that tries to deflect the Design Process and the Product Structure type from the design goals. A practical example of this in the industry is to have specific organisations for each Product Structure type, as has been done at Nokia Corporation, Philips, VAG, and B&O.

11.3.4 How to improve networks of Activity Systems?

Improvement refers to aligning the goals and motives on the network level of Activity Systems. The main causes for conflicts are the operational mode and the contribution of the Activity Systems to each operational mode. For example, if the platform organisation is involved with spearhead product development, a goal conflict may result in a long time-to-market for the spearhead product. This is why the management should define clear operational modes and optimise for minimised goal conflicts.

11.4 Further research topics

The following themes are proposed as research topics based on the results of this research:

11.4.1 The dynamics of designing during development process

This theme could cover the following research questions: What are the dynamics? What are the carriers of the dynamics? How to manage the dynamics? How to adapt the Design Processes to the design task at hand? How to minimise the iteration loops during the development? How to foresee which design task types are appropriate in new project developing new solutions?

11.4.2 The Force Field and Design Management

This theme could cover the following research questions: What is the nature of the Force Field? How to manage the Force Field? How to increase/decrease the forces? How to enable efficient designing in the Force Field? How to design in the Force Field? How to ensure Activity System is efficient yet not transforming into an Institution?

11.4.3 Product Structure, Activity System, and Operational mode

This theme could cover the following research questions: What are the dependencies between these? What is the Product Structure dependency to the strategy? What is the Product Structure link with the organisational structure? What is the link between the operational mode and the company stretegy/ies?

11.4.4 The Product Structures, Product Structuring, and Activity Systems as assets for the company

This theme would seek how to manage assets. What is a relevant asset for the company? How to know what to standardise and what to modularise? What to have as one-of-a-kind product structure? In which situations are Product Structure and Product Structuring assets? When and how do they transform into liabilities? Could the Activity System be an asset, also?

11.4.5 The Power of CHAS

This theme could cover the following research questions: How does the CHAS affect the perception of the outer world or on the requirements? On the competitiveness and on the potential technical solutions? The organisational transformation needs and the potential paths? How does this relate to the Organisational Culture? Can the organisation be profiled with the Myers-Briggs Temperament Indicator (MBTI) similarly as to individuals? What are the other mechanisms that create Institutions?

12 CONCLUSIONS

The aim of this research is to provide new insight and enhance knowledge in the field of Design Management as part of Design Science. Therefore, this research has two objectives:

1) To describe the development process of Technical Systems that have variability and commonality.
2) To describe management tasks that improve the R&D efficiency when developing a Technical System that has variability and commonality.

The objectives are transformed into three research questions:

1) Which elements of a Technical System enable variability and commonality?
2) How to develop a Technical System that has variability and commonality?
3) How to improve the R&D efficiency when developing a Technical System that has variability and commonality?

This research provides answer to the first research question by proving that the elements of a Technical System enabling variability and commonality are Standard, Configurable, One-of-a-kind and Partly-configurable Product Structure types. All the types are based on commonality which is achieved with standardisation of behaviour and properties of product element. The standardisation enables modularity and the modularity serves variability. The research describes three main goals: variability, commonality and product synthesis. The product synthesis as goal means that the development process needs to deliver a product as outcome. The product synthesis goal can be reached by using any of the above-mentioned products structures or any combination of the above-mentioned product structures.

The development of Technical System that has variability and commonality needs:

1) Design Process for each product structure type,
2) The fit between Product Structure type and Design Process type, and
3) The fit between Design Process and Project Management Process by the fit between design tasks and milestone criteria, and the fit between design goal and milestone criteria.

The list provides the answer to the research question 2.

The R&D efficiency when developing a Technical System that has variability and commonality can be improved by:

1) Managing the fit between Product Structure and Design Process,
2) Managing the fit between Design Process and Project Management Process,
3) Reducing work effort needed for capturing ready-made synthesis,
4) Managing the designing within Force Field, and
5) Managing the distributed design activities in many organisations using different operational modes.

The list provides the answer to the research question 3.

The fit between Design goals, Design Processes, project management process, product structures, and organisation increases R&D efficiency. The above-mentioned elements do not have intelligence and capability to act on their own. Therefore, the fit does not take place without help and it needs to be designed by a human. The misfit between the elements waste work effort as discussed above. Thus the conclusion is that the R&D efficiency is increased when the fit of above-mentioned elements is successfully designed because less waste effort is used in design and in management.

If efficiency is the only measure of success, it will lead the organisation to produce similar synthesis project after project regardless of initial design goals or available new technology. The "new goals" or "new technologies" are avoided because they increase work effort and the main driver is to minimise the work effort needed. Therefore, the conclusion is that product competitiveness will decrease in the long run resulting in reduction of profit if the R&D efficiency is used as the only measure in managing the R&D.

This research describes a development process for Technical Systems that have variability and commonality. It also describes management tasks that improve the R&D efficiency when developing a Technical System that has variability and commonality. Therefore, it meets the research objectives. This research provides answers to the research questions thus fulfilling the aim to provide new insight and enhance knowledge in the field of Design Management as part of Design Science.

13 CONTRIBUTION

This research contributes to the Design Science in the area of Design Management with following contributions:

1) It proves that the fit between design goals, Design Processes, project management process, and Technical System needs to be planned and adapted simultaneously to increase R&D efficiency.

2) It proves the decrease in R&D efficiency due to learning effort needed when capturing of ready-made synthesis done by someone else. The people in industry have need for product structuring capability as it brings the thinking behind synthesis visible by documenting synthesis from different product structuring viewpoints using several modelling methods.

3) It describes the phenomena "Designing within Force Field" and "Institutions" that decrease R&D efficiency thus requiring active managerial effort.

4) It elaborates the Design Management with CHAT and proves it is a useful research method in the field of Design Science.

This research contributes to the Cultural Historic Activity Theory with following contributions:

1) It verifies most elements of the theory in the operative context of an R&D organisation. The following dependencies were observed, analysed in detail and existence is proven: goal-rule-instrument, goal-object-instrument, goal-division of labour-object-instrument. The conflicts between elements and Activity Systems were also found as proposed by the CHAT.

2) It verifies the existence of more advanced central activity. That is, when the Activity System learns more it is able to create new, more advanced central activity and an aligned Activity System as proposed by the CHAT. In this research the organisation developed earlier standard elements and had learned how to develop configurable elements. In the industry, the paradigm shift from mass production to mass customisation is a solid example of this.

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In addition process descriptions and documentation was used available in PCP Library and PC Teamroom in Nokia intranet. The Cases are based on interviews of many people along the years and documentation of the development projects.

Reader notes: