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Timo Lehtonen

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Designing Modular Product Architecture in the New Product Development

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Tiivistelmä

Tässä väitöskirjatyössä on lähdetty selvittämään modulaarisen rakenteen synteesin perusteita uuden tuotteen suunnittelussa. Moduulirakenteen ensisijaiseksi lähtökohdaksi on monessa aiemmassa tutkimuksessa pyritty esittämään tuotteen toimintorakennetta. Tässä työssä osoitetaan, että tämä lähestymistapa ei ole aidossa uuden tuotteen suunnittelussa mahdollinen ilman iterointia. Lisäksi osoitetaan hermeneuttisella historiatarkastelulla ja kahdeksalla teollisuusesimerkillä, että toimintolähtöisyys moduulijaon suunnittelussa ei ole läheskään aina liiketoimintaympäristön näkökulmasta relevanttia. Työn alkupuolen väitösosassa osoitetaan, että toiminnallisen rakenteen nostaminen muiden modulointisyiden yläpuolelle on perusteetonta.

Kun näin on selvitetty, miksi yleisimmin esitetty lähestymistapa tulisi hylätä, lähdetään työn konstruktiivisessa, toisessa osassa tarkastelemaan mihin modulaarisen rakenteen synteesin tulisi perustua. Jotta tarkastelu olisi mahdollinen, modulaarisuutta tarkastellaan suunnitteluympäristöä laajemmassa liiketoimintaympäristössä. Modulaarisuuden käytön muuttumisesta historian kuluessa tehdään havaintoja ja niiden perusteella esitetään *Teoria modulaaristen tuoterakenteiden evoluutiosta*. Modulaarisuuden määritelmää tarkastellaan ja modulaarisuus ilmiönä jaetaan kahteen kategoriaan: muunteluun ja tuotteen elinkaareen liittyvään modulaarisuuteen. Pääosa tämän tutkimuksen aineistosta ja tarkasteluista liittyy muunteluun liittyvään modulaarisuuteen, jota työssä kutsutaan M-modulaarisuudeksi. M-modulaarisuudelle esitetään aiempaan tutkimukseen tukeutuva, mutta kokonaisuutena uusi määritelmä.

Moduulirakenteen muodostamiseen vaikuttavien syiden kartoittamiseksi työssä otetaan käyttöön tutkija Tero Juutin esittämä *company strategic landscape –viitekehysmalli (CSL).* Mallin avulla analysoidaan kahdeksan teollista esimerkkitapausta. Tapauksissa arvioidaan toimintaperustaisuuden vaikutusta verrattuna liiketoimintaympäristön vaikutukseen. Johtopäätöksenä esitetään, että mallin tuottava analyysiprosessi on viidessä tapauksessa selvästi toimintalähtöistä parempi, yhdessä tapauksessa todennäköisesti parempi ja kahdessa tapauksessa yhtä hyvä.

Tulosten perusteella *CSL–viitekehysmalli* hyväksytään lähtökohdaksi esitettävälle *uuden modulaarisen tuotteen suunnitteluprosessille.* Prosessi muodostetaan viitekehysmallista ja Systems Engineering -tutkimuksessa esitetystä V-mallista ja sen alatasoilla käytettävästä systemaattisen suunnittelun prosessista. V-mallin valintaa moduulijärjestelmätason suunnitteluprosessiksi perustellaan luvussa 11 ja samat asiat tulevat esiin myös esimerkissä 10.4.

Lopuksi työssä tarkastellaan tulosten valossa aiempaa tutkimusta ja pystytään osoittamaan, että tässä väitöskirjatyössä kokonaisuutena esitetty asia on sirpaleina esiintynyt jo aiemmassa tutkimuksessa. Lisäksi osoitetaan, että esitetty *uuden modulaarisen tuotteen suunnitteluprosessi* on mahdollista toteuttaa jo olemassa olevilla suunnittelutyökaluilla.

Työn Suunnittelutieteelle ja käytännön suunnittelutyölle antamat tärkeät kontribuutiot ovat:

1. Toiminnallisen lähestymistavan rajoitteiden osoittaminen moduulirakenteen määrittelyssä (luku 5)
2. Modulaarisuus-ilmiön jakaminen muunteluun liittyvään ***M-modulaarisuuteen*** ja tuotteen elinkaareen liittyvään modulaarisuuteen (luku 7)
3. ***Teoria modulaaristen tuoterakenteiden evoluutiosta*** (luku 8)
4. Viitekehysmallin kehittäminen käytännön tuoterakennetutkimuksen työkaluksi (luvut 9 ja 10)
5. Ehdotus ***uuden modulaarisen tuotteen suunnitteluprosessiksi*** (luku 11)

Abstract

In this dissertation, the bases of the synthesis of the modular structure in new product design are examined. In a number of previous studies, the functional structure of the product has been presented as the primary basis for the modular structure. However, as shown in this dissertation, this approach is actually not possible in a genuine new product design process without iteration. This is proved theoretically by examining the systematical design process and by analyzing the elements that implement the goals. In addition, it is shown with hermeneutical historical examination and eight industrial examples that functionality is not always relevant in the design of the modular division from the viewpoint of the business environment. As a result from the first part of the dissertation, it is shown that there is no justification for prioritizing the functional structure over the other motivations for modularity.

As thus functional approach has been discarded, we set out to examine the bases to which the synthesis of a modular structure ought to be based. To enable the examination, modularity is examined in a business environment that is larger than the design environment. We make observations on the changes in the use of modularity over history, and based on these, present a *theory of the development of the modular product structures*. The definition of modularity is examined, and modularity as a phenomenon is divided into two categories: variation related modularity and modularity related to the life cycle of the product. Most of the material and the examples in this study are related to variation related modularity that is called M-modularity in this dissertation.

To chart the reasons for the formation of the module structure, we use the *company strategic landscape* framework (CSL) introduced earlier and analyze eight industrial sample cases with it. In the cases, the effect of function-basedness compared to the effect of the business environment is evaluated. As a conclusion, we state that the CSL-analysis process that creates the model is clearly better than the function-based one.

On the basis of the results, the *company strategic landscape* framework is accepted as the starting point for the *design process of a new modular product* to be presented. The process is formed on the basis of the framework model and the V model presented in the Systems Engineering research and on the process of systematical design used on its bottom levels. The proposed method is compared to previous research and it is proved that it is possible to implement the presented *design process of a new modular product* even with the existing design tools.

Acknowledgements

One person cannot make this kind of large and fundamental work single handedly. Thus I want to express my gratitude towards my colleques in Science and Industry. Your opinions and ideas are those building blocks out of which this research is done. Ten years of research is a long time and I’m afraid that an attempt to list all my contributors would only lead to an incomplete result. So I’ll thank You all, even if I name here only a very few.

This research started 1997-1999 in KONSTA (providing support for designing configurable products) research project. From our team from year 1997 I want to thank researchers Antti Pulkkinen and Tero Juuti. There has been very fruitful and enjoyable co-operation with you in research but also in teaching activities in KONSTA and also later times. Also I want to thank researcher Juha Tiihonen (Lic.Tech) whose contribution in KONSTA in underlining the industrial relevance was – and still is – a valuable addition to my research work.

I want to thank my supervisor professor Asko Riitahuhta for his confidence towards the success of this work. Asko refused to talk about possible failure in this research and expressed always his opinion that sooner of later the work will be successfully done.

Last I want thank my parents, Professor (emeritus) Heikki Lehtonen and Mrs Tellervo Lehtonen. Professor Heikki Lehtonen was able to help me in finding the right perspective in my research problems. There is no substitute for advices from an experienced senior researcher when one feels that his research has reached a dead end. It seems that even the application areas are very different, the core essence of research work is similar and same methodological problems are encountered in all the theory based research.

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Motivation

The present dissertation is motivated by years of research work with product structures and design methods. Since 1997, the author has participated in a number of R&D projects for developing new modular product architecture as a member of the research team lead by Professor Asko Riitahuhta. The projects have been carried out in single-consignment production, mostly in the field of heavy engineering. Research has been carried out in projects funded by the Finnish Funding Agency for Technology and Innovation (TEKES), corporate projects, in connection with supervising Master of Science theses, as well as in corporate consulting tasks. It has been surprisingly difficult to yield results in these projects, even thought these cases has always been of limited (from the point of view of product structure systematics) and understandable, and well-known methods and the research traditions within Design Science have been applied.

Therefore, it was not unreasonable to expect results in the projects by applying existing knowledge and methodology. This, however, has not always happened, but in most successful projects we have resorted to developing new methods, and the results have not been the ones pinpointed by the theory used. The author has recurrently had the very doubt Admiral Sir David Beatty (1871-1936) crystallized in his notorious quote amidst the naval battle of Jutland on 31 May, 1916: ”*There seems to be something wrong with our bloody ships today*.”[*] Naturally, the potential latent defects in the methodologies of module design do not emerge as dramatically, but over time, the doubt has become conviction:” *There seems to be something wrong with our methods today.*”

In our research team, there has been plenty of discussion on the difficulty of yielding results in projects carried out in co-operation with the industry. The issue has also been raised as the opening of discussion on the international level in the research papers of our team [Pulkkinen, Lehtonen & Riitahuhta 2003]. The international scientific community has also expressed concern for the low utilization rate of research results in the industry. Professors Mogens Myrup Andreasen and Lucienne Blessing (e.g. Blessing in her keynote address at the ICED03 conference), among others, have raised the issue in international workshops and conferences. Varying viewpoints have emerged on the essence of the problem.

One source of problems, to be discussed in the present dissertation, lies in the correct application of the field-specific theoretical background in the development of methods. The key issue here is related to the differences in defining the modular structure and the general task of designing the product. Another problem source is the definitions and theorems in the research area that do not appear to follow the empirical observations.

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[*] The admiral observed that two of his six battle cruisers had exploded and sank, even though the battle had hardly even begun. The Admiral was right. There was a crucial design error in the battle cruisers, and also the methods used were dangerous: a third ship exploded in the battle [MacIntyre 1957, Costelleo & Hughes 1976 and Tarrant 1999].

1. Introduction

The present dissertation discusses the using of modular product architecture in physical products. The scope of application here is a product with a specific purpose of use. The research results can also be utilized in introducing modular architecture for services or processes. This dissertation, however, does not provide proof for these applications, as the theoretical background discusses primarily the design of physical products.

1.1 Preface

This study is titled”Designing modular product architecture in the new product development”. A simple title, however, has considerably more substance than first meets the eye. First, to be able to discuss the matter, we must know what the words in the title mean. In everyday language, the word”modular” is used almost as a synonym for the concept of”composed of parts”. Finnish word book *Sivistyssanakirja* [Koukkunen & al 2002] defines modularity as”composed of modules or following such a structure”. The book gives eight definitions for the word ”module”. Of these, the definition suited for this dissertation is ”an independent, separable structural part of an entity”. Corresponding definitions can be found in *Webster's Concise Dictionary* [Steinmetz & Garol 1993]. Modular is generally considered to be something ”*composed of standardized units or sections*”. Correspondingly, a module is ”*a component frequently interchangeable with other, for assembly into an integrated system*”.

Definitions on this level do not lead us anywhere, as most things in this world are constructed of parts, while very few are modular. Dictionary definitions do not eventually define the item on a level required by a synthesis. For example, the short entries in Webster use a total of three words to refer to a product part: *unit*, *section,* and *component*. In addition, the definitions can be considered excessive in some cases. ”*Frequently interchangeable*” may not be an absolute requirement for a module.

In the present dissertation, we will discuss the history of modular architecture and the related research in a wide scope, which would not be necessary if we were talking a generally well-known phenomenon and a correctly understood term. Modularity and the related research are discussed in Chapters 4, 5, and 6. In Chapter 7, we make conclusions on what modularity might be within this research area. Chapter 8 presents a theory on the development of modular product architecture. This is an integral part of the contribution of this dissertation for research.

The ”new product development” in the title is a specific term, not an everyday common noun. In the present dissertation, this refers to a blank-paper approach: product design in which no ready-made model is used as a basis for the architectural design. Such design work is, in actual fact, rather rare. Most design work in product development refers to improving existing models in an evolutive manner. The traditions of the market and the companies must be considered even in the design of entirely new models. It is often safer and more cost-effective to resort to existing solutions. Thus, we can state that new design in its pure form, as shown in the title, is seldom done.

1.2. Research Tradition

In Design Science, the German School in particular, new product design has a greater importance than first meets the eye. The design process that is generally accepted in the field and taught at universities is the process of designing a new product (see Chapter 3). The reason for this is the goal of Design Science to improve the world (as will be explained later on) and its product-oriented approach. A design process that includes an unprejudiced idea phase and the evaluation of ideas, and does not base design on the solutions of a previous design will yield a better product, as it supports the introduction of novelties. The fact that companies do not always operate in this way in reality is because the actual business situation is not product-oriented. The success requires more than having an optimal product. In addition, the manufacturer must be able to manufacture the product using the available limited resources. The number of resources used in the development is limited by the rules of business. The manufacturer has limited opportunities for communicating with the clients, and every contact costs money – thus a new revolutionary solution may not necessarily attain the approval of the market, even if it seems to be superior in an objective comparison[*]. An example of a company which has spoken out this idea is the vehicle manufacturer Saab: it says it aims at solutions that are ”the most advanced but still acceptable”.

This research is based on the fact that Design Science is not a traditional explanatory science, but it contains an active reclamation for constantly improving the state of affairs. Therefore, understanding and explaining things does not suffice; solutions must be suggested for the problems detected. In ongoing research in modularity, the aim can be formulated as developing methods or discovering mechanisms to create good modular structures. Despite the fairly large amount of research, few such tools exist and they are used in industry in limited applications or not at all.

The supply of applicable tools is particularly little in new product design. As such design work is nevertheless carried out, we have reason to ask why the state of affairs hasn't been generally acknowledged. The reason for this is the scarcity of the pure new product design mentioned above. Normally when a modular system is developed in new product development, the preliminary division into modules on an existing structure is accepted as a starting point, and design proceeds from there iteratively. This is possible in practice, but from the theoretical perspective design is no longer *new product design* after this. Systematic design process in Design Science regards using an existing solution as the basis for the new model as restricting and not desired. So we ought not to start from an old (or presumed) structure even in the design of the module division.

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[*] Sheet steel was used as the surface material for the safe boxes. The importance of the surface sheets is nonexistent in burglary and fire protection, as the following layers, the so-called filling (most olfen made of concrete, with inserted iron fittings and/or armour plates), form most of the protection. The outside layer made of sheet steel is expensive, and as safe boxes are usually located in the same environment as furniture, there is no specific reason for using a sheet metal casing. In the Konsta research project in 1998-99, the opportunity for shifting into a hard-plastic outside layer was considered. This, however, had already been tried in the field before. Chubb, an English company, had introduced a safe box with a plastic casing. Safe boxes are certified products, which means that no real reason exists for doubting the burglary protection of a certified safe box . Despite this, customers were not willing to purchase a ”plastic safe box”, and the product did not succeed on the market. The author also has personal experience of a project in which the concept, excellent as such, differed too much from the customer's expectations [see Lehtonen & al 1998 (2)].

1.3. The Method to Be Applied

Recognizing the philosophy behind the method and the views applied in the research is more difficult than is usually the case in the research of natural sciences. In natural sciences and technology, logical empiricism is most often applicable as a sound starting point. According to the tradition of logical empiricism, straightforward and consistent results can be achieved via logical deduction on the basis of empirical observation. Research based on logical empiricism considers scientific work as neutral and free of values and (external) human judgment. Taken even further, this view is preceded by the positivist tradition, according to which the researcher's effect on the object of study must not be considered (or it does not exist). According to this view, scientific discoveries represent absolute reality.

Logical empiricism – maybe even positivism – is a suitable scientific approach, for example, when studying thermal exchange in an interface of two materials. The object of study is a natural phenomenon which is not, according to our current understanding, affected by the opinions of interested parties. This does not apply for Design Science. The methodology is used in an empirical test in interaction with people, and the opinions and values of these people may have a more profound effect on the result than the internal factors in the product. The presence and the operations of researchers may also bring about changes in the test setting. In a number of sample cases in this study, the members of the author's research team have assumed the role of active participants. Therefore, it is obvious that the preconceptions of the researchers have affected the result. To eliminate this potential source of errors, this dissertation also seeks to describe projects in which our research team has not participated. As mentioned before in connection with the research tradition, Design Science does not attempt to explain things but to provide means for improving things. Based on this, research cannot be objective, as changes cannot be defined without values against which improvements are measured.

According to the critical rationalist viewpoint, prepossessed conceptions and values affect the research work. The starting point in this approach is to create a hypothesis that includes a formulation of how things stand. As the researcher has no way of knowing whether the hypothesis describes his own internal image of reality or the external reality, the hypothesis must be tested. The hypothesis is compared to reality, and it may prove erroneous. In critical rationalism, the most essential difference between a scientific and a non-scientific argument lies in the fact that a scientific argument can be proved to be wrong [Järvinen 2001]. According to this view, knowledge is relative (dependent on the observer and the environment): only approximations of final answers can be presented. The Austrian philosopher Karl Raimund Popper (1902-1994) is regarded as the founding father of critical rationalism. Popper outlines the views of the Vienna Circle and logical empiricism in his work ”Die Logik der Forschung”, first published in 1934. [A later English-language edition: Popper 1968; see also Popper 1963].

The hermeneutical tradition is usually associated with studying ancient texts. In the hermeneutical approach, past time has its own vitality. By studying products dating from earlier historical eras, we can make remarkable discoveries to assist us even today. An industrial product and a technical design are not generally regarded as a mental creation of its author in the sense and extent of, for example, a work of literary fiction or a work of art. If, however, we think about the contribution of the designer's creative work to all design, this view seriously underestimates design as a human activity. If a product is approved as a creation of its inventor, the hermeneutical approach considers the studying of its historical data of great concern. In this work, the hermeneutical viewpoint is illustrated in discussing modularity from the historical perspective and in the theory presented concerning the evolution of modular structures. This theory introduces an idea of modularity as a practice having emerged and evolved over time and further developing from the current level. In this work, the hermeneutic approach will also be also applied in discussing the industrial examples.

The starting point of this dissertation is the argument presented as a relevant problem: ”A general-purpose tool for developing a modular architecture does not exist”. This is not an objective fact. A number of researchers may consider the development of technologies and tools of modularity as successful, even though these have not been widely introduced. The dissertation would be endless if we included all the difficulties confronted in conveying knowhow from the world of science to industry. Therefore, we resort to the slightly opportunistic but severely pragmatic attitude of the late President Urho Kekkonen: ”Things are as they seem”. In the present research, this means that methodology that is not generally used in practice is no successful methodology.

In the present dissertation, we will evaluate the reasons why the known methodologies are not as practical as presumed. We will present two hypotheses: the first one concerns the approach and the second one the limitation of the scope of research. As mentioned at the beginning of this introduction, it is important to recognize the phenomenon studied – modularity – and limit the scope by using definitions that follow the research tradition in the field. Modularity is discussed on the one hand from the historical perspective as an industrial practice, and on the other hand in the light of the Design Science theories and according to the definitions of previous research. Design theory will prove the first hypothesis. If the process of systematical design is approved as a basis for deduction, this hypothesis is proved in the spirit of logical empiricism.

Hypothesis 2, the required scope of perspective for a successful method for applying modularity, cannot be proved right by the existing material or theories. A theory of the evolution of modularity is, however, presented to support this hypothesis. If we accept that modularity as an industrial practice is evolved over time in the manner presented, we will realize that the most recent elements linked with modularity are no longer related to the modular system but to the models of business operations in which modularity is used. This observation will prove the latter hypothesis. To achieve these results, we must accept the starting premises of the present research. If we refuse the view of modularity as a method and only view the issue in terms of part structure, such observations cannot be made.

In addition, the latter hypothesis will also be tried in the spirit of critical rationalism. To support the observations, we will introduce a framework model in which the interaction of elements affecting modularity is presented. The framework model is compared to the case samples in which observations for and against the argument statement are sought. In the cases presented, the success of the function-based approach is evaluated. The cases are used to highlight the critical elements in modular architecture and to estimate whether these elements were detected during the development work and whether using the framework model would have lead to their detection.

To conclude, the process of designing a new modular product is introduced on the basis of the observations and the results of the research. This process model is shown as an example of a practical solution to which the statements and ideas of research may lead. The scientific status of the process model is thus a suggestion that is not proved as the optimal solution. It is a hypothesis for further research and the starting point for tool development.

The contribution of this work is, therefore, to disprove certain semi-established conceptions and views and to present a hypothesis for further research. At the same time, we seek to raise the level of understanding the research area by showing the issues in their correct context and by pinpointing issues that have up until now been regarded as irrelevant

1.4. The Structure of the Thesis

In this dissertation, we will discuss theoretical research related to technical design and its processes, or, as it is often called, ”the design of design”. This approach is also visible in the structure of the research. The dissertation starts off with the background information and the definitions of terms in Chapter 1. Chapter 2 introduces the hypotheses of the work. Chapter 3 sheds light on the basis provided by Design Science, the process of systematical design in particular. Chapter 4 studies the industrial history of modularity. Chapter 5 presents recent research carried out in the field of modularity. The truth value of Hypothesis 1 can be considered already on the basis of the discoveries in this chapter. Chapter 6 sheds light on the use of modular structures and discusses the related models of business operations such as the paradigm of configurable products. Chapter 7 defines the research alignments that the conclusions of this dissertation follow. Chapter 8 presents a theory of the evolution of modular structures and conclusions of the importance of modularity for Design Science. Chapter 9 presents a theoretical model developed to support the hypotheses, used, for example, in examining the sample cases. Chapter 10 introduces industrial sample cases and evaluates the extent in which the observations made support the statements. On the basis of these, a proof for Hypothesis 2 is given. Chapter 11 introduces a suggestion for **a design process of a new modular product**. In Chapter 12, the results of the research are compared with the other approaches suggested for this particular field. The dissertation ends with the part in which we aim at outlining the most fruitful research directions in the light of the new ideas and views presented. The last chapter presents a conclusion of the results. The starting points and the proceeding are shown in Figure 1:

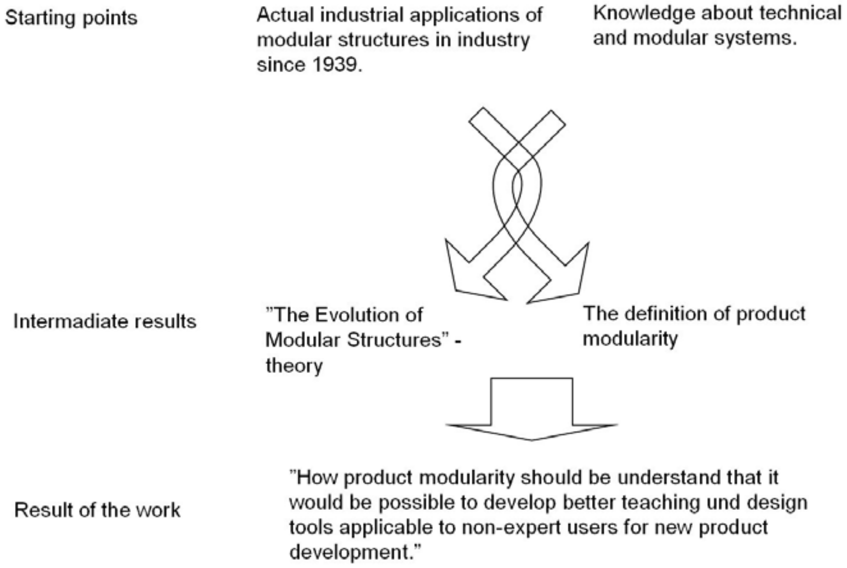


FIGURE 1. This dissertation is based on two premises: the empirical observations on the use of actual industrial applications of modular structures, and research carried out within Design Science originating from the German-speaking world. The intermediate results of the research are the "Evolution of Modular Structures" theory and the definitions of product modularity that correspond to the empirical observations. The final result of the work is a model of how product modularity ought to be designed.

2. The hypotheses

The aim of this dissertation is to present bases for the design of modular architecture for a new product. There exist previous studies and suggested methods on the subject. Methods based on the theoretical background of Design Science culminate to two issues: the mutual independence of the elemental entities in the product and the relation between the part structure and the functional structure.

However, the methods developed have not been specifically widely or successfully used. The author feels that the lack of success is not caused by lack of trying or weaknesses in the methods used. We ought to search for reasons in issues that are considerably more fundamental. Let us start with the frame of reference of the mentioned methodologies, to examine the product itself and its internal structure. The functions carried out by the product are presented as the purpose of the product. Examining the modular structure focuses on examining the internal interdependency relations. On this level of examination, modularity is seen as an internal feature of the product or product line.

In this dissertation, an important consideration is the fact that *modularity is not a natural phenomenon occurring in nature, but a way to achieve goals that has arisen with human activities*. This will be discussed in more detail in Chapter 4. For this reason, it is not relevant to study modularity in a value-free manner characteristic to natural sciences, but to always pay attention to why modularity is used, to evaluate the results, and to develop methods according to these goals. [cf. e.g. Töttö 2000] Breaking free of the complete freedom of values is a valid starting point for the research tradition of Design Science (see Chapter 3).

The success of a modular product is largely dependent on product-external factors. In a technical/economical system, a modular product has a number of other dimensions besides functionality and internal architecture. The modularity of a product does not in itself suffice to make it suitable for a business or a production environment. Even very limited modularity may be sufficient if it meets the requirements set by the business environment of the product. This might lead to a conclusion that modularity, often considered absolute and exactly defined, changes in a real business environment into relative and goal-dependent. Therefore, we must include business environment and its correspondence in the goals/criteria of the design methodology used.

However, the first thing to determine is ***whether there exists a natural division into modules for a product with a certain functionality.*** If, according to the theory of design, such a division could be found, the actual design must, of course, be based on it, modified if necessary to adapt to the current circumstances. This dissertation aims to prove that the functional structure does not naturally show a certain division into modules in the new product development.

HYPOTHESIS 1: **The functional structure is the primary base for a technical system, but secondary for a modular system. The functional structure does not directly show the modular structure in the design of new products which involve physical assembly.**

The tradition stemming from the systematical design method emphasizes the importance of functionality as the basis for a modular architecture also in the design of new products. An ideal design model in which the modular architecture is formed in the draft phase before detailed design is, however, an impossible approach if we wish to keep to the definition of new product design.

This will be proved in Chapter 5 ”The research on modularity and the proof of Hypothesis 1”. The physical structure of a product that contains mechanical structures and the resulting relations between the parts unrelated to main functions set major requirements for the product architecture. The idea of the existence of an ideal modular structure is tempting but misleading, as will be proved in this dissertation.

After this, it is logical to break free of the thought that the independence of the product-internal elements ought to be always defined from the viewpoint of functionality. This, of course, brings forth the question of which perspectives to use in the design of a modular architecture. When aiming at results with relevance for the industry, we need to break free of studying modularity in the internal mechanisms of the product and evaluate the product architecture in the business and production environments. To enable this, we must first define a model for the relations between modularity and the business environment. This model is presented in Chapter 9. In the present study, this model is used as a tool in analyzing the industrial examples and studying Hypothesis 2.

HYPOTHESIS 2: **Key issues for modular architecture arise from the business environment and the production environment. The relations in the product caused by the technical implementation must be studied in terms of these requirements.**

The following chapters will discuss the theoretical background against which these hypotheses are to be reflected. Hypothesis 1 is proved in Chapter 5. Hypothesis 2 is proved in Chapter 10.

3. Design Science and the Design Process

This research has been carried out in the field of Design Science. The leading international research community in the field is Design Society. Design Society organizes the International Conference of Engineering Design (ICED), a display of research in design science, biannually.

The legacy of design science mostly comes from the German-speaking world, and its original scope of application was machine design. Most of the founders of this field of science have been more or less involved with mechanical engineering industry, and design science has an undeniable "heavy metal" legacy. Since then, it has been noticed that the systematics and methods developed are applicable everywhere in product design. Mechanical engineering is no longer a limited application area for research: research is carried out increasingly, for example, in the electronics industry.

The predecessor of Design Society (founded in 2001) is the WDK School (Workshop Design-Konstruktion). A notable developer of the WDK theories is the Czech-born professor Vladimir Hubka whose ”*Theory of technical systems*” [Hubka 1988 and earlier Hubka 1968/74] aims to describe a technical system as a higher-level abstract description and thus provide a theoretical starting point for technical design. In his work with Ernst Eder, Hubka also describes the design process [Hubka & Eder 1996].

In their book *Design Science,* Hubka and Eder define the purpose of Design Science as creating ”*a proposal for a coherent and comprehensive view of knowledge about engineering design*”. They state the following as the aim of Design Science: ”*This knowledge [Design Science] should help to explain what designers do. It should also suggest and develop the ways in which the knowledge about engineering design (the design process and the objects being designed) can help to make the practice of designing more rational, and to improve the products resulting from designing, both in the quality of the objects and in more rapid and rational procedures.*” [Hubka & Eder 1996, p. 71]. They later revisit the issue of aim [p. 74] and summarize:

”*The situation in the design area is to be improved and the existing problems are to be eliminated.*”

Hubka and Eder formulate the term Design Science as follows: ”*The term Design Science is to be understood as a system of logically related knowledge, which should contain and organize the complete knowledge about and for designing*” [Hubka & Eder 1996, p. 73]. At the time of the publication in the mid-1990s the definition was understood very literally. As the author of this dissertation was starting his career as a researcher in 1996, the research team of Professor Asko Riitahuhta was carrying out ”Automatic Component Selection", a wide project in which computer-assisted design support systems were being developed. This 1992-96 project aimed at developing support systems to select components when designing project delivery products [Tanskanen 1997]. Our research team also developed constraint languages to model the design data (see e.g. [Lehtonen & al 1997]). Later, the question has arisen whether the rationalization of actual design data on the component level is a relevant approach for scientific research, or whether we should increasingly concentrate on modelling and rationalizing on a higher level of abstraction. In our research team, we have reached the conclusion that even though component-based systems can be developed, their maintenance is overly demanding. This observation will not be proved here, as its scope as such is subject for an entire dissertation.

Hubka and Eder set to define the contents of scientific philosophy, based on the ideas of (no less than) Kant and Aristotle. In conclusion, they state that ”*Design Science must therefore explain the causal connections and laws of the area [designing of technical systems] in its whole breadth. The knowledge system must be fixed in the forms of its terminology, classes (taxonomy), relationships (including inputs, throughputs and outputs), determination of measure, laws, theories and hypotheses, so that it can serve as basis for consciously guided design activity.*” [Hubka & Eder 1996, p. 73]. Let us note that the ”*complete knowledge*” quoted does not refer to detailed information but the comprehensive nature of knowledge. Instead of product details, attention must also be paid to design processes and the effects of their internal and mutual relations in the product.

3.1. Theory of Technical Systems

The history of engineering sciences is full of examples of how practical applications have existed before the actual theories. Even though theory has often been developed afterwards, its importance cannot be missed, as it has served as a tool in understanding the phenomenon and therefore also in its practical improvements [Hubka 1984/88] .

A practical example of this might be a detail from the development of the steam engine, the enabler of the industrial revolution, in railway use in the 1920s and 1930s. In locomotives that use piston engines, exhaust steam was used to cause draught in the furnace. A critical point in this method was how to blow the steam exiting the cylinder to the chimney in the smoke box that is located in the front of the fire-tube boiler of the locomotive. The speed in which the steam exits is always great in comparison with that of the smoke gases. Therefore, using a simple round pipe end as the exhaust steam nozzle is a functional solution.

This, however, is not an ideal solution in any way. Only a small percentage of the exhaust-steam energy can be utilized, and the draught pulsates considerably. On occasion, even temporary counter pressure may emerge and the peak suction sucks out the unburned fuel from the grate via the fire tubes. In 1919, locomotive driver Kylälä suggested an innovation to divide one exhaust-steam pipe into four smaller pipes, as shown in the figure below. Kylälä seems to have had a good understanding of the behavior of rapid flows, but in those days theoretical understanding did not enable calculating or modelling the advantages of the innovation. Despite the tests, the Finnish State Railways did not introduce the new structure. News about the invention were, however, spread in professional publications. André Chapelon, a French locomotive designer, further improved the idea, and the Kylchap chimney structure invented by him was introduced in several steam locomotive models in the 1920s and 1930s. The name merges the names of its inventors. Chapelon greatly appreciated Kylälä's draft and erroneously calls him an engineer in his book on the structures of steam locomotives [Chapelon 1937/52]

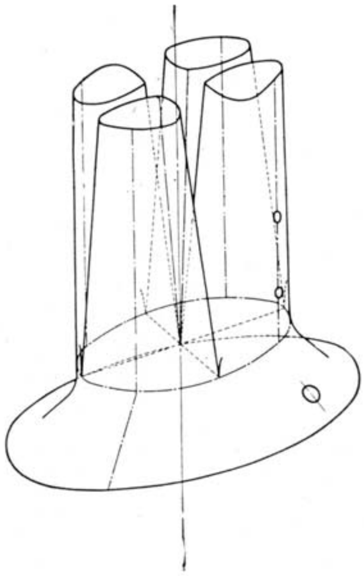


FIG. 58. — AJUTAGE INTERMÉDIAIRE KYLÄLÄ, A 4 LOBES.

Figure 2. Kylälä's exhaust-steam nozzle was not based on the theory of rapid jet steams, but on practical experience. [Chapelon 1937/52 p. 133]

The advantages of the Kylchap architecture were seen in the test drive. Let us add that the British steam locomotive that holds the world speed record was equipped with a structurally corresponding twin chimney.

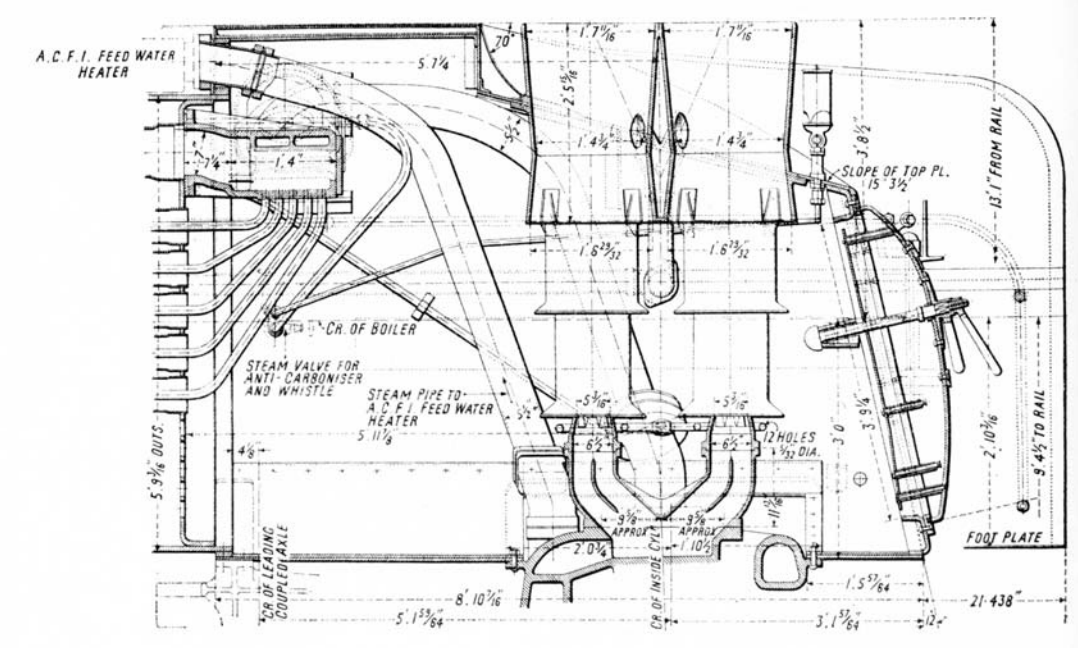


Figure 3. On the basis of Kylälä's drafts, André Chapelon constructed the Kylchap architecture which was de facto very efficient. [Nock 1973,75,82 p. 140].

However, limited tests could not yet prove the optimality of the solution. In 1951, tests were started in Austria with the wide exhaust-steam nozzle structure invented by Dr. Adolph Giesl-Gieslingen. Giesl-Gieslingen was able to provide calculations for the fuel savings brought about by his invention. For example, when driving on a high power in an Austrian locomotive of Class 78, the calculated fuel saved could reach 14 per cent, while driving with partial power, it could be as low as four per cent. The test runs showed that coal quality also considerably affected the result. In tests run in Germany and Austria, the mentioned 14 per cent could even be exceeded. [Giesl-Gieslingen 1967].

If progress had been made in practice, it would also have been reflected on the development of the theories. In his 648-page book, Chapelon never once presents calculations to show the benefits of his own structure. Let us note that the last steam locomotives introduced in Finland in 1957 were still equipped with a simple exhaust pipe – the same that Kylälä had improved. Currently, theoretical understanding of rapid flows is on the level that this simplest structure would hardly be suggested.

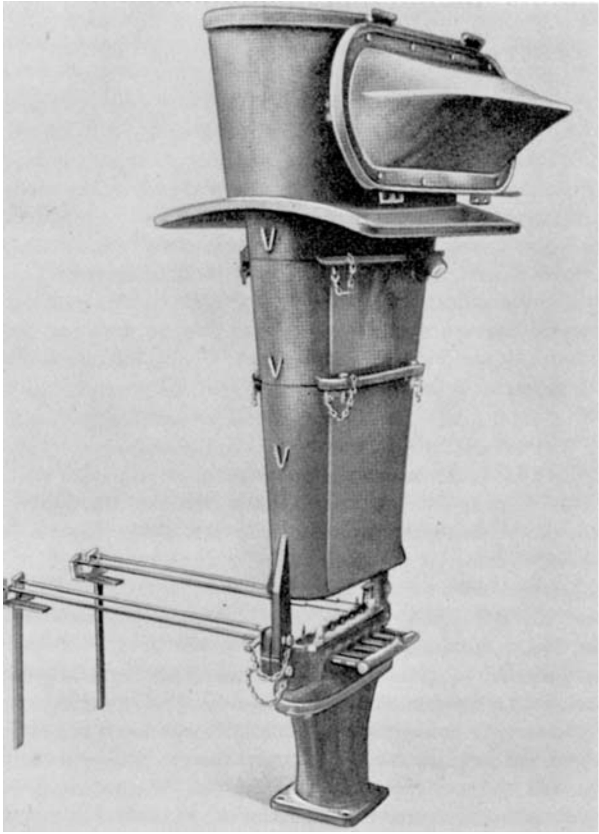


Figure 4. Adolph Giesl-Gieslingen was the first one to evaluate the exhaust-steam nozzle solution on the basis of accurate calculations. Structurally, the Giesl exhaust steam nozzle differs considerably from the Kylchap, which may mean that the increasing of theoretical understanding had possibly affected the design of the solution. [Giesl-Gieslingen 1967].

Practical knowhow thus requires in the long run theoretical development to support it: to better understand the phenomenon, but also as a tool for communication and training. The ambitious aim of the work of Vladimir Hubka is to present a comprehensive theory that would explain the nature of any technical system. Hubka opts for the idea of transformation as the basis of his theory. This is not the only possible approach. Machines and mechanical devices consist of parts that form machine elements. Mechanisms are the first such recognized and separately studied machine elements. At the beginning of the 19th century, Carnot, Hâchette, and Lanz defined first 10 and then 21 classes for various mechanisms that change movement [Hubka 1984/88]. Plenty of research was carried out in this field by the 20th century. The ideas of F. Reuleaux (1829-1905) were also well known. He regarded mechanics and particularly cinematics as the basis for searching for the operational principles of new machines. Based on the work of F. Redtenbach (1809-1869), Reuleaux aimed to formulate a general machine theory in his book (original 1876, a more recent edition [Reuleaux 1963]). Such machine modelling on the basis of mechanisms and cinematics is often the starting point in machine design and its teaching [Hubka 1984/88]. However, this approach is not sufficient in designing multitechnical products, and, according to Hubka, neither in traditional machine design.

Hubka starts with his theory from a different perspective. He uses needs and demands as the bases for his theories. He defines that the aim and the reason for the existence of a technical system is to fulfill a need. He describes this fulfilling of a need as moving from an original state in which the need remains unfulfilled, to an end state in which the need is fulfilled. This moving from one state to another involves a number of intermediary states. Hubka uses the term transformation to refer to this process. Hubka describes the general process of transformation as follows.

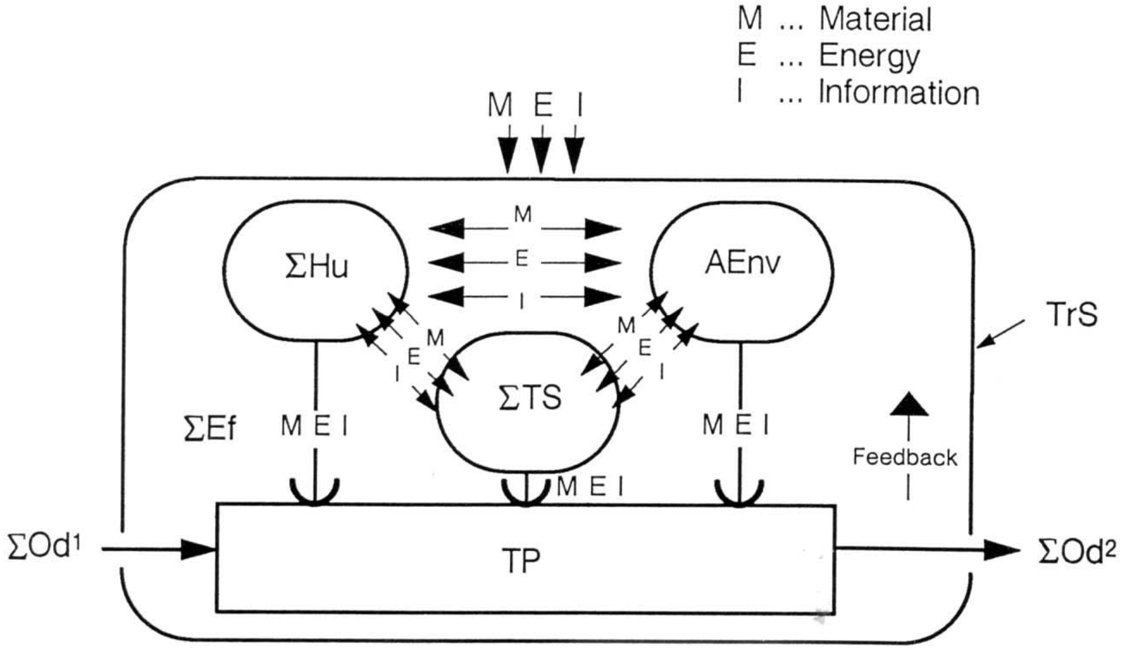


Figure 5. The transformation caused by a technical system, according to Hubka. (The symbols are explained in the text.)

The starting point is the original state (sum) Od^1. The result of the process is the desired end state Od^2. ´The operations that convert Od^1 into Od^2 are called transformation. The operations are called technical processes (TP). This process is caused by, together or separately, the technical system (TS), the human system (Hu), and the active environment (AEnv). The relations of the causative agents of the process to the technical process are divided into those that convey the material, the energy, and the information.

Therefore, the key content of Hubka's approach is that technical systems ought not to be categorized according to implementation but purpose of use! We also notice that Hubka's theory lies in a considerably higher level of abstraction that the mechanistic one. Hubka himself formulates this as follows [Hubka 1984/88 p 7]:

”When visiting a technical museum, we can see thousands objects and we recognize them as products of technology. Their variety in functions, forms, sizes, etc. tends to obscure the common features and properties among these objects... ...Let us therefore ... attempt to develop a term that conceptually describes all classes of technical objects.”

Hubka lists several issues as the advantages of the suggested approach. The author regards the following three as the most important ones: (pp. 10 and 11).

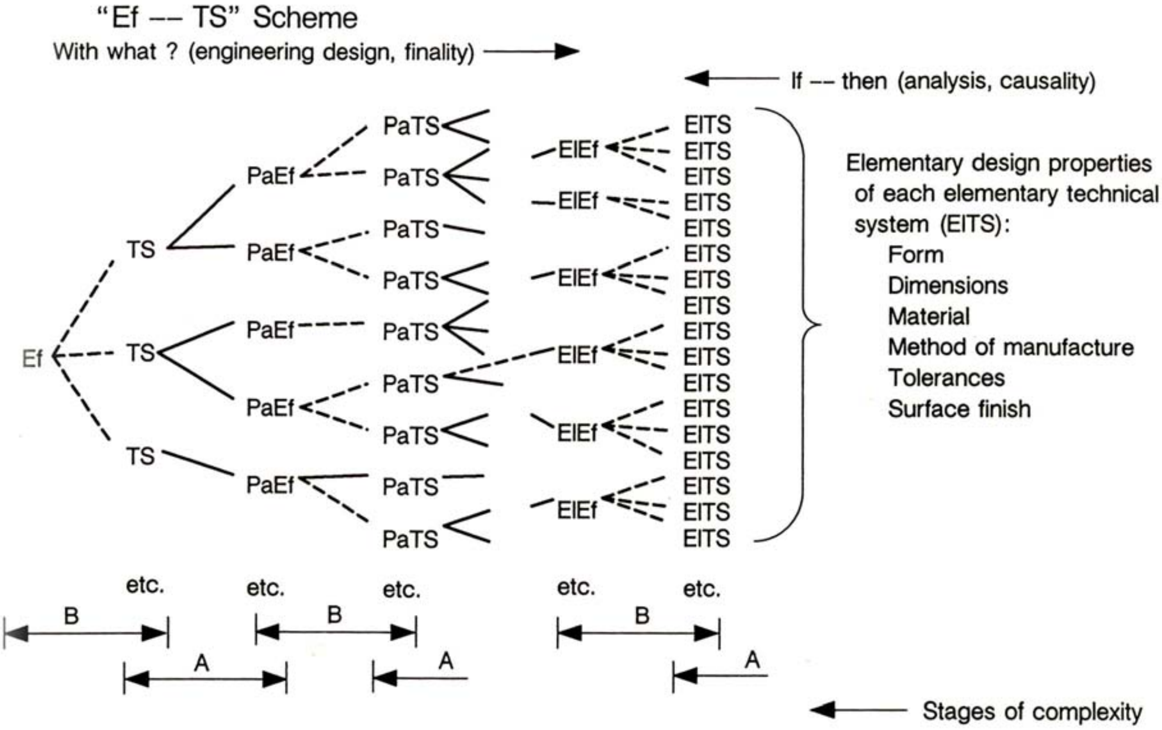
The theory of technical systems delivers relationships that are claimed to be valid for all technical means. It should serve to assist transferring technological experiences from one area to another, based on the relationships between categories and homomorphism that exist between technical objects.

Classifying the technical products uniformly as technical systems should enable us to develop working methods for engineers that are independent of product, and transferable between areas of endeavour. We thus learn and teach the processes and contexts of designing technical systems, and not only the design of pumps or lifting equipment.

Systems thinking incorporated into the theory of technical systems presents the opportunity to treat problems as a whole. This is necessary pre-condition for consistently successful design and other engineering effort.

The steam locomotive example above can be used to justify these views. The example concentrated on utilizing the waste energy of the exhaust steam by speeding up the flow of exit gases. This is merely a small subsolution, and it does not seek an answer to the conceptual problems of a traditional steam locomotive. If we were to study in a wider frame, in the spirit of the TTS, how the energy from coal could be best converted to a power that moves the train, we would soon no longer be pondering the original problem. Both the exit gases and the exhaust steam have energy that could be utilized, for example, in the preheating of feed water, as was done in locomotives with a Franco-Crosti boiler [Witte 1955]. These locomotives do not even have a smoke box or a chimney, as appeared in the original problem. A more radical addition of efficiency would be brought about by removing the fire-tube boiler and the piston engine. The number of such prototype locomotives from the end of the steam-engine era, based on steam turbines and engines and water-tube boilers is actually rather large. Even if we hadn't proceeded from solid fuels to liquid ones, the new locomotives would not have resembled the old ones [see Stoffels 1976].

In addition to the approach, two other important issues emerge in Hubka's work: absolute causality and the existence of the technical system on multiple levels of abstraction. According to Hubka, one of the key links in technical design is the relation between the aims (Ziel) to the means (Mittel) that enable them. In his theory, there is always a causal relation between these two. This philosophy and its potential utilization in practice can be illustrated as an aims-means-tree graph. This shows how the main function of the technical system is divided into subfunctions, and the description of the technical system becomes ever more detailed, eventually reaching elementary design properties. This is shown in the figure below.



Stages "A": In order to achieve its total effects (as aims), every TS needs a sequence of certain partial effects (as means);
Stages "B": Each effect can be achieved with the aid of various TS.

Figure 6. The aims-means-tree according to Hubka [Hubka 1984/88 p 89]).

In the figure, *Ef* on the left is the effect carried out by the technical system, that is, the aim and the reason for the existence of the technical system. This is usually carried out by several technical systems (*TS*) that carry out some of the desired functions (*PaEF*). To enable these functions, we again need new elements of a technical system (*PaTS*). We proceed thus until we reach the characteristic basic functions for the application area of the product, which are not divided in design (*ElEf, Elementary Effect).* The whole will eventually consist of these corresponding undividable elements of technical systems.

This has been included in the teaching of machine design in Denmark, and the approach is adequate for design analysis. The rather abstract description above is in actual fact very tangible, as shown in the figure below. In Denmark, this tree is drawn vertically and it is called the Functions-Means - tree.

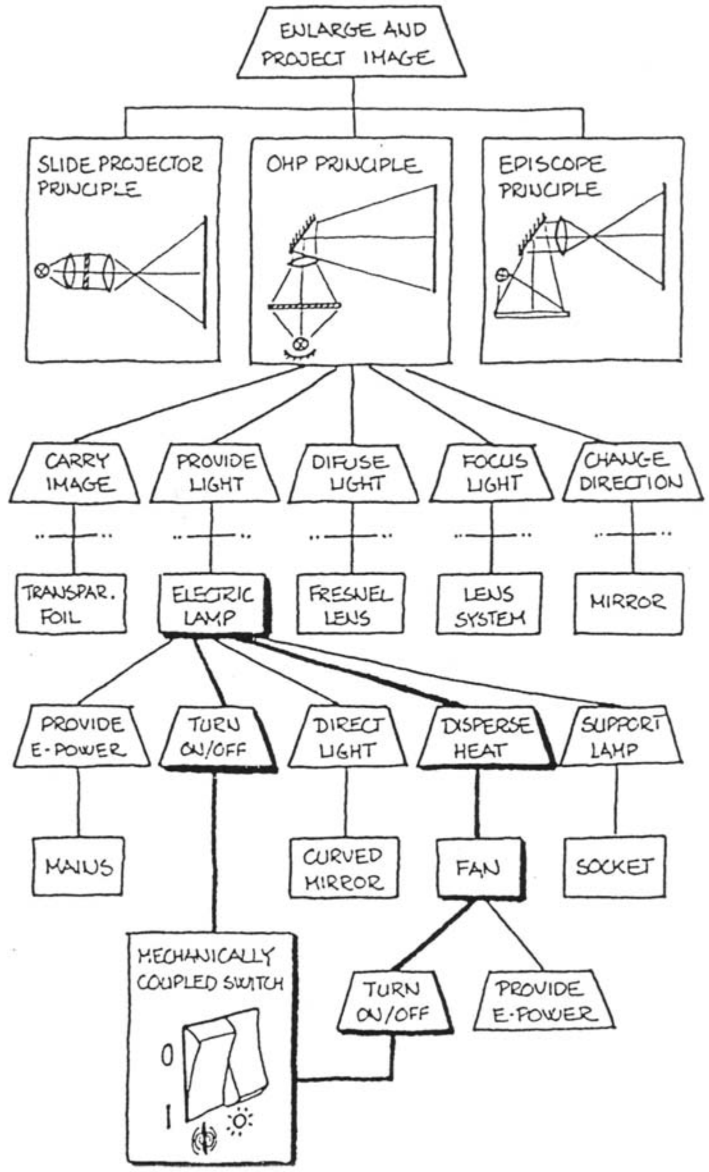


Figure 7. The functions-means-tree of an overhead projector. The top row shows the function and its solutions (function carriers) below. The next row shows the part functions of the solution, and the following their respective solutions. The figure only shows the tree of selected solutions. The division of the functions could be continued inside the components (an on/off rocking lever), were it to be necessary for the design task. [Buur 1990]

The latter of the two important issues, the existence of a technical system on multiple levels of abstraction is in part a result of the previous issues. As effect is essential in a technical system, it can be described on the highest level of abstraction as a ”black box” and not commit on the way the function is carried out. When the carrying out of the function is outlined in more detail, we have the function structure. At this point, we know which subfunctions together make up the desired main function. When we next outline the principle of solution to carry out the subfunctions, we have the structure of the function carriers. These function carriers (*Funktionsträger*) Hubka calls organs. He justifies the naming choice by saying that organs in technical systems have a similar position and status as organs in a biological system. Reuleaux has also used the word in his research, even if not in such a limited sense [Hubka 1984/88 p. 77-79]. When moving from abstract to tangible, the organ structure is followed by the structure of the parts of the product. According to the Theory of

Technical System, there are thus three more abstract levels above the part structure generally used in design.

If, instead of abstract thinking, we start pondering on the design process and the outlining of the design, we soon see that the different levels can also be considered the different phases of design. If we then proceed even further, we realize that the different levels represent the viewpoints of the various production process participants such as sales, designers, and manufacturing. From these issues we enter the more recent theoretical developments, to be discussed later in section 3.3 ”The Theory of Domains”.

As Hubka's theory aimed at showing methods for finding similarities between various technical systems, the book concentrates on various alternative ways to categorize technical systems and their *properties*. No categorization is preferred over others in the book. In addition, the suggested categorizations are very down-to-earth and practical, and many are also product-oriented. These are not part of the theory, but sketches of the directions in which the application of the theory and further research might take.

It may be difficult for a non-initiated reader of Design Science to perceive why the viewpoint provided by the Theory of Technical Systems would open up an essential vista for design in particular. To clarify this, let us compare the TTS to another object theory. Hubka, too, mentions a museum of technology, so we can take our point of reference from the present-day museology in which one also needs to take a stand in whether and to what extent an object is more than the sum of its parts. The object theory of Peter van Mensch [van Mensch 1990] is based on life cycles in which the value of the object changes in the different phases of its life cycle. An object consists of properties on four levels:

1) Structural properties, including the physical essence of the product
2) Functional properties, referring to ways to use the product
3) The context of the object, the conceptual and physical environment of the product
4) The representation of the object, based on the representations and values conveyed with the product.

TTS recognizes the first three of these four levels. The Van Mensch object theory does not, however, explain how these object properties are interrelated. Instead, the TTS explains that functional properties are realized in structural properties, and that context is an agent of transformation. Thus, the TTS provides us with plenty more information. The fact that the TTS does not recognize the representational aspect is a weakness. The issues discussed in the present dissertation will provide further visions into this area.

3.2. Systematical design Process and the Design of A New Product

In the teaching of machine design, the emphasis was - and still mostly is - on existing mechanical engineering, that is, existing machine parts and the related measuring and drawing. It is much more difficult to teach the designing of new machines. Despite all attempts (see previous chapter), there is no comprehensive machine design theory to aid the designer in receiving most of his knowhow via teaching. In the 1960s, the problem was the lack of constructors threatening the industry. As a result, the research of the methodology of machine design was born in Germany, funded by the State. The aim was to make machine design a learnable and teachable subject. [Konttinen 1990]

Creating a systematic design process was chosen as the way to develop the methodology of machine design. The design work was divided into phases, and specific methods and tools were created for each phase. A number of textbooks were written on this subject, of which the most widely used is probably ”Konstruktionslehre” by Gerhard Pahl and Wolfgang Beitz [Pahl & Beitz 1986/90] (see Chapter 5.3.). Another important part of the introduction of the systematical design method were the instructions (richtlinie) of the Verein der Deutschen Ingenieurs. The most important of these is VDI 2221 ”*Methodik zum Entwickeln und Konstruiren technisher Systeme und Produkte”* which defined the course of the systematical design process [VDI 1985/1987]. Other related instructions include VDI 2222, ”*Konstruktionsmethodik: Konzipieren technishen Produkte*” [VDI 1977(1)], VDI 2223 ”*Begriffe und Bezeichnungen im Konstruktionsbereich*” [VDI 1969], and VDI 2225 ”*Technisch-wirtschaftliches Konstruieren*” [VDI 1977(2)].

The creation of a design process is based on the experiences of its developers in practical design work. The starting point of the presented systematical design process is the abstraction of the task formulation. The goal is to break free form existing solutions, to be able to openly search for the optimal solution for the situation at hand on the basis of defining general functions. The systematical design process is not a law of nature. Design may also proceed in other manners, for example using the Altschuler approach [e.g. Altschuler 2000]. The systematical design process is, however, a generally accepted procedure within Design Science, and the methodologies developed within the field are created for this particular process.

The systematical design process as presented in the VDI 2221 standard is shown in the figure below. Please note that this is the design process of a new product. The starting point is that the design process is not modeled on any existing model. Previous knowledge enters the picture in Phase 3 in the form of outlining the principles of solution. The process does not always proceed in a linear manner, but steps may have to be taken to return to the previous phase. This, however, does not affect the principal order of accomplishing the tasks.

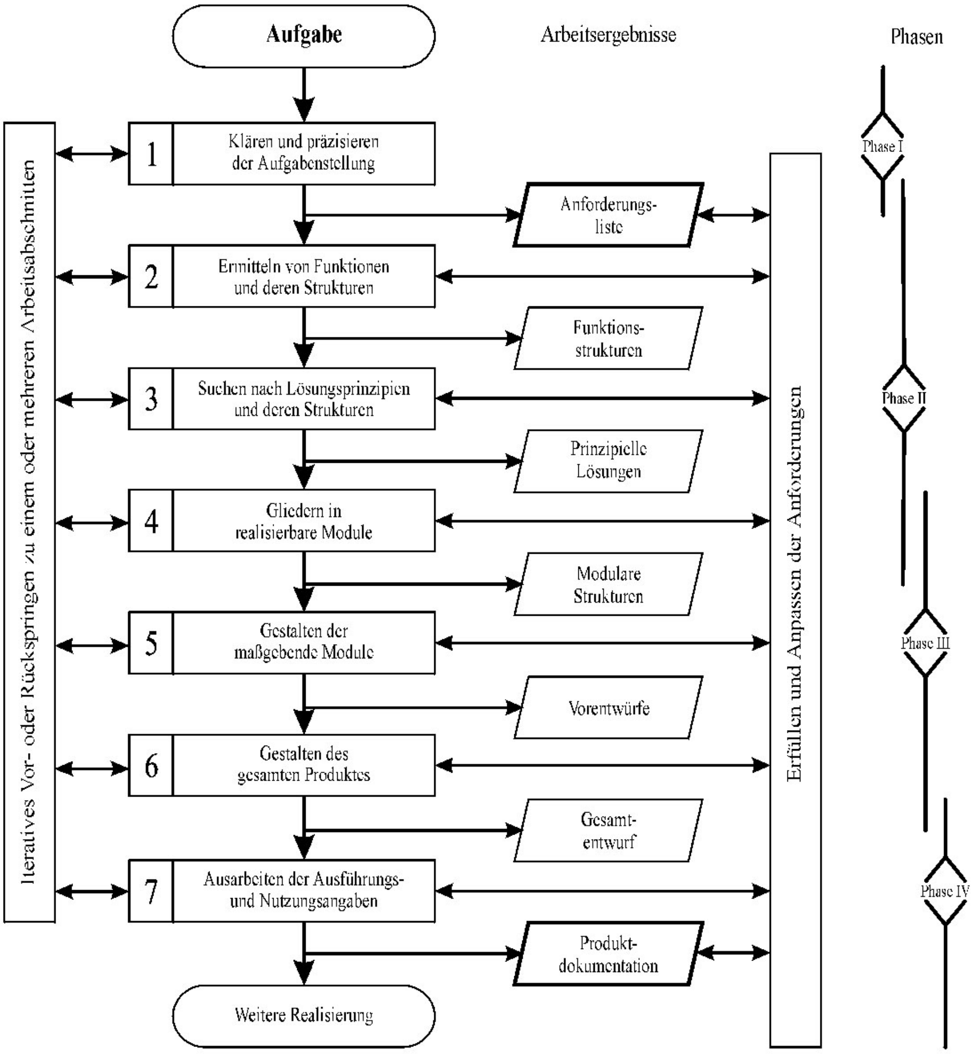


FIGURE 8. The process of systematical design according to the VDI 2221standard

The VDI 2221 standard does not regard the design of a new modular product as any kind of a problem. The VDI 2221 standard even mentions ”modular design” and thinks that all parts of all products are designed as ”modules”. This philosophy is poorly grounded, as it leads to a situation in which anything constructed of parts is labeled modular (see Chapter ”Pahl, Beitz, and the Modular System”). This is tempting but too straightforward, as will be proved in this thesis.

The view to the systematical design process described above is not, however, the one raised among the German School. Within WDK, there were two approaches to Design Science: the theoretical and the pragmatical (as named by the author of this thesis). The VDI 2221 definitions obviously belong to the pragmatical approach. They are not based on transformational thinking, but design is regarded as a process, and their starting point is an acknowledged sound practice. For this reason, they do not refer to ”organs”, and the process does not include all parts of the Theory of Technical Systems.

Hubka represented a more theoretical approach within WDK. In the process of systematical design presented by Hubka, modules are not mentioned, as shown in the figure below. While the VDI 2221 standard speaks of principal solutions (*Prinzipielle Lösungen*), Hubka speaks of organs. While according to the VDI 2221, the modular structure (*Modulare Strukturen*) is formed next, Hubka speaks of *Optimal preliminary layout*.

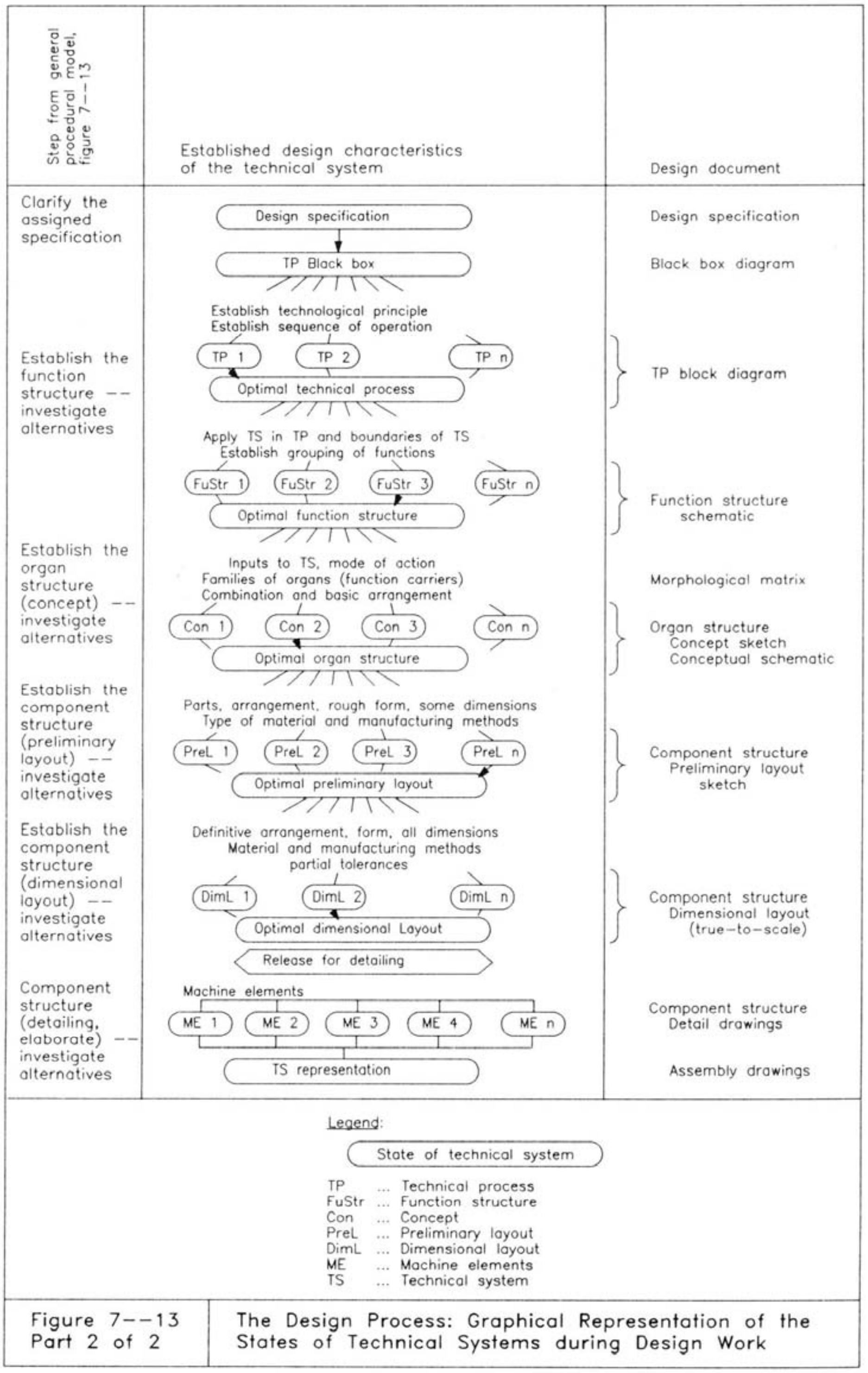


FIGURE 9. The states of systematical design process and the ensuing design results, and the contents of the design task according to the Theory of Technical Systems (TTS). [Hubka & Eder 1996 p. 137].

It is generally thought that the process figures above describe the same process, and the differences therein are merely semantic. This, however, does not apply to the level of precision relevant for the present thesis. According to the VDI 2221 standard, a modular architecture can be created for a product on the basis of the principal solution alternatives (or organs, according to the Theory of Technical Systems). According to Hubka, only *an optimal preliminary structure* can be created for a product. This difference is very little discussed in research and even lesser is the number of conclusions on the subject. Ernst Eder, a long-time colleague of Hubka's will revisit the issue in the 2007 ICED07 conference. In his paper ”*Tranformations Systems Revisited”*, Eder aims to illustrate with examples that the *fully operationalized* introduction of the functional division by Pahl and Beitz requires the utilization of a demanding view into the process of change [Eder & Hosnedl 2007]. The reciprocal contribution of these fundamental studies published in the 1970s (Hubka ”*Theorie der Maschinensysteme”* 1974 and Pahl & Beitz ”*Konstruktionslehre. Methoden und Anwendungen”* 1977*)* is not fully clear even after 30 years of research!

The systematical design process will hereafter in this dissertation refer to ***the process of systematical design according to Hubka's terminology.*** When following the data flows of design and the results of the design tasks, it is important to unambiguously understand what are the starting information and what the resulting design decisions. In the figure above, the phases of the design process according to Hubka's model are shown in the left column (see also the more detailed presentation of Hubka's process in Chapter 5.9). The middle columns show the meaning of each design phase in the theory of technical systems. The columns on the right show the form in which the design yields results.

3.3 The Theory of Domains

Danish professor Mogens Myrup Andreasen has further elaborated Hubka's work and philosophy. In his work, Andreasen has brought Hubka's theoretical views closer to the practical design environment. ”The Theory of Domains” by Andreasen corresponds content-wise to Hubka's model, but interpretation has grown in importance. Andreasen presents the domains as phases of proceeding in the design. At the same time, meaning is generated for the relations leading from one domain to another, as shown in the figure below.

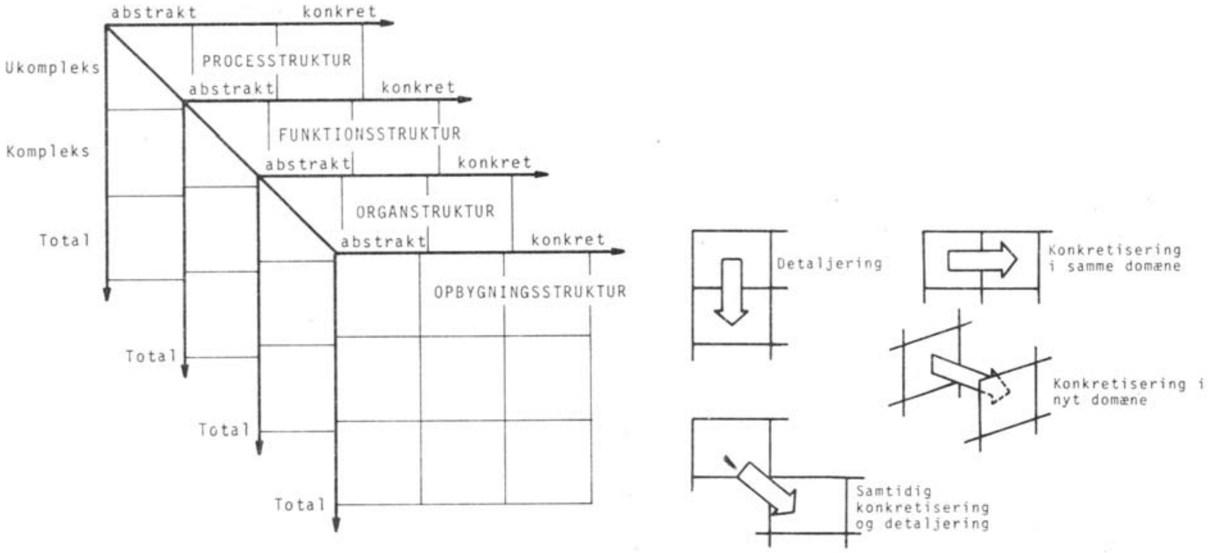


FIGURE 10. The four domains and the four directions of design, according to the Domain theory: detailing, concretization in the same domain, concretization to the next domain, and simultaneous detailing and concretization. [Andreasen 1980 p.170]

Later, these relations are divided into two groups. The relations of vertical causality affect one domain, while the relations of horizontal causality affect between domains. When thinking of, for example, the effect of decisions made in the definition of functions, we are talking horizontal causality. The Danish have studied these phenomena, as they are one factor affecting the manufacturability and assemblibility of the product. When the effect of the actual operational environment of the company and the implementation of the product are acknowledged in the chain of design and manufacturing, these principles of effect are called ”*dispositional mechanisms*”.

Andreasen presents that the levels of abstraction of a technical system primarily correspond to the viewpoints to the product of the participants of the production process: sales, designers, manufacturers etc. This is shown in the classic figure below:

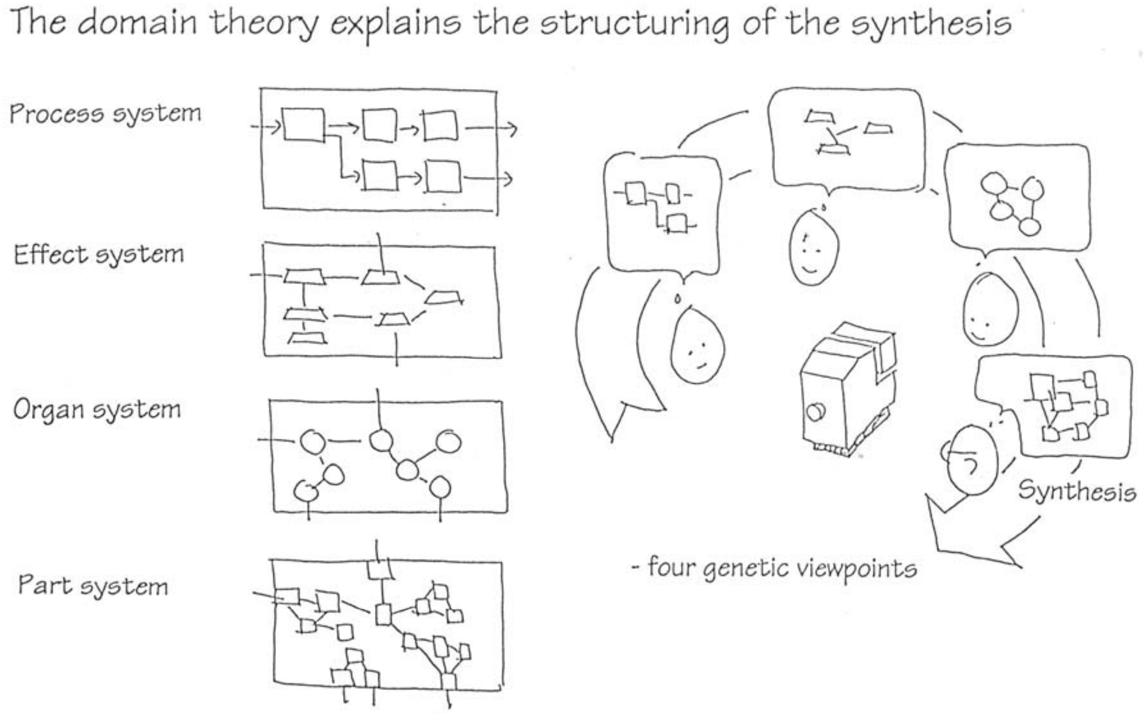


FIGURE 11. The four domains of the domain theory also correspond to some extent to the views of the functions of the companies participating in the research and development. This observation has been utilized, for example, in the research of systematical product configuration (see Chapter 6). [Adreasen: lecture handout from 1997]

Functionalities are (usually) arguments for product sales. For this reason, the functional structure often corresponds to the salesperson's viewpoint of the product, and sales often present their arguments in this domain. According to the German School, designers ought to develop models for solution instead of components. These are considered the organs of the theory. Thus, the organ structure is the design viewpoint to the product. In production, the product is physically realized. For this reason, the production viewpoint is and must be the part structure. During the past few years, there has been discussion on whether the transformation structure and the functional structure could be combined as one domain to aid practical design work. Occasionally, this has been done (e.g. Riitahuhta A., Andreasen M. M. “Configuration by Modularisation”, Proceedings of NordDesign 98, KTH, Stockholm, 1998). However, justifications for keeping the transformations and the corresponding functions do exist.

In Danish research and teaching, Hubka's ideas have been widely applied. The relationship between the contribution of the present dissertation and the methods developed in Denmark is evaluated in Chapter 12.

3.4 Summary

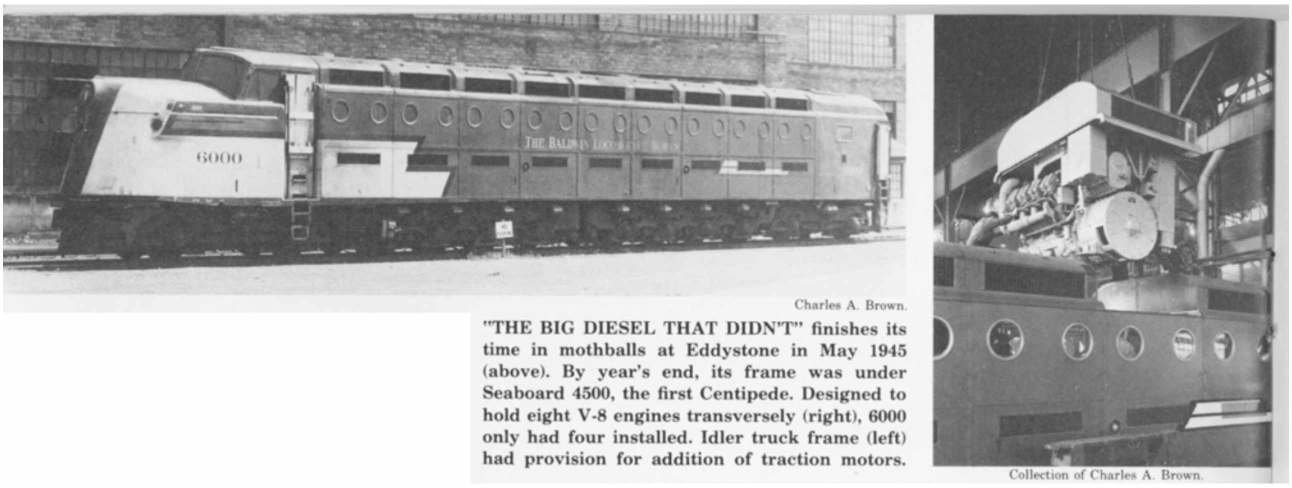
The most important contribution of Design Science is the theoretical description of a technical system as a transformational system. This results in causality between the aims and the means as well as the recognition of the existence of a technical system on multiple levels of abstraction. Based on the tenets of the German School, we may also consider the design process well-known, although the differing details force us to check whose definitions are being followed. A major legacy of Design Science is the raising of the importance of functionality on top of the hierarchy. This can be regarded as the undeniable order of priority when designing a system that carries out functions.

4. Modularity as a historical phenomenon

Using modules in products and utilizing the benefits from modular structures are solutions developed in practical design work in the industrial history of the 20th century. In practical industrial operations, modularity is not, of course, defined, but the word is used in connection with products with defined internal interfaces between assemblies. Occasionally, this has been associated with the idea of interchangeable modules and the configurability of the product, but this is not always the case. Products labeled modular in the industry share the fact that *they feature an internal division or divisions based on some more abstract reason than the general component structure.* This more abstract reason is generally related to the organizing of production or to the life cycle or the configurability of the product.

Reasons related to the organizing of production include, for example, the assembly of main components and auxiliary devices into separate assembled frames in the manufacturing of diesel engines, or dividing the hull of a ship into ”lift blocks” that can be lifted with the available lifting equipment. An example of a division related to life cycles is the classification of the components whose life span is shorter than that of the entire product as replaceable ”service modules”. An example of configurability could be limiting the renovations brought about by technological development into one block of the product, or gathering the special wishes related to one customer order into a ”customer module”. We have placed the words in quotes to indicate that the words are borrowed from a standard-language text and they will not be defined or used as terms in this dissertation.

Products can be found even in the remote history that feature at least the ideas in the Baukastensystem defined by Borowski (see Chapter 5). It may be impossible to indisputably show the first modular product in the world. For the scope of this dissertation, we do not need step back in time further than to the year 1939. At that time, a diesel engine with a modular architecture was introduced in an American patent. Baldwin Locomotive Works applied for a patent on 27 February, 1939 (U.S. Patent No. 2249628, granted 15 June, 1941) for a 4,000hp diesel engine with six engine generator modules.



Charles A. Brown.

"THE BIG DIESEL THAT DIDN'T" finishes its time in mothballs at Eddystone in May 1945 (above). By year's end, its frame was under Seaboard 4500, the first Centipede. Designed to hold eight V-8 engines transversely (right), 6000 only had four installed. Idler truck frame (left) had provision for addition of traction motors.

Collection of Charles A. Brown.

FIGURE 12. Baldwin's locomotive was functionally modular, but still it did not enjoy success on the market. [Brown 1982]

The advantage of this structure was the opportunity to use different power ranges in trains of different weight by starting and stopping the engine modules as necessary. Later, the firm applied for a new patent for a locomotive with eight engine modules (U.S. Patent No. 2317849, granted 27 April, 1943). A prototype engine was built, but it was not finished due to the lack of buyers. The US railroad companies solved the issue of changing traction force in another way. A necessary number of smaller engines – up to five locomotives – were linked to the train, and electrical steering enabled the same two-man crew steering from the first locomotive. The modular, in actual fact *functionally modular* locomotive (in the figure below) was disassembled and the platform was used in the following product development projects. *[Brown 1982]*

The following case dates back to 1943-45 and the Blohm & Voss, AG Weser, and Schichau Werft shipyards. At that time, the German shipbuilding industry manufactured submarines in serial production under a considerable wartime pressure. To boost production, ”a modular submarine” of the type XXI was developed. In this case, ”modularity” referred to dividing the hull of the submarine in longitudinal blocks. These blocks could be manufactured outside the basin. Basin capacity was one of the problems in the production, which means that operations were boosted as only the phase of joining the blocks together was carried out in the basin. In principle, the final assembly time of the submarine was reduced to 176 days. At the same time, this new type of submarine was more powerful than any previous model. The achievement has later been evaluated as follows: [Williamson 2005]

”*With the advent of the Type XXI, the Germans had made a quantum leap in submarine design and manufacture. This amazing vessel was the first to be mass-produced in modular form.*”

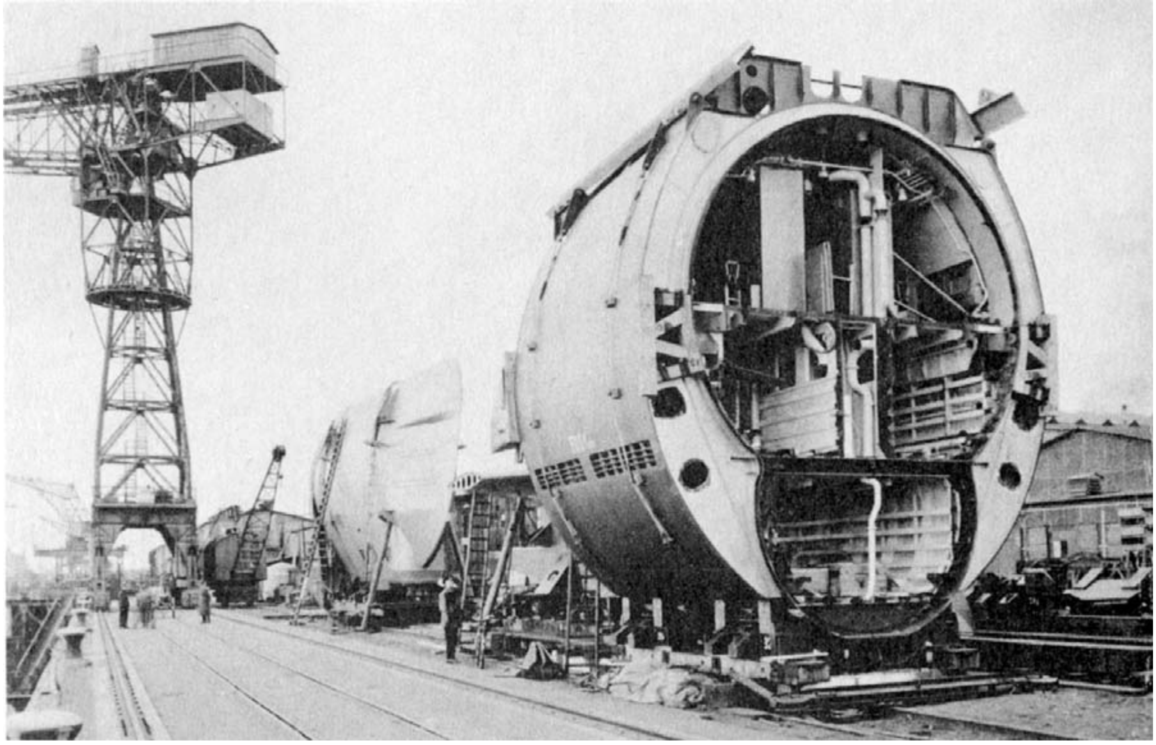


FIGURE 13. A submarine of the type XXI under construction in Bremen, circa 1944. The submarine was divided into longitudinal assembly blocks that were manufactured outside the basin. This is a good example of modularity related to a better organization of production; it is of interest even today. [Weir 1993/98]

This is a classical example of a reason to divide the product into parts to meet the requirements of the organization of production. Large production numbers, however, were not achieved due to external reasons, primarily the air raids of the US Air Force. Only 133 submarines were manufactured. [Williamson 2005, Weir 1993/98]

Let us note that this method that was fresh and new in the marine industry in the 1940s is still being used one way or another in shipbuilding. The building-block technique was not, of course, invented in 1943. The method had been used in, for example, bridge-building long before, but not as serial production.

Examples of modularity related to the life cycle of the product emerged in the 1970s. The Electro Motive Division (EMD) of the US diesel engine manufacturer General Motors introduced the GP38-2 and the SD40-2 locomotives, the flagships of the ”Dash 2” series. Dash 2 referred to the fact that the electrical steering system of the locomotives and the related circuitry had been renewed. The system structure had been rationalized and the steering components were placed in pressurized cubicles. In addition, the entire steering system consisted of separable modules, and a defective module could be replaced without having the entire locomotive standing in repair. In a typical delivered locomotive, there were 17 such modules. The improved shielding of the system increased the reliability of the locomotives, and the modular structure facilitated service and, what was the most important, raised the usability level of the locomotives. The Dash 2 locomotives proved to be very reliable, and they were a success on the market. The EMD SD40-2 became the most successful General Motors model up until then. It was the most manufactured diesel engine in the Western world. A total of 4,149 engines were sold in 1972-1981. [Kerr 2004, Salomon 2000]. The modularity of the electrical steering system is said to have been one of the key factors to success – at least it was the only remarkable difference compared to the competitors. Exclusive of the electrical system, the locomotive was not modular and not very configurable, either. Actually, only four (!) variations existed of the basic locomotive.

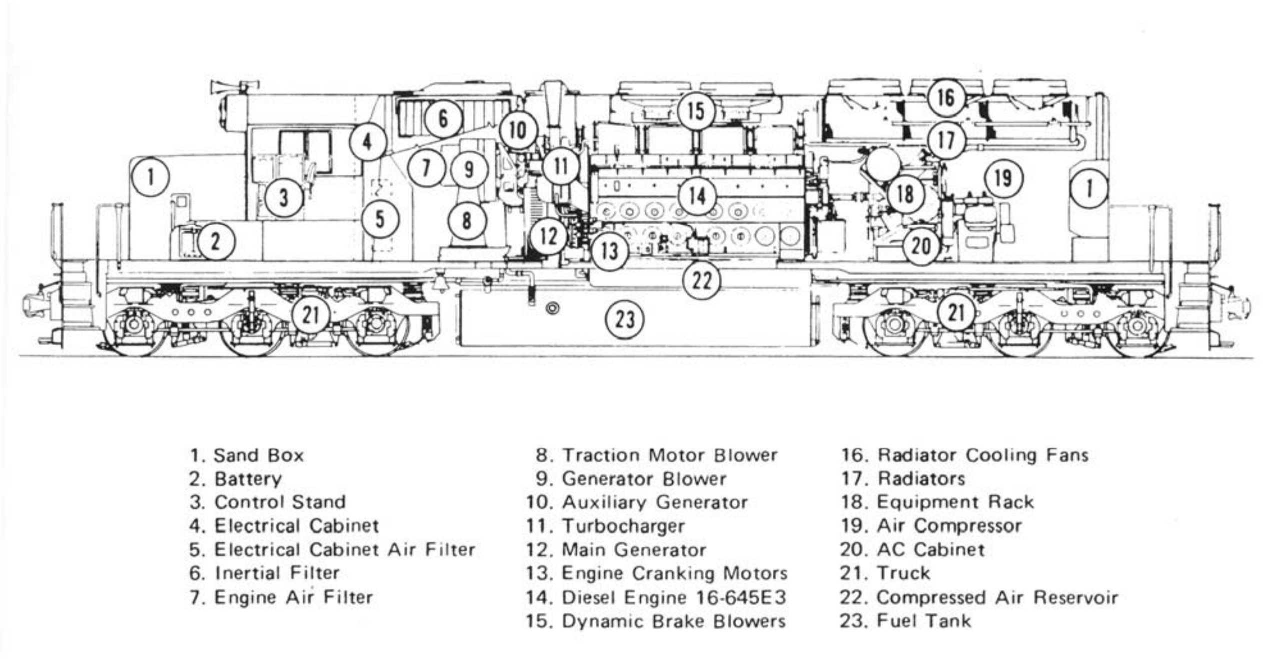


FIGURE 14. The ”Dash 2” locomotives of the Electro Motive Division of General Motors were not modular as a whole. The modules of electronic steering are so small that they are not even indicated in this diagram. Their modularity, however, was a critical success factor. [Kerr 2004]

Managing product variation and implementing configurations via modular solutions re-emerged in the 1980s. In 1980, the Swedish truck and bus manufacturer Scania introduced a new model line, the so-called Series Two. Compared to the previous models, the novelty was the advanced standardization of structural elements. This created a prerequisite for the implementation of modular solutions in Series Three in 1987 [Sandell & Steiffert 1990, Lindh 1992]. The structural changes made considerably rationalized the products, as shown in the well-known example below, presented by, for example, Erixon in his dissertation. While the numbers of necessary parts and tools were considerably reduced (for example, from 1,600 to 280 in sheet metal tools), Scania's cabin variations extended. In this case, modularity was pure assembly modularity, perhaps even standardization in part.

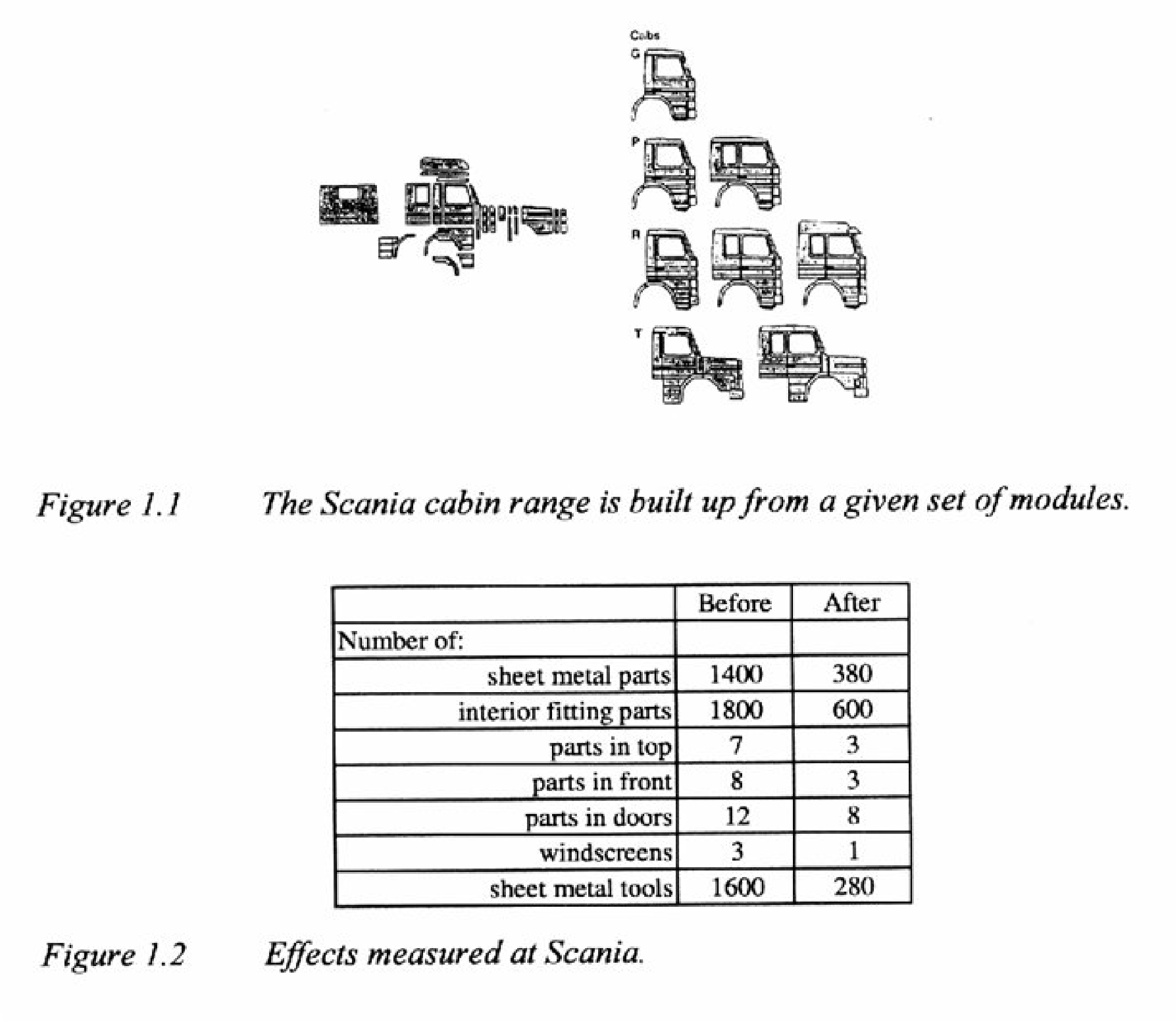


Figure 1.1 *The Scania cabin range is built up from a given set of modules.*

	Before	After
Number of:		
sheet metal parts	1400	380
interior fitting parts	1800	600
parts in top	7	3
parts in front	8	3
parts in doors	12	8
windscreens	3	1
sheet metal tools	1600	280

Figure 1.2 *Effects measured at Scania.*

FIGURE 15. The so-called Scanian Series Three, modularity was utilized by assembling the cabins of the entire truck series using standardized elements only. This brought about a considerable cost effect. [Sjöström 1990, Erixon 1998].

Along Series Four in 1998, the modular structure was finished and its benefits were used as sales arguments in marketing, which means that the renewal was not only internal. According to Scania, the number of components was reduced from 20,000 to 12,000 in the shift from Series Three to Series Four. The range of variations remained the same or extended; Scania has 360 different truck models available, of which thousands of different versions [Scania 2003]. *Scania started to offer a* *product that is systematically modifiable or configurable* (see Chapter 6). It is well justified to consider Scania as one of the leading utilizers of modularity today. Scania is one of the sample cases to be discussed in detail in Chapter 10.

The main steps of product configuration at Scania are shown in the figure below. The selection of the purpose of use determines the product family from which the truck chassis is selected. At that time, there were three weight-optimized product families (L, D, and C). In addition to these, there existed a chassis series G intended for oversize transport, as a chassis for special vehicles, and for other special uses. A limited number of possible axles layout plans were available for each chassis series (cf. Chapter 5.2 The Borowski design of a closed structure system). The engine and powerline set to be selected in the next phase fit all models with minimal limitations. Similarly, there are few limitations of the selection of cabins. In addition to these main selections, equipment are also selected that can be added to the basic configuration without removing anything (the so-called plus-modular approach). Therefore, we can state that Series Four was a *fully configurable product*.

Use case + chassi layout + powerline + cabin = truck

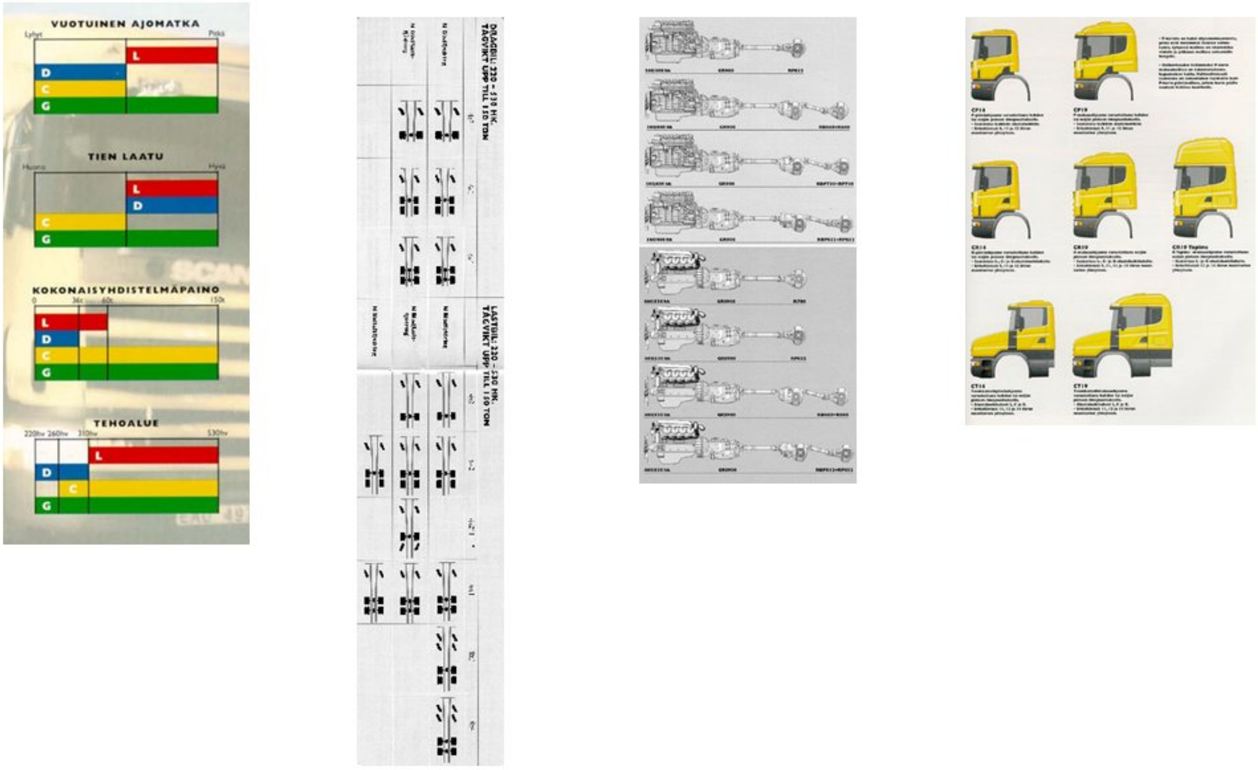


FIGURE 16. In their next product line, Scania was able to manage customer variation by means of modularity. One of the four product families is selected using four criteria (annual mileage, road conditions, total weight, desired engine power). The product families have ready-made chassis layouts. All available powerlines and cabin structures fits these layouts with minimal limitations.

Summary

A modular product is an industrial innovation and as such at least 68 years old. There are different kinds of modularity depending on the respective aims of design. There exist companies and products whose success can be considered as a direct result of using modular structures.

5. Research of modularity and the proof of Hypothesis 1

The original meaning of the word 'module' derives from ancient Rome where it was used as a standard measure. It was mentioned in the work *De Architectura libri decem* by Marcus Vitruvius Pollio, an architect who lived in the era of Emperor Augustus. At that time, pillars formed a considerable part of the facade. The module of a building was half the diameter of the bottom of the pillar [*Nykysuomen sanakirja (Modern Finnish wordbook)* 1992].

5.1 Walter Gropius and architects

A module is thus associated with standardization even in its original sense. Therefore it does not surprise us to discover that modularity as a theme also appeared in the works of the Bauhaus school (Germany, 1919-33). Bauhaus is largely related to the industrial revolution: a handicraft tradition had to pave way for industrial production. The purpose of Walter Gropius, the founder of the school, was to replace the handicraft tradition by a new tradition of model designers [Gropius 1965]. In present terms, we would be talking about industrial design. This aim resulted in the excessive emphasis of standardization and simplification in Bauhaus. Even though Bauhaus is often mentioned in connection with modularity, the school did not contribute to the philosophy in any remarkable way.

The ideas of modularity in architecture are perhaps most clearly expressed in the design philosophy of *"flexible standardization"* by Alvar Aalto. Related plans were designed by Aalto and researched in his lead since 1940. In the autumn of 1940, Alvar Aalto was appointed as research professor at the Massachusetts Institute of Technology (MIT) and placed in the lead of a research institute whose goals included that of developing models of systematically configurable residential houses and to write down the outlines of implementing these configurations. In actual fact, their task was to develop a configurable product range (see Chapter 6), even though the term *configurable product paradigm* was not, of course, used at the time. During World War II, Aalto's operations in the US remained minimal, but tables of the different combinatory variations were developed, lead by Aalto's assistant Arnold W. Tucker. These would alter have been called structural designs (Borowski) and decades later configuration models.

The idea in the houses standardized by Alvar Aalto was the adaptation to the external variables of the construction site (disadvantages such as high traffic, advantages such as a beautiful view). This is shown in Figure 17. Another idea was the adaptation of the buildings to the increasing requirements. The houses could be erected as basic residences comparable to emergency accommodation, but they could be extended and equipped within the system into high-quality one-family houses modern conveniences. The houses would have thus been configurable according to their location and the requirements of use.

In Finland, a natural constructor of Aalto's ideas would have been Ahlström, who founded a housing factory to manufacture the constructional elements of houses following Aalto's type designs (the so-called AA houses). At this stage, Aalto declared that it would be possible to construct 96 different housing models of prefabricated elements on the basis of the housing system developed at the MIT [Schildt 1989 p. 54]. As shown in the example in Figure 18, the configurations enabled the construction of considerably differing houses.

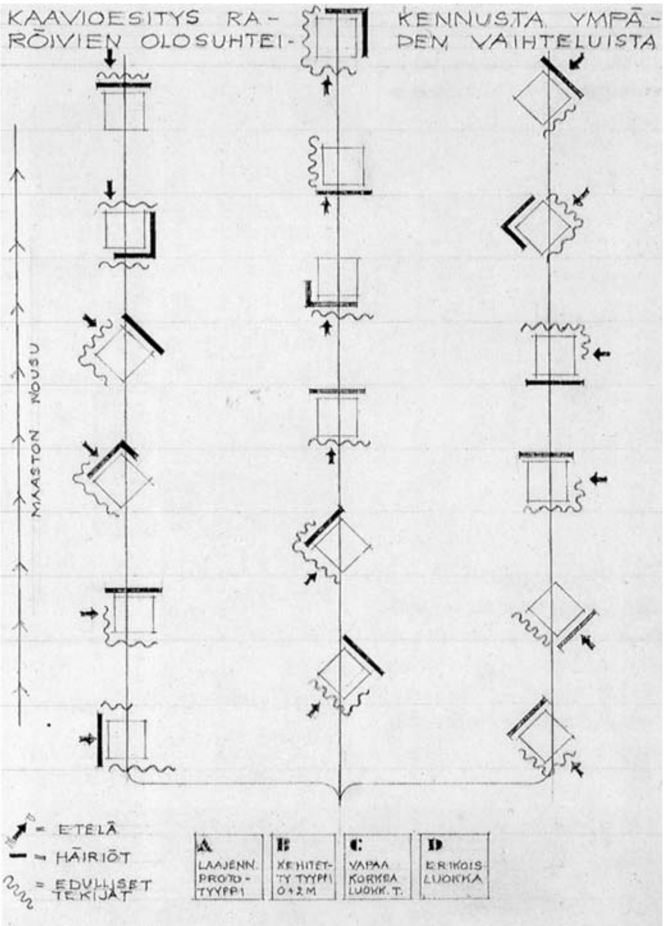


FIGURE 17. Adapting the location of the standardized house to the environment, according to Alvar Aalto. The variables considered are the elevation of land, the compass point, and the disadvantages and the advantages of the lot. [Schildt 1989]

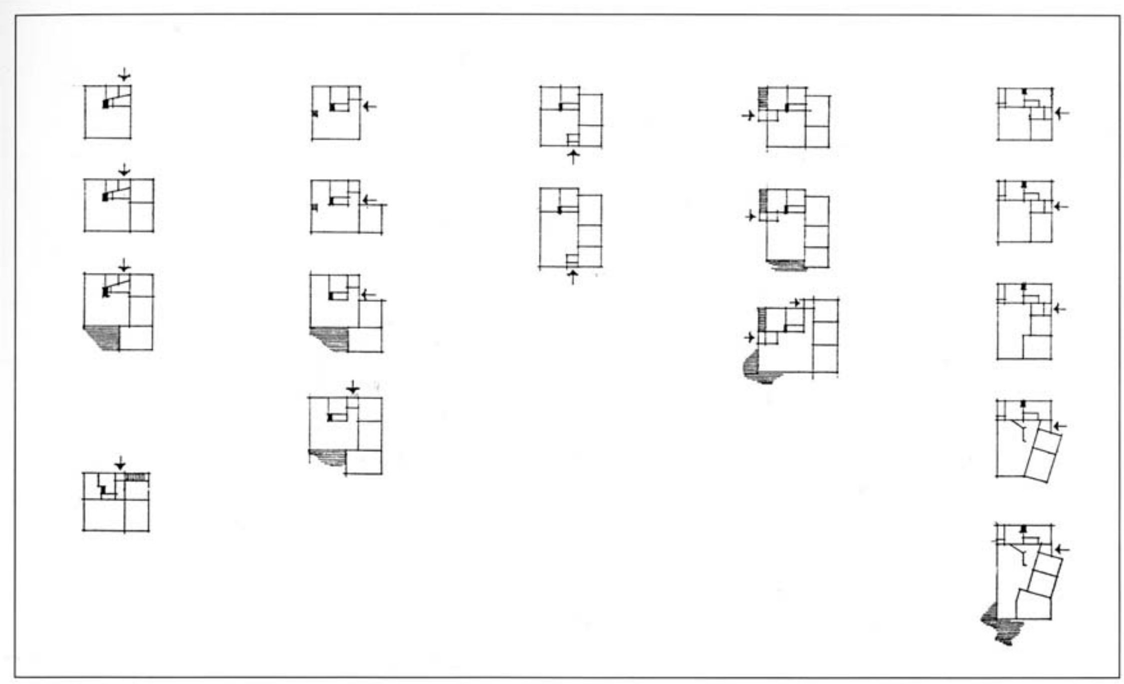


FIGURE 18. Various floor plan configurations of the AA-system houses [Schildt 1989]

Aalto's ideas seem very rational and implementable even by today's standards. However, it was a time of a different industrial paradigm in which mass production and standardization were prioritized over configuration. Eventually, Ahlström did not even start experimenting with configurable houses, but soon focused on manufacturing only a few basic types by the market name of AA houses. These were standard products. Neither were Aalto's ideas understood in the United States. In 1951, a 466-page book on the problematics of element houses was published at the MIT, but it does not mention Aalto's ideas [Schildt 1989 p. 40]. The time for configurable products had not yet come.

In architecture, the modular ideas of houses as living machines are even better illustrated in a later Design Patterns research paper [Alexander & al 1977]. In his work, Alexander aims to discover the functions related to a residential house. Graphical symbols are given to the functions, and the house-related operations carried out by the resident (this corresponds to some extent to the so-called ”use case” approach) are described as a space-to-space arrowhead diagram. This approach has apparently remained rather insignificant in its field; however, it has served as an inspiration for the development of a corresponding approach in software engineering [Gamma & al 1997]. We mention these, as corresponding theoretical systems were not developed in Design Science until the 1960s and 1970s.

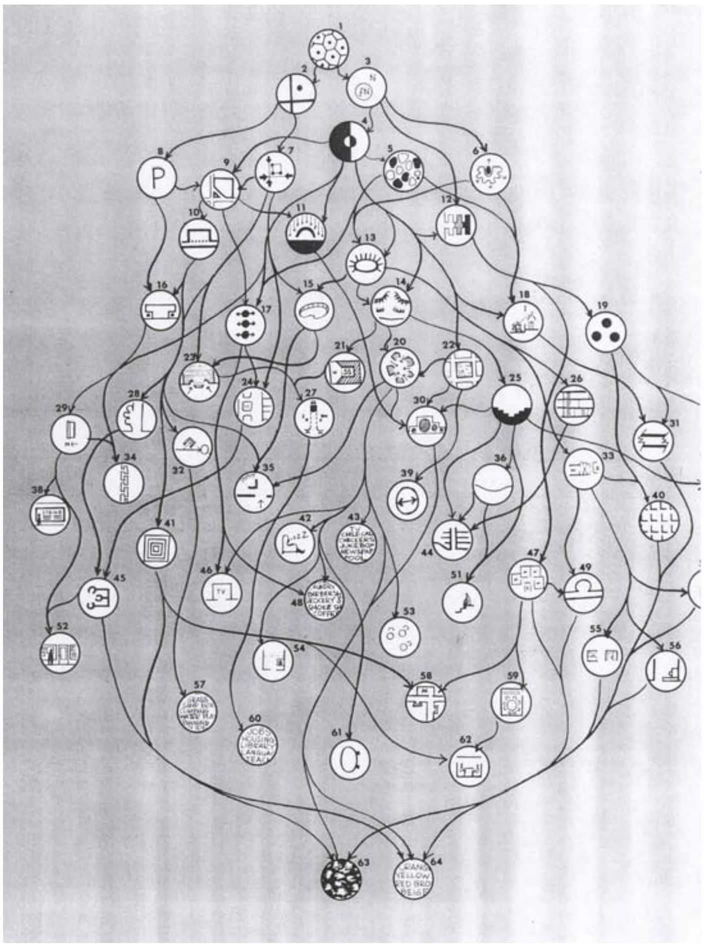


FIGURE 19. In the Pattern Language technique by Christopher Alexander, the house to be designed is described as a network of operations and the related moving from space to space. the symbols thus indicate the events taking place in the house or the needs of the residents; following the arrowheads, planned purposes of use can be detected. The symbol meanings are to be found in the original source [Alexander & al 1977].

5.2. Karl-Heinz Borowski

From the viewpoint of the current research in modularity, the work of Karl-Heinz Borowski may be considered fundamental. In his book *Das Baukastensystem in der Technik*, published in 1961, Borowski outlines a product family system based on constructional elements (Baustein), and presents industrial examples of implementing this approach. Borowski's work is based on the previous definitions in the book *Die Gesetzmaßigkeiten kombinatorischer Normen*, published in 1953 and written by A. Nasvytis. The definitions of a constructional element (Baukasten) and a constructional part (Baustein) derive from this book. The greatest contribution of Borowski's work is the establishment of the rules of a constructional element system (Baukastensystem); Nasvytis does not define a system. In addition, Borowski presents his observations on the use and the nature of such a system; these still remain problematic in the development of modular structures.

A constructional element (Baukasten) is an element on the level to be examined that consists of small constructional elements (Baustein). These small constructional elements may form a new Baukastensystem in which they act as constructional elements (Baukasten). However, Borowski does not recommend the use of embedded internal constructional element systems but states that one must select the levels to be included in the constructional element system from among the possible size ranges (Rangstufen). He calls this limitation the solution level (Auflösungsgrad), as shown in the figure below.

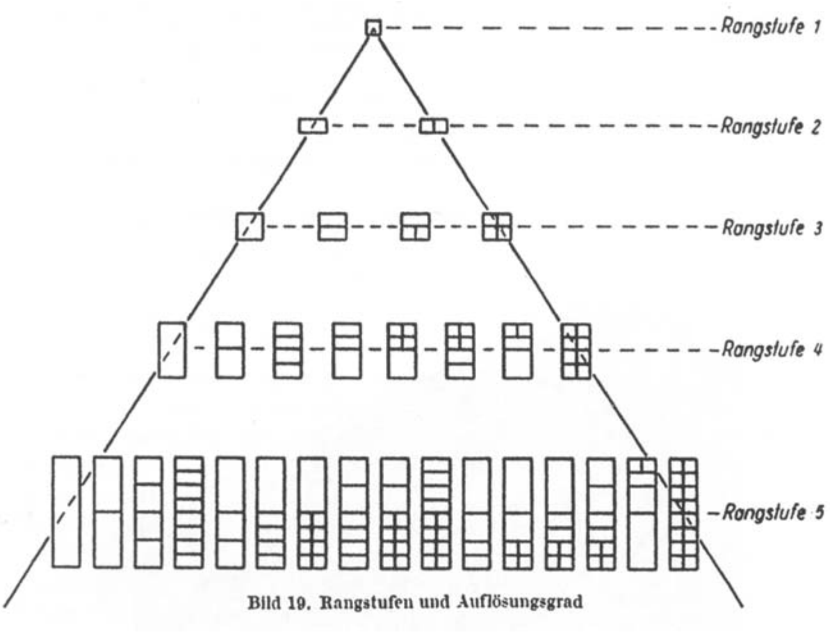


FIGURE 20. The solution level (Auflösungsgrad) defines the elements of which size to be handled as modules. Any bigger elements are module assemblies, or combinations of the module system, while the smaller ones belong to the internal structure of the module. Borowski does not use the word "module". (Actually, Borowski has not drawn a solution level in the picture – he only shows a two-level model; author's note)

Borowski presents an interesting three-level example from the field of railway engineering: a train consists of locomotives and rail cars. A rail car consists of the chassis (Fahrgestelle) and the superstructure. The chassis, in turn, consists of wheel sets, the supporting structures, and the suspension. The idea of size ranges and solution levels is an important part of the classification of constructional element systems to be present in the following, as it recognizes a difference between a small constructional element and a large constructional element (*Kleinbausteine* and *Großbausteine*).

According to Borowski's definition, the constructional element system (*Baukastensystem*) thus consists of constructional elements (*Baustein*) of various size ranges (*Rangstufe*) within a selected solutional level (*Auflösungsgrad*). A constructional element is an undivided entity within the system, which refers to the fact that it has a continuous interface in a physical or other sense. This is indicated by the division into small and large constructional elements.

Borowski defines the constructional element system as follows:

"Das Baukastensystem ist ein Ordnungsprinzip, das den Aufbau einer begrenzten oder unbegrenzten Zahl verschiedener Dinge, aus einer Sammlung genormter Bausteine auf Grund eines Programmes oder Baumusterplanes in einem bestimmen Anwendungsbereich darstellt."

He also states that the interchangeability of the components is an obligatory requirement for the system:

"Das Baukastensystem tritt erst in dem Augenblick auf, wo das Vorhandensein der Baugruppen zur Fertigung verschiedener Dinge durch verschiedene Kombination der Baugruppen ausgenutzt wird".

A constructional element system is thus a collection of standardized (*genormter*) constructional elements that can be used to build a limited or unlimited set of various products according to the construction plan (*Baumusterplan*). Borowski, therefore, requires configuration, which means that the mentioned German submarine is not a Baukastensystem. Borowski further defines that only an element that belongs to a system with configurations ought to qualify for a constructional element.

Borowksi defines nine different cases as the various types of the Baukastensystem. These serve as meta-level models for the constructional plans (*Baumusterplan*).

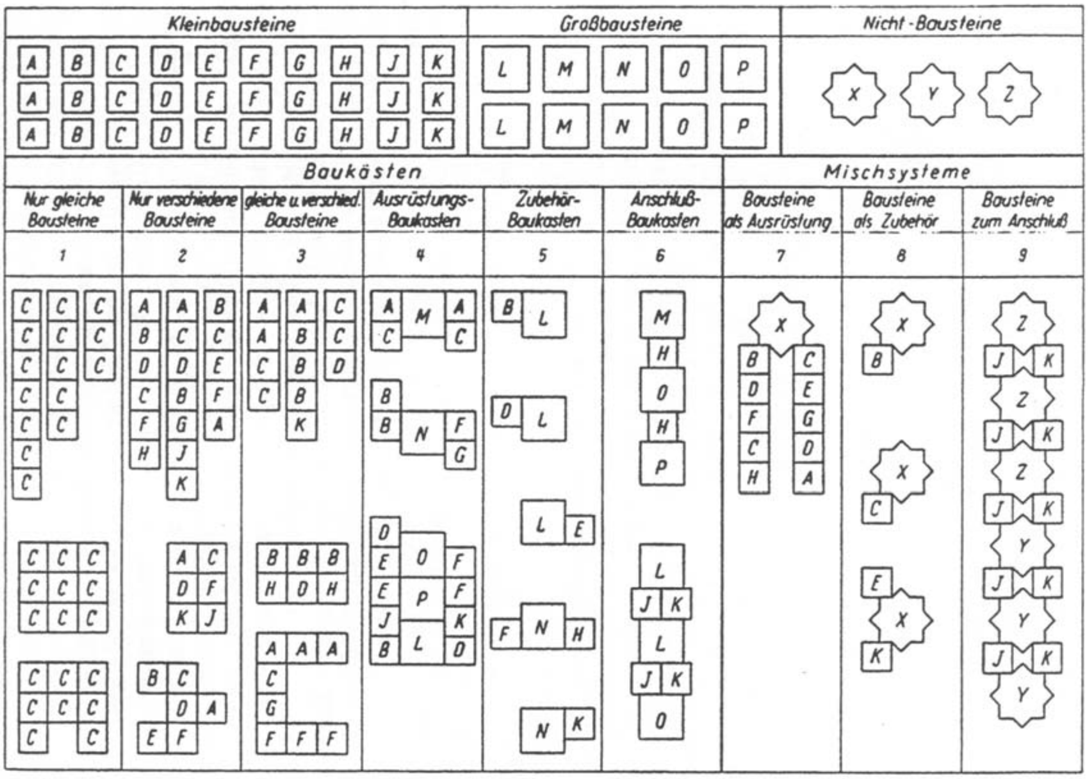


FIGURE 21. The meta models of Borowski's structural designs

The small constructional elements in the figure above are elements of the smaller size range. Large constructional elements may thus consist of elements the size of small elements (even elements similar to small constructional elements!), but they are not separated on the chosen level of examination. Constructional elements are undivided in relation to the system on the chosen solution level. Non-constructional elements (Nicht-Bausteine) are nonstandardized elements and they thus remain outside the system.

In Borowski's classification of constructional element systems, there are two categorizations that can be considered arbitrary. The first one is examining only two size ranges in one system. Nothing prevents a different number of size ranges. The second arbitrary categorization is considering non-constructional elements as big entities. Both definitions are functional as long as we remain in the technology and size range of the devices (from machine parts and switch cabinets to diesel engines and machine tools) presented by Borowski. In this case, two size ranges suffice and we can presume that small elements can always be standardized. In big mechatronic products including system products and software, these definitions are no longer justified.

According to Borowski, a constructional element system is always created on a level of parts, which means that the product range must be designed or otherwise well known. The division of the product into constructional elements (*Elementarisierung*) is acknowledged as the most demanding task in design. As the level of examination is the level of parts, no specific methods are presented, but it is merely stated that the guidelines of rationalization and standardization are followed.

“Die Elementarisierung bedeutet noch nicht den Übergang zum Baukastensystem, sie wurde meist allein einer Rationalisierung der Fertigung wegen durchgeführt.”

At the end of the book, rough divisions are listed for a number of typical industrial products. they are valid conclusions only as long as the product structure and their method of manufacturing remain the same as at the time of definition. They are not very universal or timeless.

Borowski presents a number of industrial examples of constructional element systems. The oldest of these, an “Ideal-Bücherschränke” bookshelf system manufactured by Soennecken, dates back to approximately the year 1900. The system, shown in the figure below, meets many of the requirements for modularity. The word “module”, however, is not used in connection with the product.

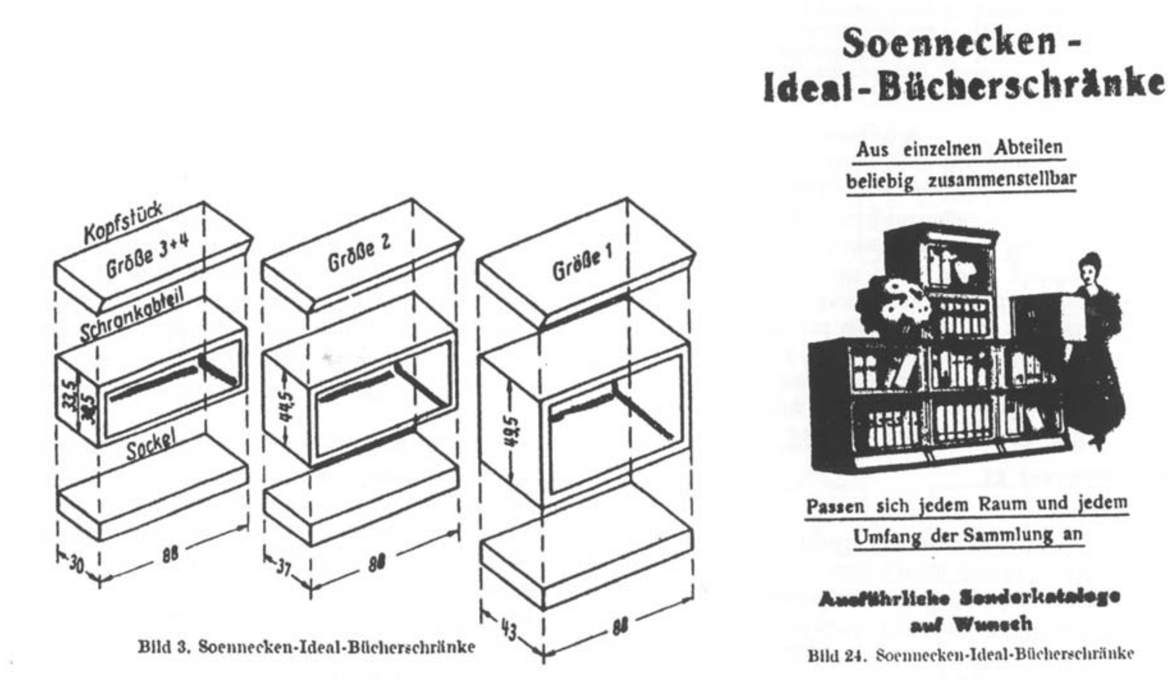


FIGURE 22. Borowski's example of a modular product is older than those presented in Chapter 4 (circa year 1900). The word “module”, however, is not used in this connection.[*]

The following figure shows desks by Mauser-Werke and is a good example of the structural design of a closed system. All constructional elements and their combinations are known. This product could also be called modular.

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[*] The word 'module' ought perhaps not to be used when referring to old furniture constructions. John Heskett presented similar examples from as early as the 1880s, but notes that “*These designs were not modular systems, but rather a series of compatible units...*” [Heskett 1980/87 p. 75]. According to Heskett, the first truly modular furniture system was a kitchen by the Bruynzeel company, designed by Piet Zwart in 1933.

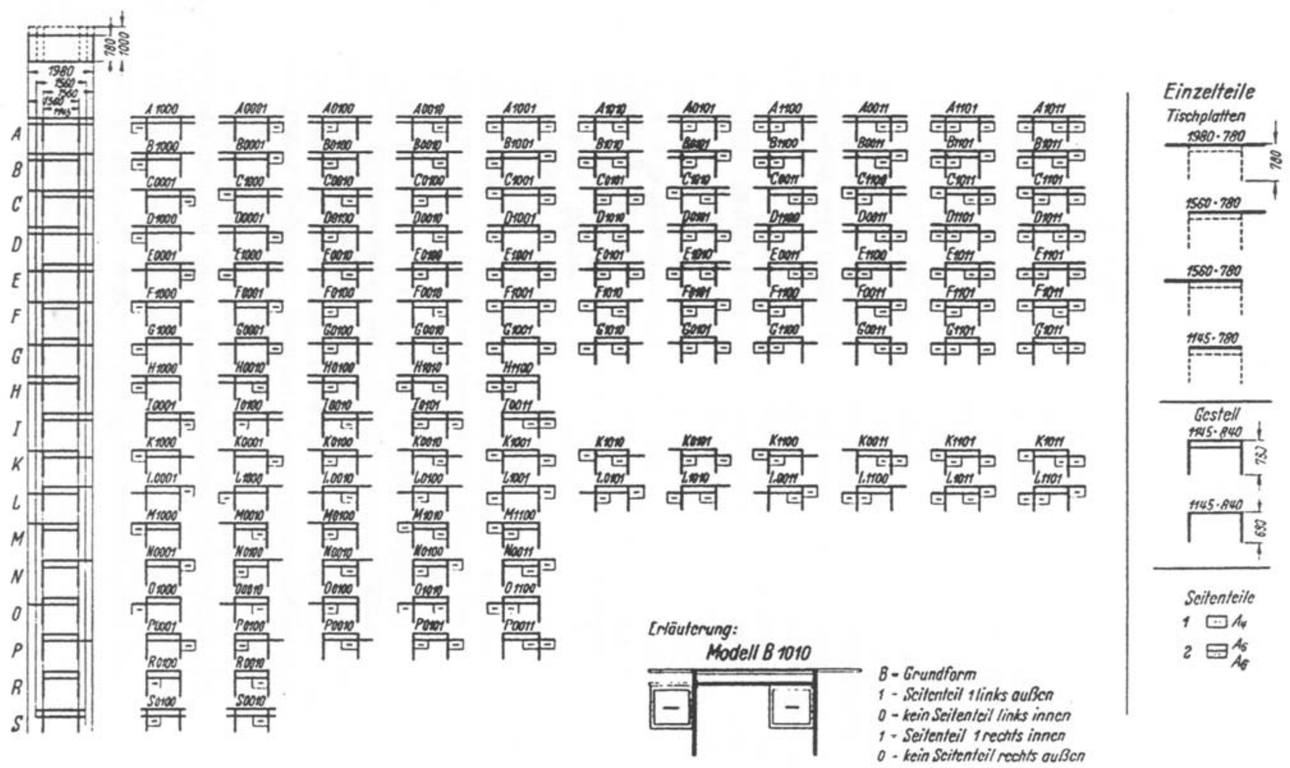


FIGURE 23. Detail from the structural plan of a closed system: Mauser-Werke drawing desk

All Borowski's examples would not qualify for modular systems. For example, the constructional element systems for the diesel engine line of the company Klöckner-Humboldt-Deutz AG hardly consider issues related to modifying the product. As shown in the figure below, most of the engine is defined as a non-constructional element to which the cylinder sets and lids are joined. Auxiliary devices, the various speed classes from the same engine, the fittings and the optional equipment belonging to various installation environments are not mentioned. Thus, we are talking partial standardization. This was not a novelty in the early 1960s: as will be explained in Section 10.2, such a structure was implemented at Scania-Vabis 20 years prior to this.

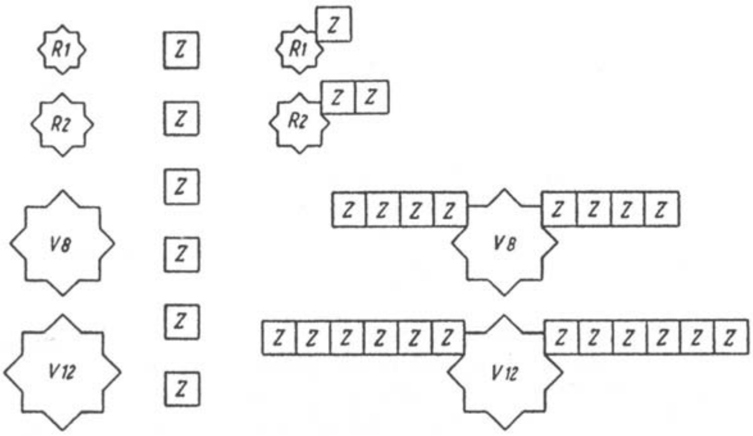


FIGURE 24. The constructional element system of the Deutz product family barely exceeds standardization. Irrelevancies are emphasized in the variations, and vast entities exist as one non-constructional element.

This leads us to drawing the boundary between standardization and potential modularity. A better example than Borowski's Deutz products would originate from the United States, a country that profoundly understands the methods of mass production. The following figure shows variations of the industrial versions of the two-cycle diesel engine of the General Motors 71 Series. The 71 Series was a long-lived engine series with a wide range of variations from four-cylinder engines to a twelve-cylinder two-cycle double engine. However, this is not a result of applying an advanced product structure technology, but of adapting to the requirements of mass production. The original design of the engine series has considered basic variation alternatives, such as the locations and the different running directions of the auxiliary devices as required by different applications, as shown in the figure below.

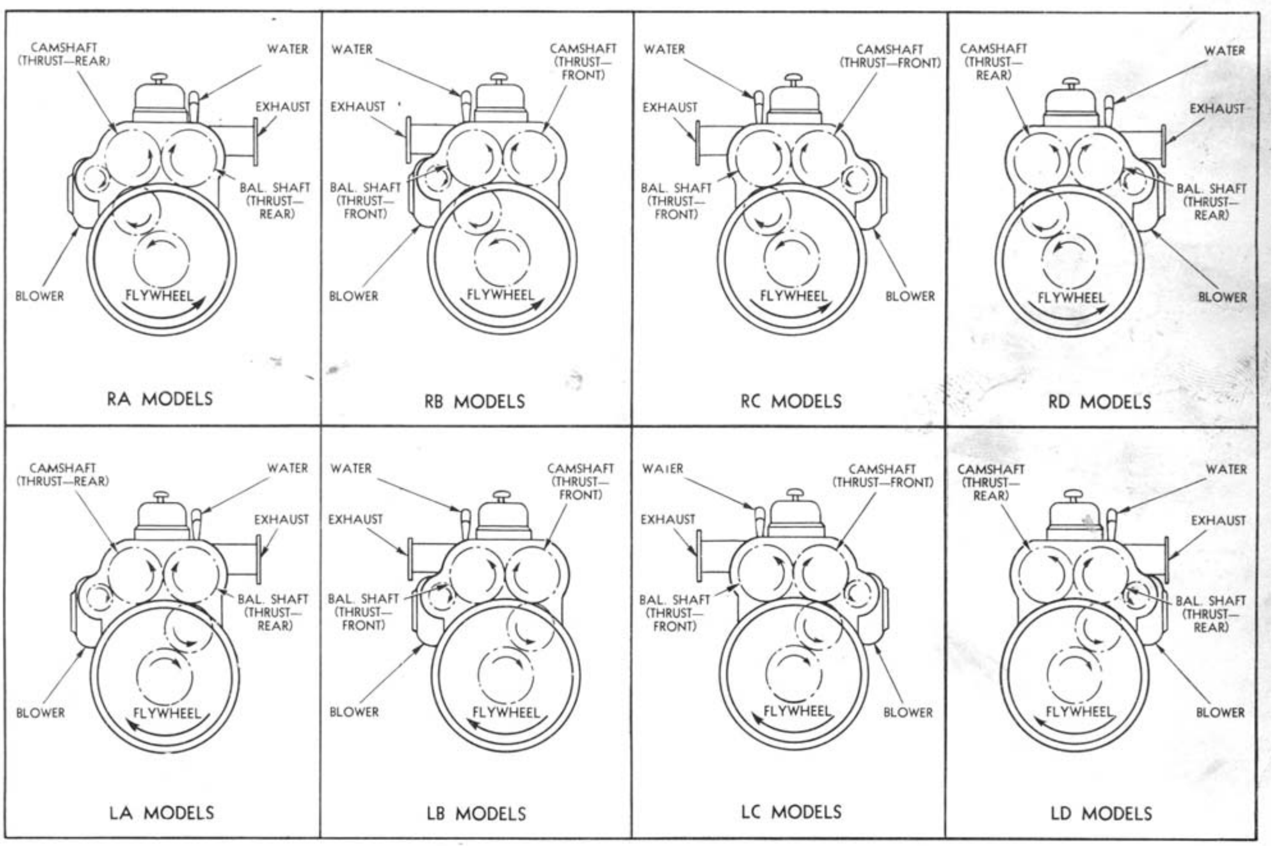


FIGURE 25. An example of standardization which may lead to a product range that resembles one using constructional elements. Shown above are the main variations of the two-cycle diesel engine of the General Motors 71 Series – note that the cylinder number is not a considerable source of variation! The engines are seen from the flywheel end. [General Motors 1953]

After this, each variation is designed to use existing parts as much as possible. However, elements have been redesigned as necessary, which makes it impossible to estimate the number of common elements in the sample engines in the next figure.

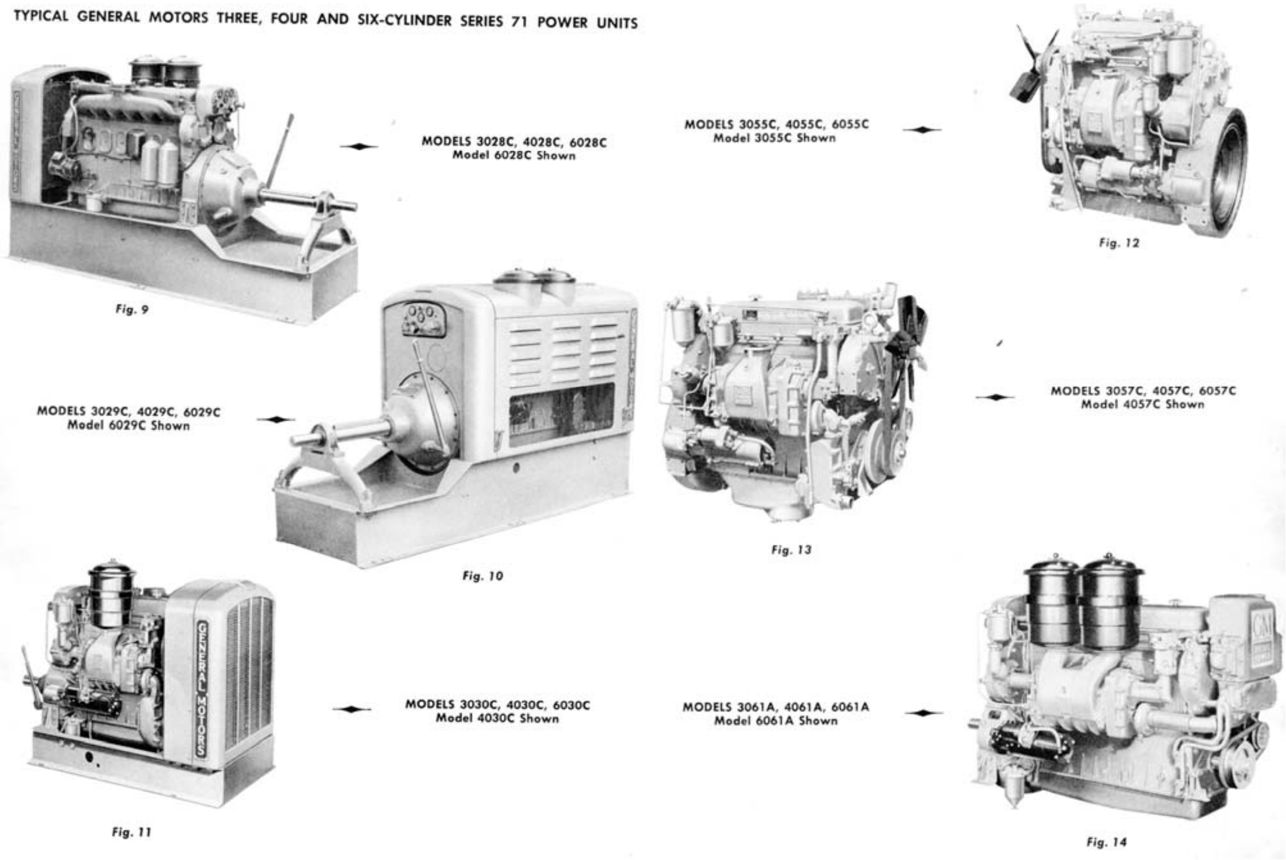


FIGURE 26. The engines in the 71 Series form a product series, but the similarities between the engines are not dictated by product architecture but by common-use components required by mass production. On the outlook, it is impossible to estimate the number of common components in the engines of the series. In addition, the number of common-use components varies according to the model. The 12-cylinder double engine mentioned in the text is not included in the illustration; it was used as the power source for locomotives and military tanks. [General Motors 1953]

As can be seen, most features of modular systems have been defined by Borowski. Borowski recognizes closed and open systems (begrenzte und unbegrenzte Zahl von Kombinationen). According to him, designing the two system types differs in that the design of a closed system begins with defining the usage cases (Anwendungsbereiches) meanwhile, the design of an open system begins with defining the necessary functions (der erforderlichen Funktionen). Otherwise, the design steps are similar. Admittedly, the starting points are so different that the content of the design tasks is changed. *According to Borowski, functionality serves as the starting point of the product structure division in an open system only!* This becomes even more apparent in the ideas of Brankamp and Herrmann who have continued the Baukastensystem thinking. [Brankamp & Herrmann 1969]. The following figure illustrates their design processes for closed and open systems.

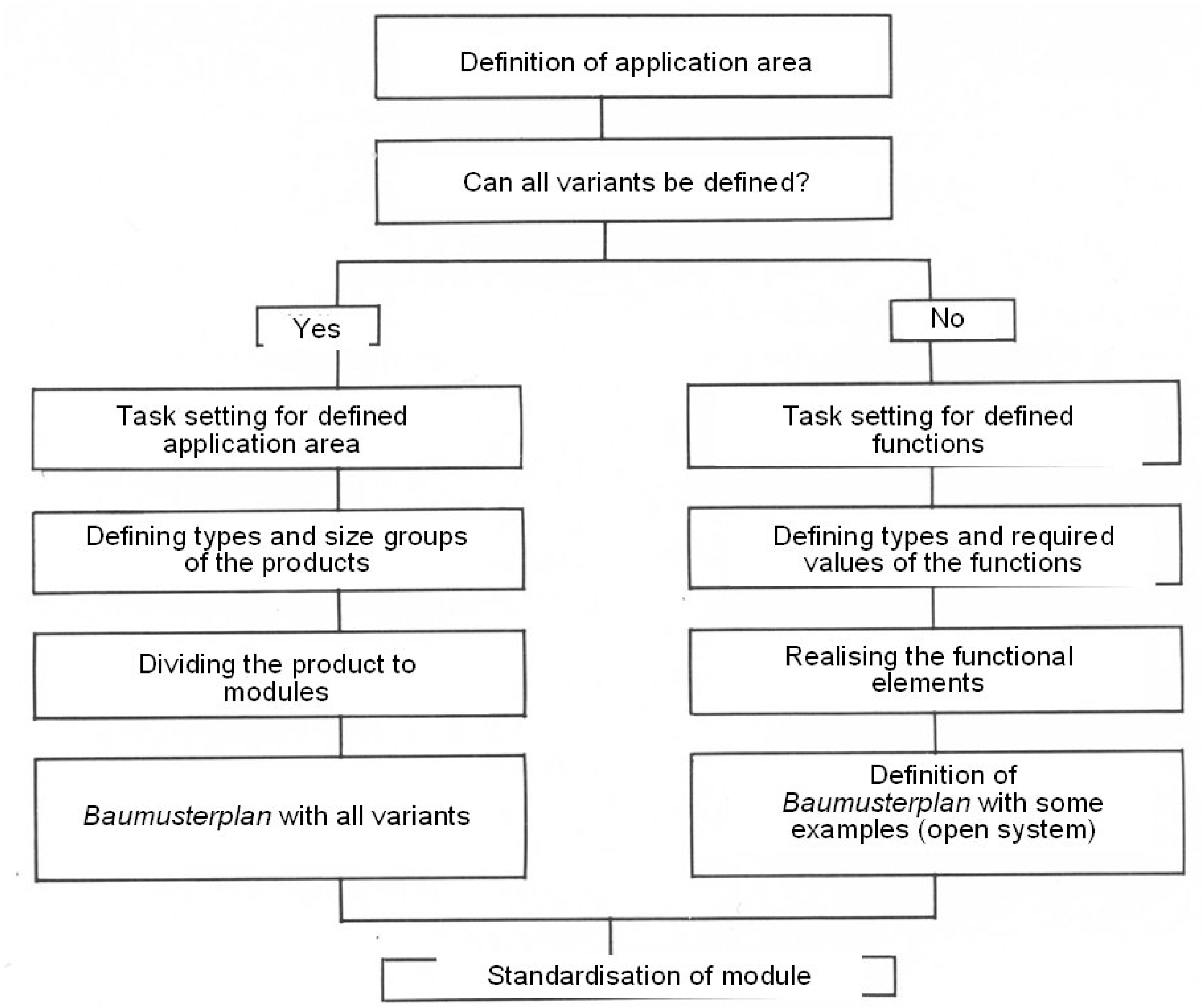


FIGURE 27. The phases of the design of a closed and an open system, as presented by Brankamp and Herrmann.

Brankamp and Herrmann also dismiss one of the Baukastensystem types. According to them, a system consisting of large non-constructional elements in which standardized constructional elements are only used as fitting pieces, does not meet the requirements for a system. *Thus, a fitting-piece system cannot alone be a basis for a modular system.*

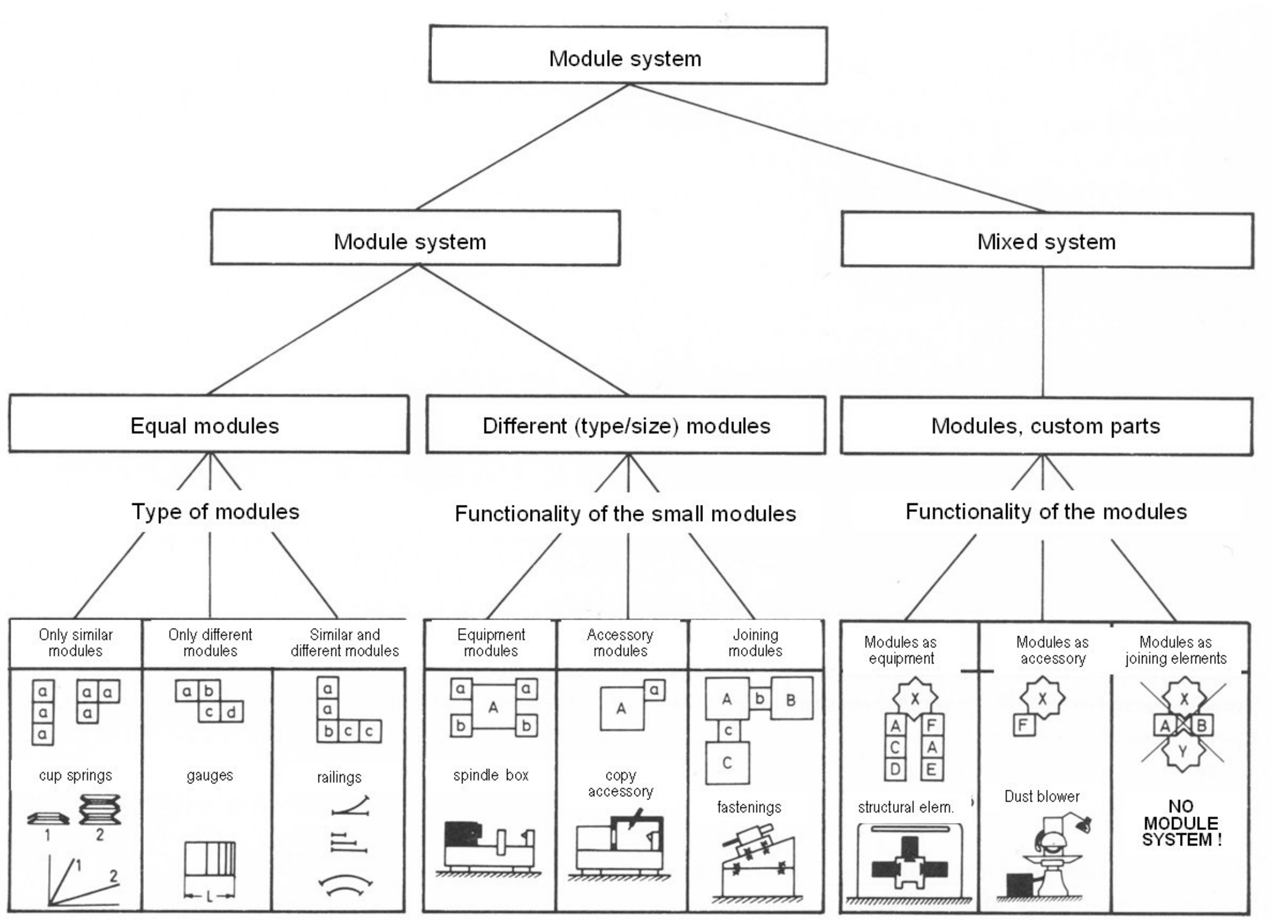


FIGURE 28. Brankamp and Herrmann do not accept modularity that is merely based on the use of fitting pieces.

5.3 Gerhard Pahl and Wolfgang Beitz

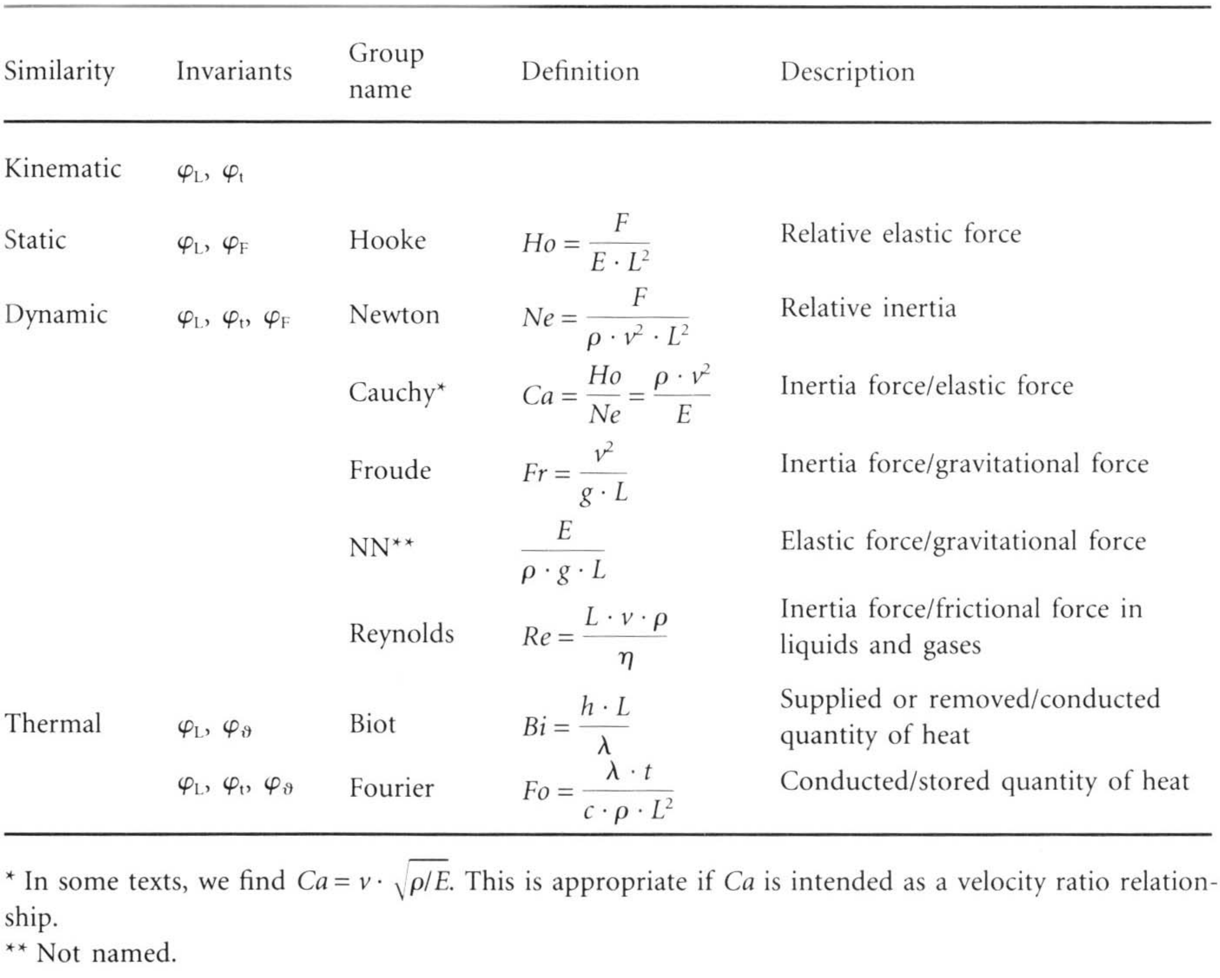
The book *Konstruktionslehre* by Pahl and Beitz is intended as a textbook and its examination of the issues as theories do not make justice for the authors. This cannot be avoided, as the status of the ideas presented in the book has established already in the previous research. The book also teaches modular design in one chapter [Pahl & Beitz 2. ed, pp. 433-453]. This is often referred to in research related to modularity.

Pahl and Beitz consider the modular system as a direct continuum to size ranges. ”*(When) other associated fuctions have to be implemented, then modular products will have to be developed side by side with size ranges*” (page 405) A product series is, according to the authors, a group of products with the following characteristics:

- fulfil the same function
- are based on the same solution principle
- are made in varying sizes
- involve similar production processes

According to Pahl and Beitz, creating product series (size ranges) is based on utilizing similarity laws. The term similarity is used to refer to a situation in which the relations of at least one physical quantity remain unchanged between the basic design and the derivative. P&B base their ideas on the assumption that there is an existing "basic design" of a product, on which the model series is constructed by utilizing the similarity laws. This is not, then, a question of actual new product design.

Similarity laws are clauses based on known laws of nature that indicate the proportion in which the quantities change in relation to each other. There is no specific term to refer to the most obvious similarity law; it is called dynamic similarity (congruence). It stipulates that "the relation of the force is constant while the temporal and geometrical congruence holds true". Temporal congruence must here be understood as the time between the process phases; in other words, we could also speak of spatial transfer. The following are presented as relevant similarity laws for the design of size ranges:



Similarity	Invariants	Group name	Definition	Description
Kinematic	φ_L, φ_t			
Static	φ_L, φ_F	Hooke	$Ho = \frac{F}{E \cdot L^2}$	Relative elastic force
Dynamic	φ_L, φ_t, φ_F	Newton	$Ne = \frac{F}{\rho \cdot v^2 \cdot L^2}$	Relative inertia
		Cauchy*	$Ca = \frac{Ho}{Ne} = \frac{\rho \cdot v^2}{E}$	Inertia force/elastic force
		Froude	$Fr = \frac{v^2}{g \cdot L}$	Inertia force/gravitational force
		NN**	$\frac{E}{\rho \cdot g \cdot L}$	Elastic force/gravitational force
		Reynolds	$Re = \frac{L \cdot v \cdot \rho}{\eta}$	Inertia force/frictional force in liquids and gases
Thermal	φ_L, φ_ϑ	Biot	$Bi = \frac{h \cdot L}{\lambda}$	Supplied or removed/conducted quantity of heat
	φ_L, φ_t, φ_ϑ	Fourier	$Fo = \frac{\lambda \cdot t}{c \cdot \rho \cdot L^2}$	Conducted/stored quantity of heat

* In some texts, we find $Ca = v \cdot \sqrt{\rho/E}$. This is appropriate if Ca is intended as a velocity ratio relationship.

** Not named.

FIGURE 29. Similarity laws suggested for the design of product series based on size ranges.

In addition to similarity laws, decimal geometrical standard number series must be used in the design of product series. Selecting the standard number series is based on a general agreement, and they are less absolute than the model laws that are based on laws of nature.[*] Pahl and Beitz recommend using basic series of numbers complying with the German industrial norm DIN 323. From the design theoretical viewpoint, this is an arbitrary standardization, which means that we will not go into detail in this dissertation as to whether a DIN 323 -compliant basic series is better than any alternative basic series.

Of similar size ranges, Pahl and Beitz discuss geometrically similar product series and semi-similar product series. In a geometrically similar product series, the various size ranges are geometrically same. In a semi-similar model series, then, the size ranges exist in the same proportions to each other, following the similarity laws used.

The size range view is a well-known practice in the engineering industry. Ideas related to this practice have been included in various methods of rationalizing production suggested over the decades. The best known approach is probably that of *group technology*. [see for example Arn 1975] A feature-based product modelling leads us to geometrically similar product series. [Isotalo & al 1995] However, similarity may also exist on the level of elements. In the size range / product series approach, the term *parametrical design* is nowadays most often used.

5.4 Product series, similarity laws, feature-basedness, and modularity

The *(design) feature-based a*pproach to design is currently more often used than geometrically similar product series in CAD design. The feature-based approach aims to discover shared design elements, *(design) features*, for the product range that can then be reused in design. Even though an expert of modularity would first think of reusing the design work, this might only come third in priority in the goals of feature-basedness. The most desired issues are related to the price of the components to be manufactured and to the rationalization of production. The first goal is aimed at by manufacturing products by using such features that are cheap to manufacture with the available production tools. The production is rationalized by using a maximum number of similar features, whereby the numbers of necessary fasteners and tools is reduced, the assembly times are shortened, and the work phases of different parts can be merged into longer manufacturing series. The latter already sounds like the *group technology* approach, which is what is essentially represents, although this old trend is not often mentioned these days.

Compared to modularity, feature-basedness highlights in part similar and in part different solutions. The difference derives from the essence of a *feature*. A feature is an element in a 3D image drawn on the computer screen, and its specific essence is related to the way in which three-dimensional modelling is performed. Three-dimensional items are created in modelling by, for example, cutting an object of a standard geometrical shape in a certain angle with another object with a known standard geometrical shape. In this way, all the features are not material elements created in the object, but they may also represent material or materials to be removed from the work object or material that does not even exist. In other words, a feature may also represent a hole, gap, or empty space. Neither is a single feature bound to a certain manufacturing method or phase. Instead, for example, in milling a number of features can be created on the same level simultaneously.

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[*] This is the case from the viewpoint of design. In actual manufacturing, the size ranges of the available bolts still remain a *de facto* limiting factor.

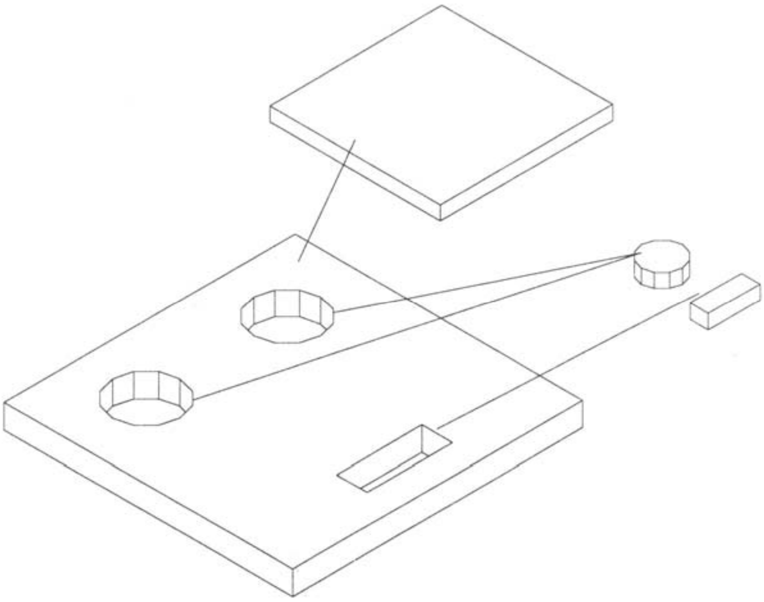


FIGURE 30. Implementation methods of design features in three-dimensional CAD design: a geometrical shape is cut with another. [Isotalo & al 1995 p. 29]

Feature-basedness does not require congruence on the element level. In theory, the features can be regarded as forming a module system whose combinations are used to create the elements. In this case, the product involves modularity in the design phase, even though it is not visible in the end-product unless analyzed.

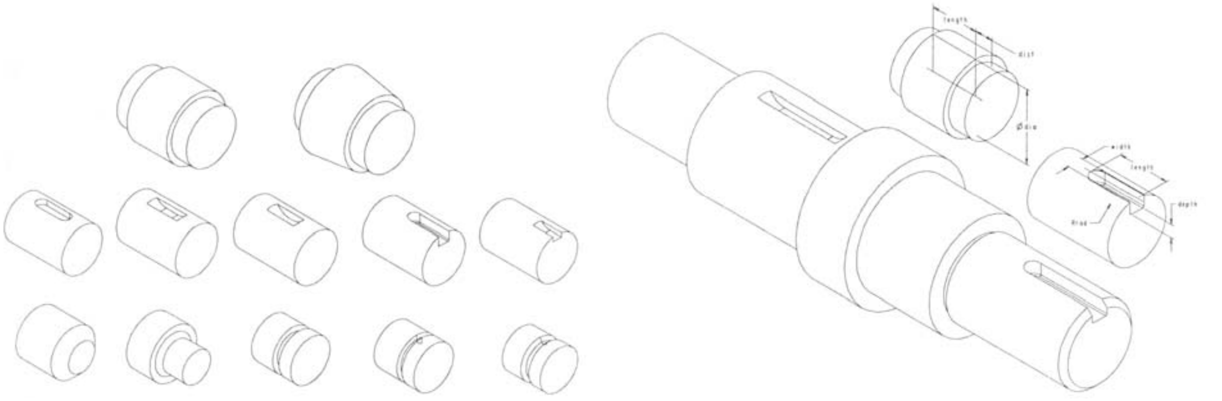


FIGURE 31. In feature-based design, modularity can be detected on the design level, but it is difficult or impossible to detect in the end-product. The figure on the left-hand side shows design features which are used in the design of the axles on the right. [Isotalo & al 1995 p. 51]

In their research, Thomas Miller and Per Elgård suggest some principles of structuring that may lead to a product-family-type result [Miller & Elgård 1999]. These include narrowing and widening. In the narrowing principle, the largest common denominators are sought for the product series and standard elements are formed thereof. The widening principle, in turn, seeks to include the features required by all the variations in the element (even if some of them were not used in the delivered product). Both are product family design principles, and they may lead to standardization or modularity depending on what is meant by elements in each case. They may also lead to a reuse strategy of design work, in which case the thing itself is not visible in the part structure of the end-product. The principles of structuring are shown in the figure below.

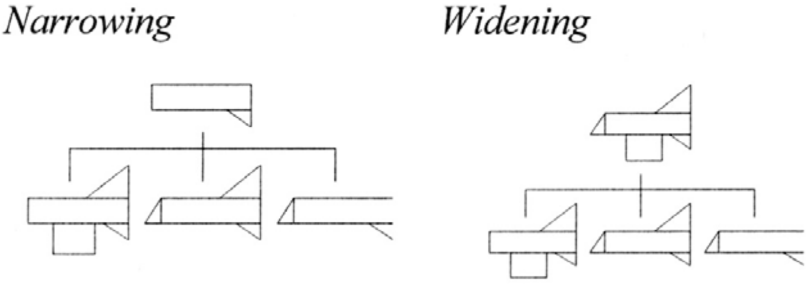


FIGURE 32. The two principles of structuring, to be used in product-family design, presented by Miller and Elgård [Miller & Elgård 1999]

Size ranges, similarity laws, and feature-basedness as a basis for modularity

By using similarity laws, good results have been achieved in design-intensive products in terms of the amount of work and product quality. In these, certain solutions are standardized, and we might start to regard them as bases for a modular system.

This is, however, most often not the case. On the contrary, using geometrically similar product series may prevent the formation of a modular system. As all the measures of the elements change (geometrical similarity), also the measures of the joint surface change and no replaceability exists between the size ranges. As a higher power rating component (exceeding the requirements) cannot be used to replace an item in a lower power rating environment, a module system including replaceability cannot be created. In applying modularity, it is a question of dividing the product into parts and using the division, for example, in manufacturing the product via combinatory means. Using model laws, for example, the design of size or power ranges remains neutral in the issue of dividing the product into parts. *Similarity laws are thus primarily related to the standardization of design solutions and they are a relevant solution in a product environment in which the design costs form a considerable part of the delivery costs of a product item.*

Feature-basedness leads to standardization; however, standardization may focus on irrelevant issues from the viewpoint of modularity. Applying modularity on the design level is a similarly profitable solution if the share of design costs in the delivery is considerable. Such a situation may arise, for example, at an engineering workshop that delivers complex, components made to customer orders and designs the components itself.

5.5 Pahl, Beitz, and module system

In their text on modular products, Pahl and Beitz refer directly to Borowski and Brankamp & Herrmann. Pahl and Beitz discuss the matter from a distinctly industrial point of view. In their book, they discuss modularity as much as the design of similar and semi-similar product series and, as stated previously, the regard modularity as a continuum to these. Similarly to the previous sources, they state that if the range of main functionalities is wide, the classification into functional modules must be used as the selected approach. If, on the other hand, few variations of the main functionalities exist, the classification into production modules (assembly-based) is to be prioritized. They thus state that modules may either be functional modules or production modules, depending on whether the division is based on a functional structure or an assembly structure. Surprisingly enough, this division is not used in the sample cases of the book, and a bearing, an item with a standard main function, is used as an example of functional modularity. In other regards as well, the emphasis of design based on the functional structure is absolute: *“The establishment of function structures is of particular importance in the development of modular systems. With the function structure – that is splitting up of the required overall function into subfunctions – the structure of the system is already laid down, at least in principle”* No justification is presented for this statement in the book, but, as mentioned in Chapter 3.2, this view is even written in the VDI standard. The division into closed and open systems in design is not acknowledged. The two module types presented are functional modules, divided into basic modules, auxiliary modules, special modules, adaptive modules, and non-modules; and manufacturing modules, divided into obligatory modules and accessory modules. The classification into functional modules is primarily based on the status of the module in the product in which modularity is to be applied, rather than on the features of the modules. The book does not tell how this classification is supposed to be used in the actual design.

The most detailed example in the book is that of a slide bearing. On the transformational level, the main function of a slide bearing remains the same, regardless of version. Variation appears in the methods of technical implementation. Despite this, modularity is applied from the bases of functional modularity, and a functional structure is created for the bearing, as shown in the figure below.

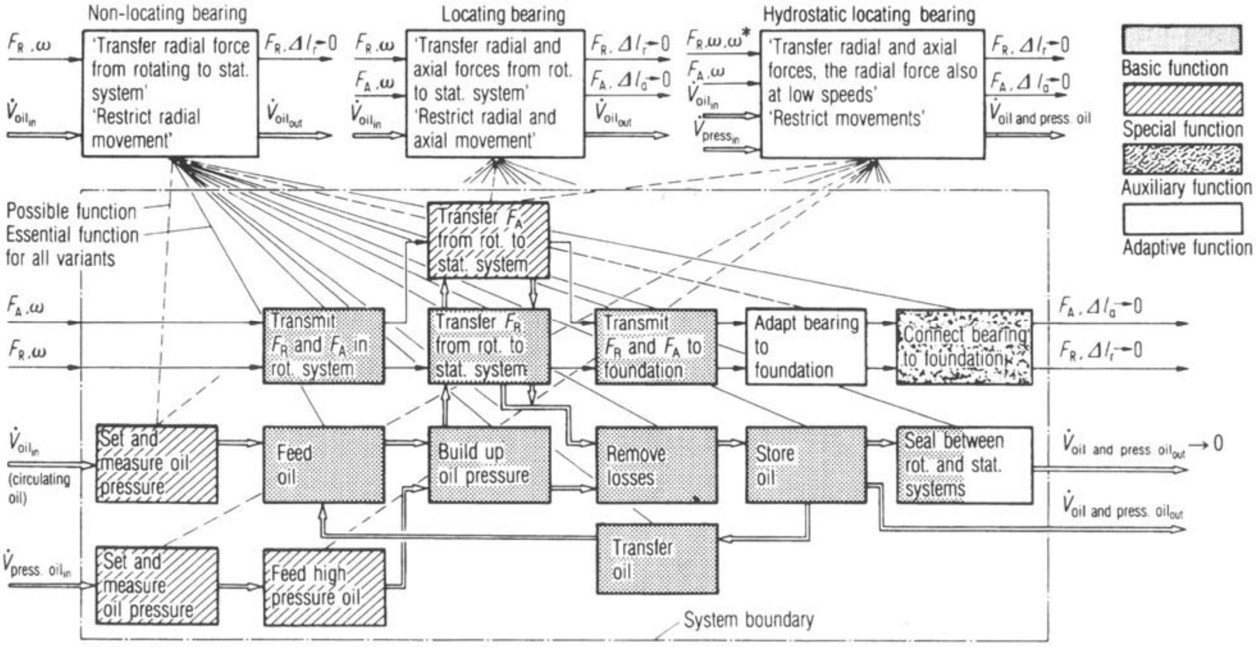


FIGURE 33. The functional structure of a bearing, according to Pahl and Beitz

Further, the example describes the design of a bearing following the process of systematical design, holding the opportunities of using expensive main parts in a maximal number of variations as one criterion. This does not, however, differ in any way from normal product-line design that Borowski regards as a natural part of any rational design (Borowski p. 15). The slide bearing example in Pahl & Beitz does not define on which solution level (Auflösunggrad) the modular structure is form. This leads to the fact that individual components are accepted as modules, as shown in the “assembly structure of a bearing” figure below.

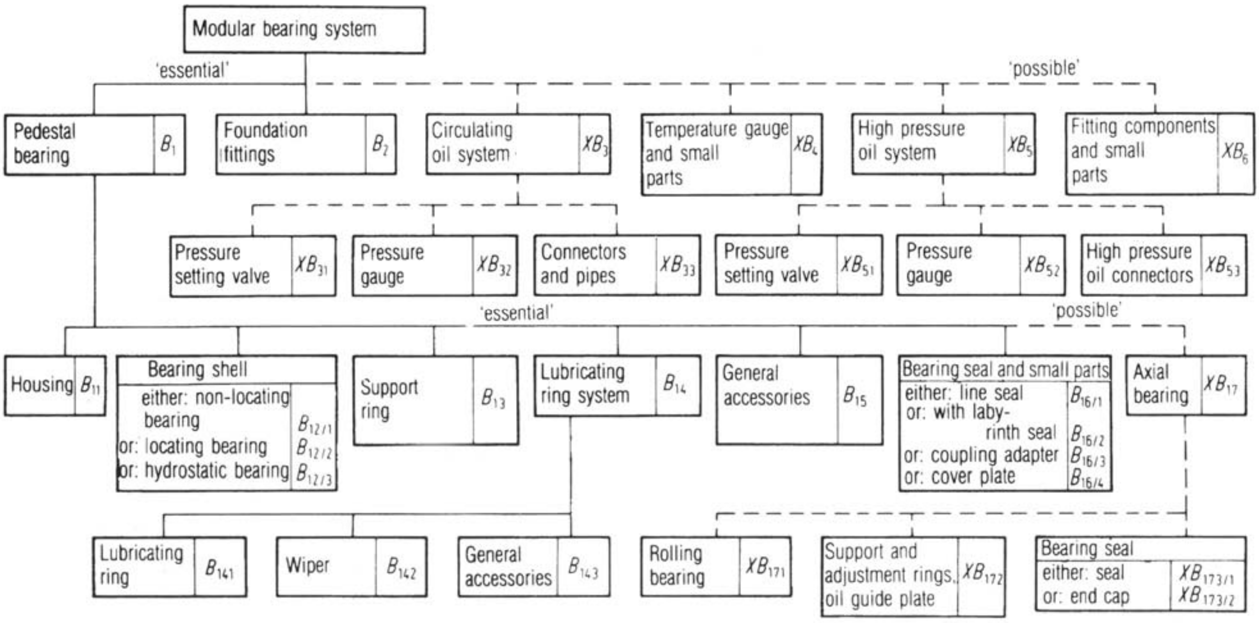
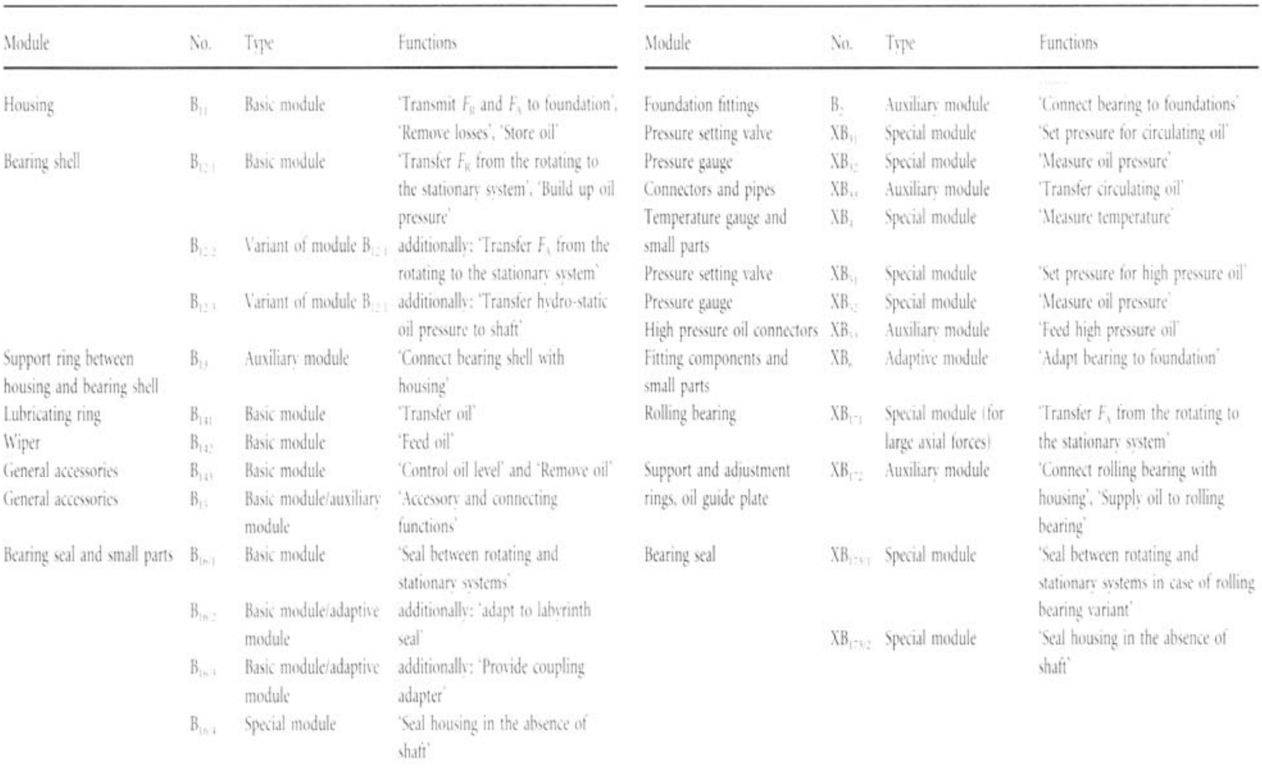


FIGURE 34. The assembly structure of a bearing, according to Pahl and Beitz

The figure below seeks to prove that the components of a bearing are functional modules. It cannot be denied that each part of the bearing has a specific function that can be written in the form of a function. The question remains, however, whether such functions are *parts of the main function of a modular system* or even *parts of the auxiliary functions of a modular system?* For example, "adapt to labyrinth seal" is a design requirement for assembly – it is not related to the functioning of the slide bearing. This perhaps most clearly proves that the idea introduced by Pahl and Beitz is not based on the Theory of Technical Systems which is based on transformations.



Module	No.	Type	Functions
Housing	B_{11}	Basic module	'Transmit F_R and F_A to foundation', 'Remove losses', 'Store oil'
Bearing shell	$B_{12/1}$	Basic module	'Transfer F_R from the rotating to the stationary system', 'Build up oil pressure'
	$B_{12/2}$	Variant of module $B_{12/1}$	additionally: 'Transfer F_A from the rotating to the stationary system'
	$B_{12/3}$	Variant of module $B_{12/1}$	additionally: 'Transfer hydro-static oil pressure to shaft'
Support ring between housing and bearing shell	B_{13}	Auxiliary module	'Connect bearing shell with housing'
Lubricating ring	B_{141}	Basic module	'Transfer oil'
Wiper	B_{142}	Basic module	'Feed oil'
General accessories	B_{143}	Basic module	'Control oil level' and 'Remove oil'
General accessories	B_{15}	Basic module/auxiliary module	'Accessory and connecting functions'
Bearing seal and small parts	$B_{16/1}$	Basic module	'Seal between rotating and stationary systems'
	$B_{16/2}$	Basic module/adaptive module	additionally: 'adapt to labyrinth seal'
	$B_{16/3}$	Basic module/adaptive module	additionally: 'Provide coupling adapter'
	$B_{16/4}$	Special module	'Seal housing in the absence of shaft'
Foundation fittings	B_2	Auxiliary module	'Connect bearing to foundations'
Pressure setting valve	XB_{31}	Special module	'Set pressure for circulating oil'
Pressure gauge	XB_{32}	Special module	'Measure oil pressure'
Connectors and pipes	XB_{33}	Auxiliary module	'Transfer circulating oil'
Temperature gauge and small parts	XB_4	Special module	'Measure temperature'
Pressure setting valve	XB_{51}	Special module	'Set pressure for high pressure oil'
Pressure gauge	XB_{52}	Special module	'Measure oil pressure'
High pressure oil connectors	XB_{53}	Auxiliary module	'Feed high pressure oil'
Fitting components and small parts	XB_6	Adaptive module	'Adapt bearing to foundation'
Rolling bearing	XB_{171}	Special module (for large axial forces)	'Transfer F_A from the rotating to the stationary system'
Support and adjustment rings, oil guide plate	XB_{172}	Auxiliary module	'Connect rolling bearing with housing', 'Supply oil to rolling bearing'
Bearing seal	$XB_{173/1}$	Special module	'Seal between rotating and stationary systems in case of rolling bearing variant'
	$XB_{173/2}$	Special module	'Seal housing in the absence of shaft'

FIGURE 35. The functional "modules" of a bearing, according to Pahl and Beitz

In the figure below, we have selected “a draft for the modular system of a slide bearing” from the example. It is not clear what makes the bearing in the picture “modular". Does the bearing meet the requirements of the Baukasten system? The answer is probably no.

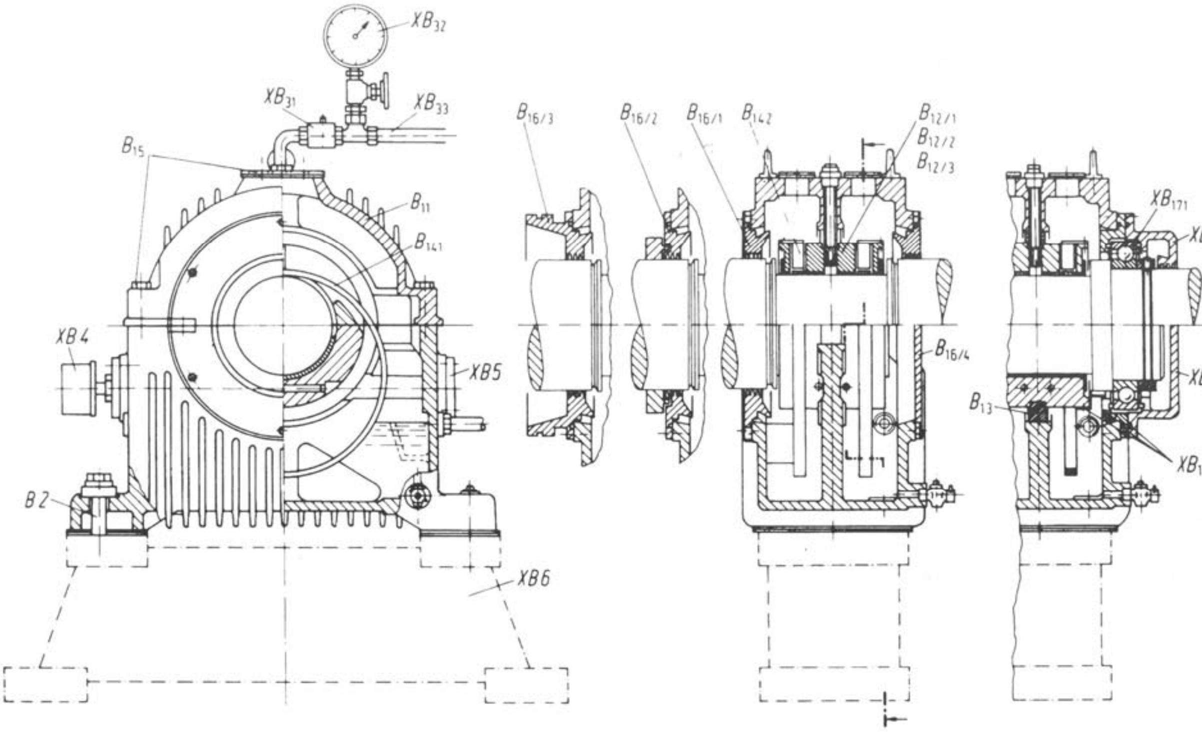


FIGURE 36. “A draft for the modular system of a slide bearing”, according to Pahl and Beitz

Even though the textbook status of Pahl and Beitz in systematical design is unquestionable, it does not discuss the problems of modularity in detail. The ideas presented in the book do not add value to the previous sources. We could even say that the examples do not follow Borowski's principles, which considerably lessens their value.

5.6 Karl Ulrich & al

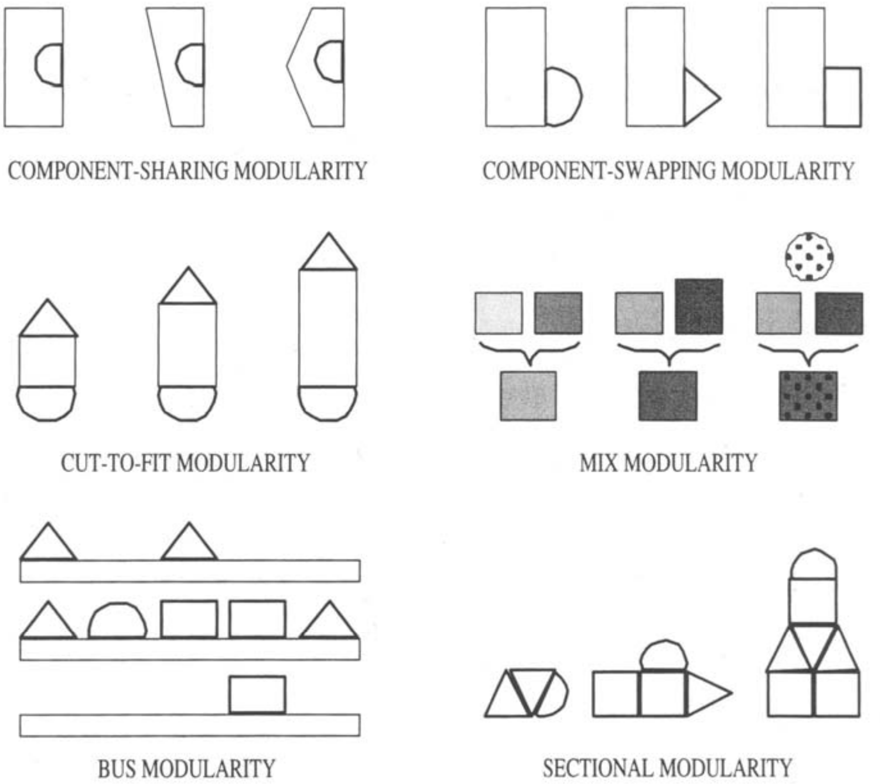
In their work, Karl Ulrich and Karen Tung aim to define *modularity* as a system feature. For example, in their article “*Fundamentals of Product Modularity*”, published in 1991, they remain neutral in the issue of what modules are like, but instead define that modularity is a relative product property [Ulrich91]. Ulrich defines the goal of his research as using modularity in the creation of product variations while increasing standardization. Ulrich thus speaks of systematical product configuration, even though this word is not mentioned in the text as such. This limitation excludes some areas of industrial modularity (see Chapter 4 and for configuration Chapter 6).

Ulrich defines that “*Modularity arises from the way a product is physically divided into independent components.*”

Ulrich defines independence as the property of a design allows standardization and interchangeability.

According to Ulrich, there exist five types of interchangeability within a system. Actually, Ulrich was not the first to present these types: they were already included in the book ”Pattern of Industrial Automation” by William Abernathy and James Utterback, published in 1978. The types of interchangeability are shown in the figure below. The types are:

1. Component-sharing modularity
2. Component-swapping modularity
3. Parametrical configuration of elements (not a sufficient criteria as such)
4. A bus or frame-type structure with standard interfaces
5. Free assembly enabled by standard interfaces



Source: From "Patterns of Industrial Automation," by William J. Abernathy and James M. Utterback. Reprinted with permission from Technology Review, copyright 1978.

FIGURE 37. The types of modularity, according to Joseph Pine. The figure also includes mix modularity (second row on the right).

In addition to these, for example Joseph Pine [Pine93] suggests mix(ed) modularity, in which the modular product consists of mixable ingredients. This is an interesting idea which can, however, be dismissed as a form of modularity, as it is impossible or impractical to define the solution level for ingredients in a non-fixed space (the atom level is a possible level of examination).

In addition to these five main types of modularity, special cases of two types can be presented. These are on-off modularity and stack modularity, shown schematically in the figure below. On-off Modularity is a special case of component interchangeability, in which the module is either selected or its reserved space is left empty. Stack modularity is a subtype of parametrical modularity, in which parametrical configuration for example in length is implemented by multiplying the number of modules. An example of this could be the adjustment of distance by using distance plates.

FIGURE 38. The suggested additional types of modularity. Thomas Miller and Per Elgård introduce stack modularity in their research [Elgård & Miller 1998 and Miller & Elgård 1999]. The idea of on-off modularity emerged at a meeting of PhD students at the Danish University of Technology (DTU) in 1998.

Ulrich defines that modularity depends on two product properties: the similarity of the physical and the functional structure, and the number of unnecessary (unrelated to the functions) relations between the physical elements. (In his article, Ulrich uses the term component to refer to a potential module, but here we call these elements).

According to Ulrich, modularity is a relative property of the product which increases if the functional structure and the physical structure become similar and no dependencies exist between the various elements unrelated to the (main) function. Ulrich thus goes even further in emphasizing functionality than Pahl and Beitz. Ulrich does not present justifications for emphasizing functionality.

The most problematic aspect related to this approach is the easiest to illustrate using Ulrich's own example. The example, shown in the figure below, features three structural solutions for joining an engine and an alternating-current generator. According to Ulrich, the independence of the engine and the generator, and thus modularity, increases in the pictures from top to bottom. However, this is disputable. Let us examine the two bottom versions in which the generator is first directly attached to the engine head and power is transmitted with a shaft locking (the second-to-last picture), and then to the engine side and power is transmitted with a V belt (the last picture). From the design viewpoint, we cannot say that the number of dependencies had been reduced in the case at the bottom! There is a mechanical joint between the elements. The requirement of perpendicularity between the axles still remains. In actual fact, the V belt has brought about new dependency requirements for the elements (the scale of tightening; the new requirements for the bearing in the neck of the engine and the generator in terms of lateral support; the shaft locking must be of the same width and the same profile while the V belt must be measured according to the changing power range, as power measuring is more critical and more cost-accounting in the V belt than in a mechanical joint etc.). A machine designer might even choose the solution in the middle as the basis for a modular structure. In the top picture, too, the generator may be a separate module on a standardized interface, even though it is physically located inside a shell. We note that modularity is not only related to the functional structure.

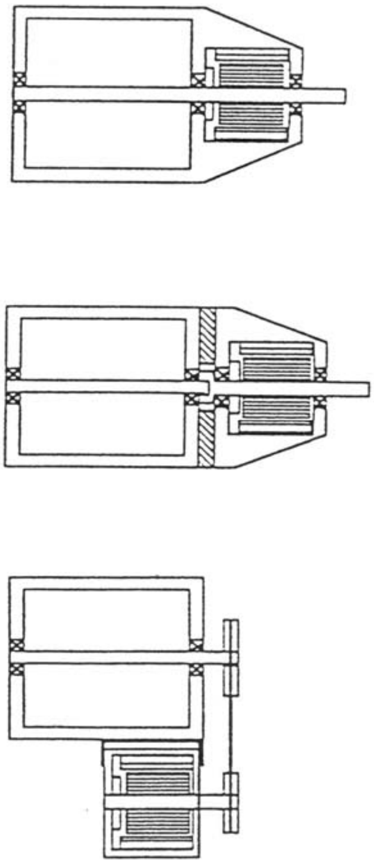


FIGURE 39. Ulrich presents the above engine generators as an example of increasing modularity (from top to bottom), but justifications exist for a differing opinion.

Despite the shortcomings, the ideas presented in Ulrich's work form in part a basis for the conception of modularity also used in this dissertation. Borowski does not define the combinatories in a system, so the typification based on interchangeability formalizes the idea to a great extent. Instead, defining modularity on the basis of functionality is – as will be seen later on – disputable.

5.7. TOOLS FOR THE SYNTHESIS OF MODULARITY

In research, a number of tools have been suggested for the synthesis of a modular structure. These tools are often developed in practical work, and the main principles or theories used in their development have not often been expressed in public. However, each tool is based on some principal idea of the essence of modularity. These views are examined here as theorems – even though they were not introduced as such in every case.

5.7.1 Dependency matrices

We have concluded that the independence of the elements that form system is a key factor in modularity. Well-known tools have been developed for the evaluation of the independence. The roots of the best-known method lie in project management. In 1981, Donald V. Steward criticized the defective ability of the critical path method and PERT (Program Evaluation and Review Technique) to show the order in which the design tasks ought to be performed to avoid unnecessary iterations. He introduced a theory which he called the Design Structure System [Steward 1981]. This analysis tool is based on a square matrix in which the subtasks of design are entered on the horizontal rows in their order of execution. The same tasks are entered on the vertical columns in the same order. After this, the dependencies are marked in the matrix by proceeding from the first row and the first task. Each task in the columns is examined, and it is discovered whether “*the task on the horizontal row requires the result of the task in the vertical column as its initial value.*” If the answer is yes, there is a dependency between the tasks. On the diagonal line, the task is compared to itself, and no significant markings are entered there.

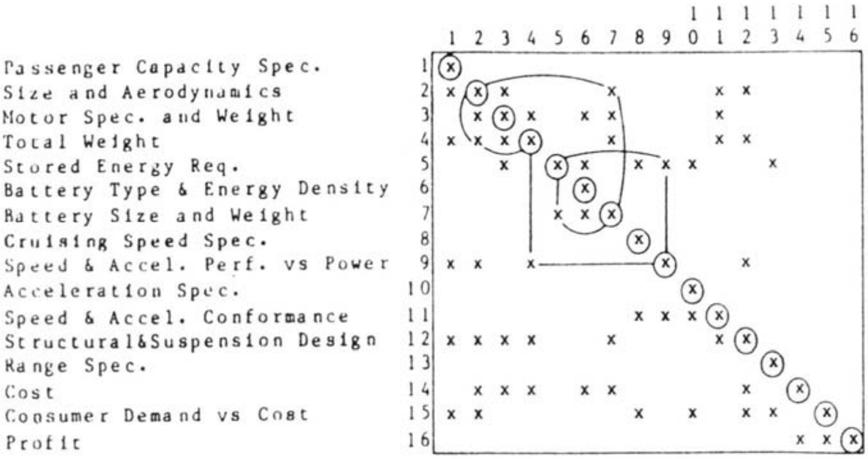


FIGURE 40. Steward's sample matrix. For illustrative purposes, the matrix also shows the iteration loop (which is not part of the presentation). [Steward 1981]

A matrix filled as illustrated above is a *directional* matrix: each relation marked in it is an arrow that shows the direction of the design data flow. All relations in the triangle below the diagonal line point forward in the order of the execution of the tasks and it is thus possible to execute them one after another following the cascade model. The relations above the diagonal line refer to iterations back to the previously executed task, and they are problematic dependencies for the management of the project. Steward's method seeks to eliminate these dependencies by reorganizing the tasks so that iterations are minimized and the ones that might remain are as short as possible. This is a task of mechanical optimization in which we aim to form a bottom triangle matrix, and to bring the relations as close to the diagonal line as possible. The task of reorganization can be carried out as an imperative procedure which can be written in the form of a genetic algorithm (as for example in [Rogers 1997]). A more detailed method is created by Marimont [Marimont 1959] and Sargent & Westerberg [Sargent & Westerberg 1964]. Steward proves the competency of the method in his two articles, [Steward 1965] and [Steward 1981B], but we will pass these proofs as they are not relevant for the scope of the present study.

When the matrix arrangement nears the optimum, the relations causing iterations form limited task groups that Steward calls “blocks”, but whose later much-used name is *cluster*. The tasks in a cluster are the smallest possible number of tasks that must be simultaneously examined when design cannot be performed iteratively on the basis of estimations. Thus, the project tasks are divided into independent clusters. This is called *partitioning*.

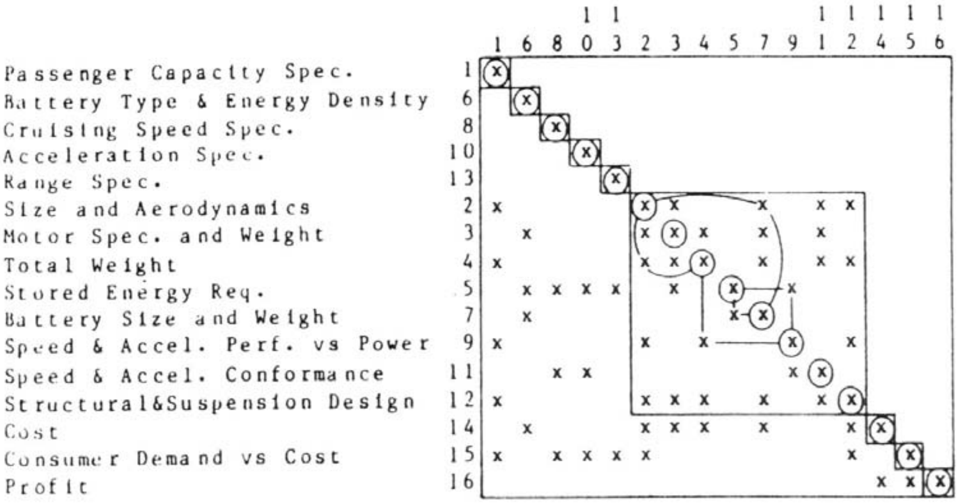


FIGURE 41. Steward's sample matrix shown organized, the procedure of which is called partitioning. Each squared area is an independent design entity, and they can be executed one after another without iterations, following the cascade model. In this sample figure, there is only one big subtask. [Steward 1981]

Steward further introduces a method for tearing apart the blocks/clusters. For tearing, we need to examine the internal dependencies in the cluster. For this, Steward suggests drawing a diagram that is usually called a *shunt diagram*, which shows how the iteration proceeds within the cluster of tasks. In the figure above, the iteration was drawn in the figure. The resulting *shunt diagram* is shown in the figure below. We must note that Task 4 also exists in another, simpler iteration with Task 12. This is illustrated in the figure on the right. According to Steward, these diagrams show that, for example, replacing the dependency between Task 2 and Task 7 by using an estimate would not shorten the iteration and remove hardly any of the dependency. Instead, is would be beneficial to tear apart the dependency between Task 5 and Task 9 if technically possible so that the risks can be managed.

FIGURE 42. Steward's shunt diagrams on iteration [Steward 1981]

A better-known example of dependency matrices is the research on the composition of engine design teams, conducted by McCord and Eppinger for General Motors [McCord & Eppinger 1993]. This case is so well known that it is only shown here as figures. The data on the dependencies between the various element entities in the engine was collected via interviews. The importance of the dependency was divided into three strength classes. An engine is an integrated product in the sense that it contains a number of strong dependencies, which means that partitioning was not entirely successful. As it was a question of the composition of design teams, two clusters could share some elements. Thus, teams were formed and the participants reported that the design task was carried out successfully and in a company-specific record time.

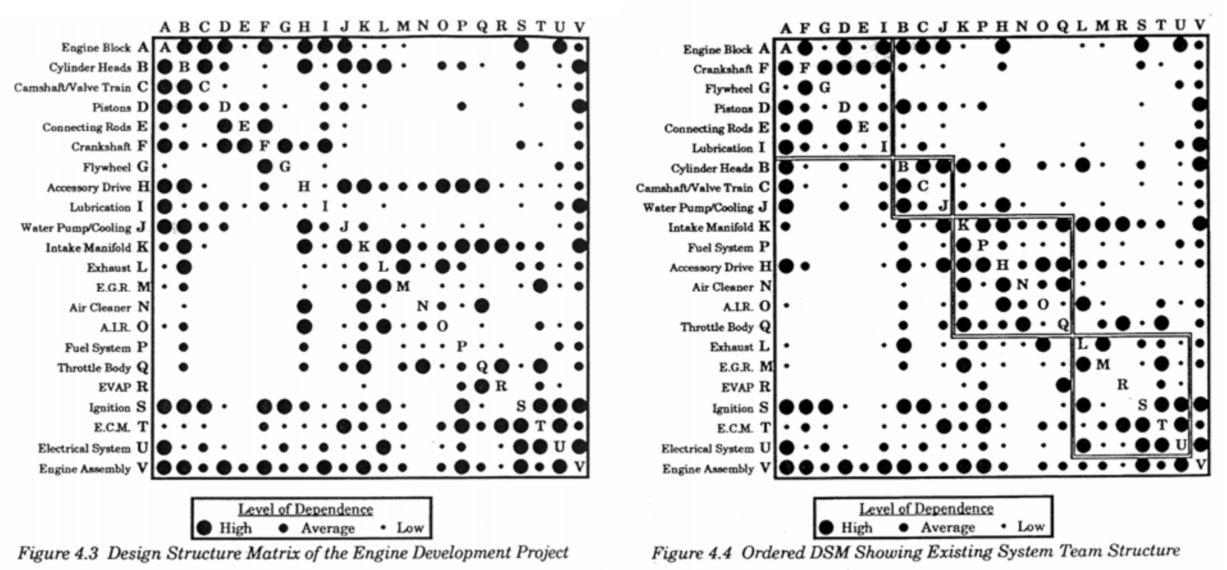


Figure 4.3 Design Structure Matrix of the Engine Development Project

Figure 4.4 Ordered DSM Showing Existing System Team Structure

FIGURE 43. The GM engine case: the original dependency matrix and the first organized matrix

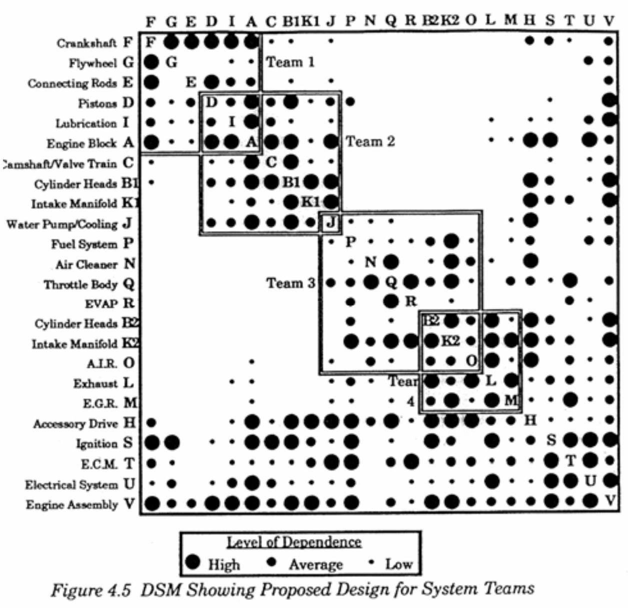


Figure 4.5 DSM Showing Proposed Design for System Teams

FIGURE 44. The final divided matrix and a matrix in which partial cluster overlap is accepted

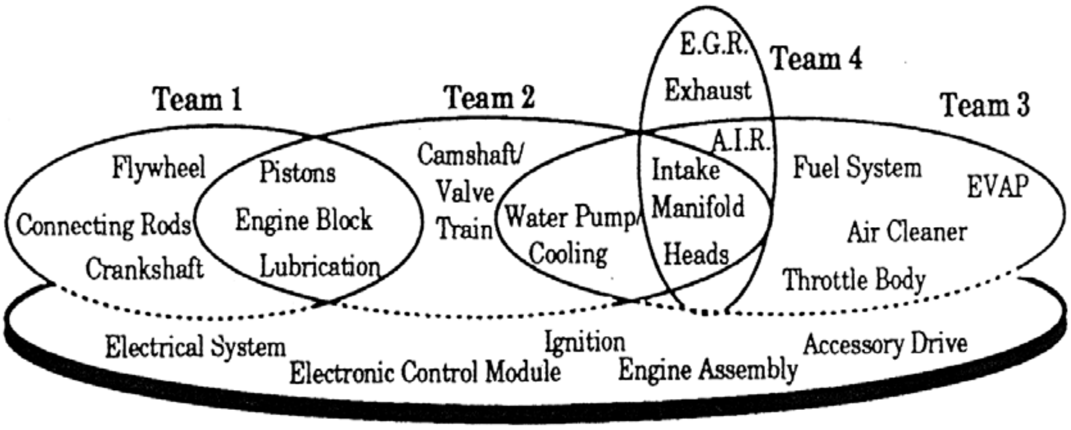


Figure 4.6 Proposed Design for System Teams

FIGURE 45. The proposed division for system teams which is said to have contributed to the success of the development project

McCord and Eppinger call their matrix a *design structure matrix*. As this example is better known than the original, the matrix is usually referred to by this name.

So far, we have only touched upon the internal structure of products. The next innovation was to discover that the clusters *could also represent a module*. This is a natural conclusion, the cluster-internal dependency is great and independent of the environment. At this point, however, the method essentially changes: *it is no longer reasonable to present the matrix as directional*. The product structure of modular products is usually considered static, which means it is not important which of the elements needs the other. While the matrix becomes symmetrical in proportion to the diagonal line, we attain new mathematical methods for the optimization. The most used of these methods is the so-called bandwidth algorithm which optimizes the points indicating the relations as close to the diagonal line as possible (into what resembles a band). An example of using this method could be Erkki Ahola's dissertation in which bus components of a similar life cycle were combined as replaceable units [Ahola 2000]. Another example of this will be found from among the industrial sample cases in Chapter 10.1.

A symmetrical dependency matrix is not by far the only approach when using matrices in product design and modelling. Johan Malmqvist has presented a summary of the presentation and analysis methods of the matrices [Malmqvist 2002]. The figure below illustrates the presentation types of the matrix methods: what is being compared and to what. The matrices presented above were of the intra-domain type, that is, they have examined the relations of the internal elements in the product. Such a matrix is a square matrix by nature. The relations may be non-directional, in which case the matrix is symmetrical, or directional, in which case causality is related to the dependency.

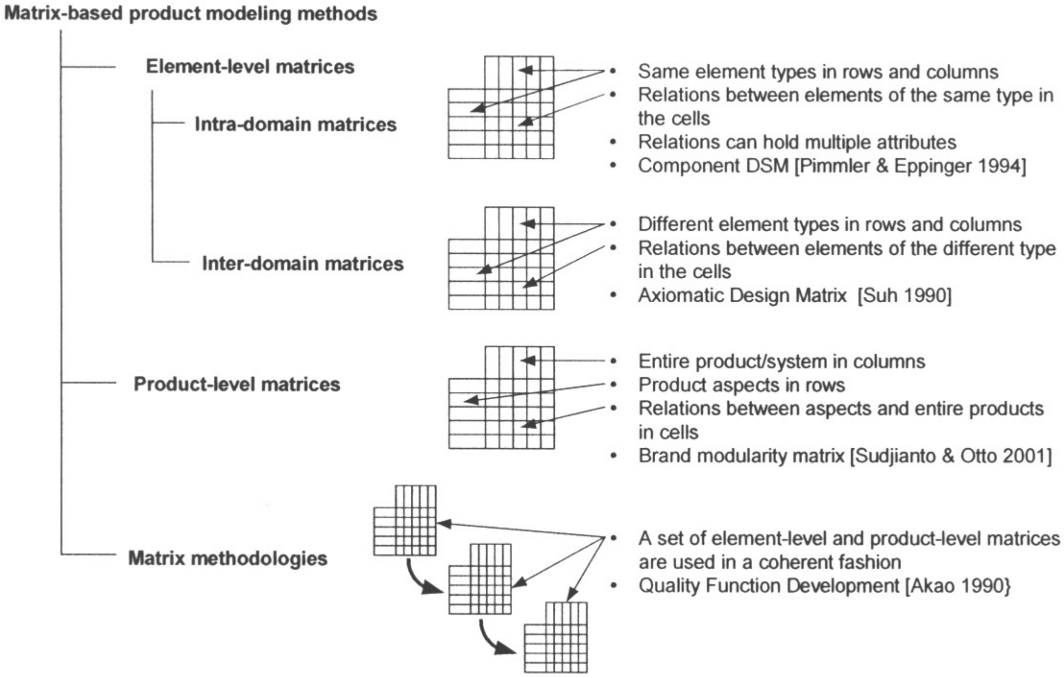


FIGURE 46. The types of matrix methodologies, according to Malmqvist [Malmqvist 2002]

In another presentation, the focus remains on product-internal relations, but the objects proper are the elements in different domains, for example, on different levels of abstraction or *domains*. An example of this is Nam Pyo Suh's presentation of the linking of elements in the functional and the physical domain with a matrix presentation in axiomatic design [Suh 2001]. According to Suh's axiomatic design, the *design world* consists of four *domains* in which the items within the same product exist as having a different form depending on the context of examination. Suh's theory is discussed in greater detail in Chapter 12.3.

In product-level matrices, the elements in and the properties of the product range are compared. Malmqvist presents the *brand modularity matrix* by Sudjanto & Otto [Sudjanto & Otto 2001] as an example of this. Malmqvist classifies methods in which several matrix presentations are linked together as belonging to the matrix methodology class, as for example the Quality Function Deployment method (see e.g. [Clausing 1994]). In some methods, various different forms may exist, such as in the *Konfigurations- & Verträglichkeits* matrix method by Luca Bongulielmi [Bongulielmi 2003]. The K/V matrices consist of two matrices of the intra-domain type and one matrix of the inter-domain type, but as these are linked together, the method can be classified as belonging to the matrix methodologies class. The matrices in this method are shown in the figure below.

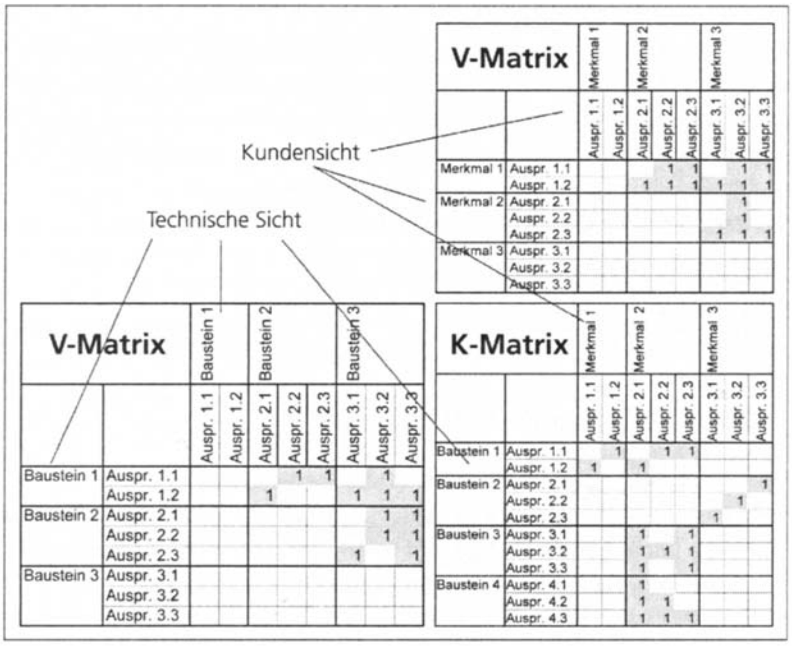


FIGURE 47. The Konfigurations- & Verträglichkeits matrix method consists of three matrices that are linked together. The matrix is used in the management of configuration data. [Bongulielmi 2003]

Malmqvist recognizes seven methods of analysis. Of these methods, we are already familiar with *partitioning* and *clustering*, but the slight difference between the two methods was not yet explained.

- *Clustering*, in which the elements are grouped as clusters with strong internal relations and weak cluster-external relations
- *Partitioning*, in which the iterations in the process are minimized (design).
- *Coverage*, in which the completeness and the coverage of the entity is examined
- *Index computation*, in which indices are computed to produce deductions
- *Interaction* focuses on the contents of the relations and guides the redesign
- *Change propagation*, in which the effect of the changes can be estimated by examining the relations
- *Alignment*, in which the relations of the product and the organization structure are compared

Of these methods, *clustering, partitioning, index computation*, and *alignment* can be considered in producing a modular structure (synthesis). In analyzing a modular structure, all of the methods are applicable. Erixon's method, to be presented in the following, begins with an analysis of the *index computation* type. In the industrial examples, we will introduce an alignment tool, the *Late Point Differentiation analysis*, in section 10.1.

Problems of the matrix methods

The simple logic of matrix methods makes them easy to use. The most problematic issue in developing modularity lies in *problem setting.* **What relations are to be examined and how to interpret the results?** The methods *per se* remain neutral in this issue, which means that *the matrix methods are only auxiliary tools for designing a modular structure, not methods proper.* A very detailed level of examination must also often be selected in matrix presentations to be able to unambiguously define the relations. This, in turn, often leads to an excessive amount of work compared to the value of the end-result.

5.7.2 Gunnar Erixon and MFD

Alternative approaches exist in the field of product structure research. One of these is the *Modular function deployment* (MFD) approach by Gunnar Erixon. In his dissertation, [Erixon 1998] Erixon defines modularity without the aspect of functionality:

"***Modularisation** = decomposition of a product into building blocks (modules) with specified interfaces, driven by company-specific reasons*"

Erixon thus suggests *company-specific reasons* as the basis for decomposition. He divides these reasons into 12 categories that he calls *module drivers*. They are drivers, or motivators, for calling a certain building block a module.

The motivations for modularity, according to Erixon, are:

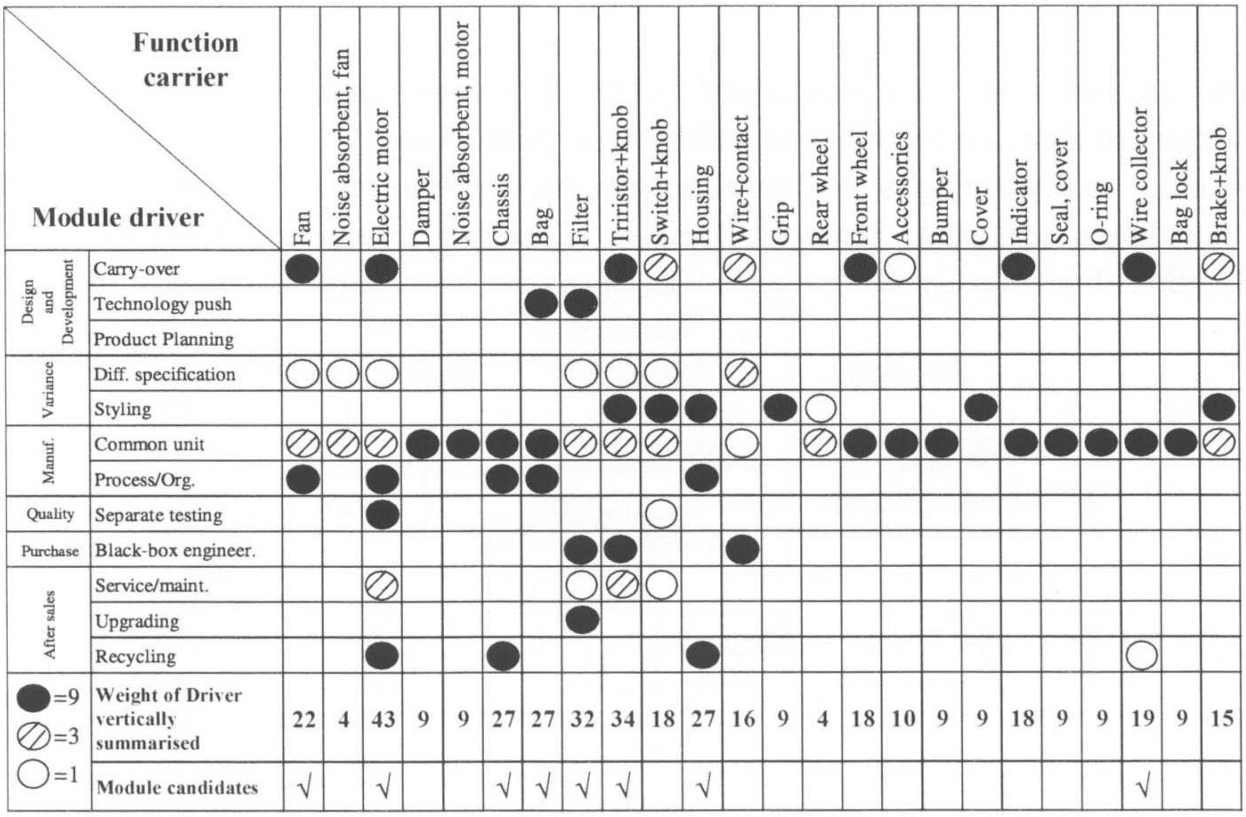
1. Carry over
2. Technology push
3. Planned design changes
4. Variance
5. Styling
6. Common unit
7. Process/Organisation
8. Separate testing
9. Blackbox-engineering
10. Service/maintenance
11. Upgrading
12. Recycling

Of these, 1 and 6 refer to **decomposing the module into different uses**, 2, 3, and 5 to the **long-term management** of the product, 4 to **configuration**, 7, 8, and 9 to **manufacturing-related reasons**, 10 and 11 to **maintenance**, and 12 to **environmental reasons**. By using the main criteria only, the number of real module drivers is six. Erixon divides the motivations for modularity as follows:

- **Product development and design-related** 1,2, and 3
- **Variance-related** 2 (referred to as "technical specification" on page 72), 5
- **Production-related** 6 and 7
- **Quality-related** 8
- **Purchase-related** 9
- **After-sales-related** 10,11, and 12

This division does not bring anything new to the matter, and it follows a rather formulaic conception of the issues (for example, associating separate testing to quality only). However, it is interesting that Erixon regards technical specification as belonging to configuration in particular! Functional structure is thus linked to design; this is where Erixon admits to following to some extent the path of Pahl & Beitz and Ulrich.

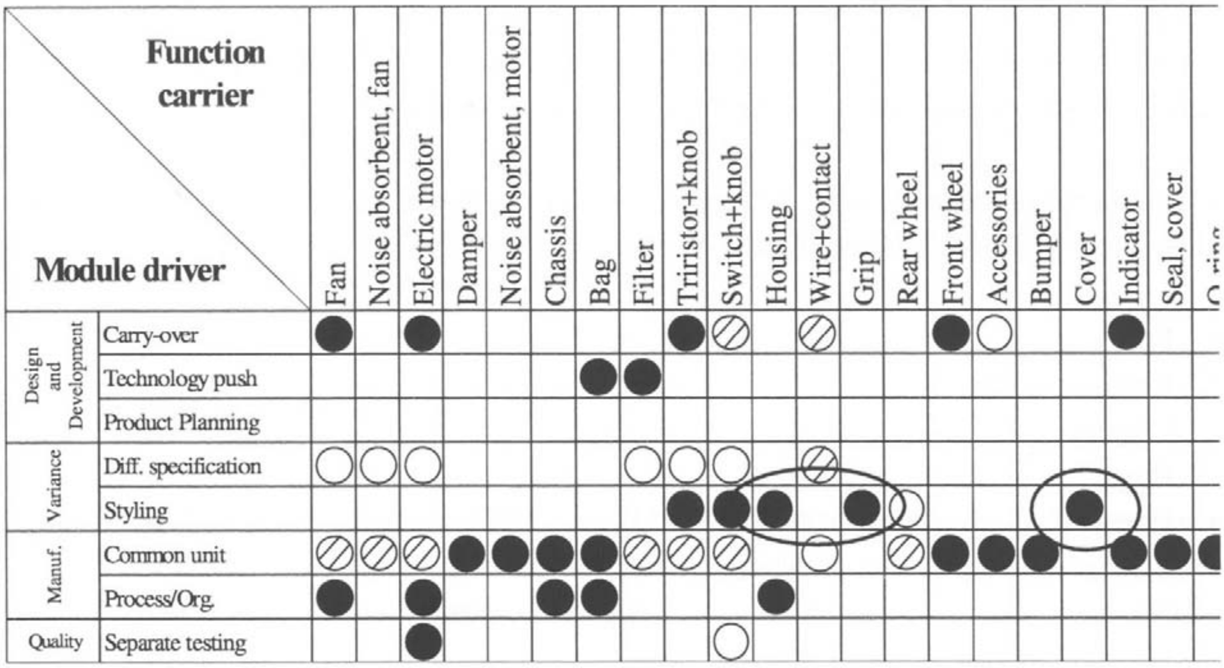
In the modular function deployment approach, the starting point is in the part structure of the existing product. It is, therefore, not applicable as a design method for a *new product* sought in this dissertation. The ideas therein are, however, worth looking into. First, the (main) parts of the product are collected in the *Module Indication Matrix* tool. The horizontal rows show the parts, and the importance of various motivations for modularity is evaluated for each part as shown in the figure below. The matrix tool is based on calculating indices. The logarithmical division of priorities on a scale of 9, 3, and 1 is familiar from the Quality Function Deployment (QFD) methodology [Clausing 1994]. According to the author's critical view, no valid observation proves that the priority of the issues in product development would follow a logarithmical scale. Rather, a psychological factor is used here, that is, people are forced to decide between “important” and “very important” issues. In practice, this division leads to the fact that *the lesser weightings hardly make a difference in the analysis*. For example, the figure shows that it has been decided that function carriers with 18 points are not module candidates, but those with 19 points are. The total number of points varies between 4 and 43, which means that the difference of one point cannot be decisive if any error margin is applied in the analysis.



	Function carrier Module driver	Fan	Noise absorbent, fan	Electric motor	Damper	Noise absorbent, motor	Chassis	Bag	Filter	Triristor+knob	Switch+knob	Housing	Wire+contact	Grip	Rear wheel	Front wheel	Accessories	Bumper	Cover	Indicator	Seal, cover	O-ring	Wire collector	Bag lock	Brake+knob
Design and Development	Carry-over	●		●						●	▨		▨			●	○			●			●		▨
	Technology push							●	●																
	Product Planning																								
Variance	Diff. specification	○	○	○					○	○	○		▨												
	Styling									●	●	●		●	○				●						●
Manuf.	Common unit	▨	▨	▨	●	●	●	●	▨	▨	▨		○		▨	●	●	●		●	●	●	●	●	▨
	Process/Org.	●		●			●	●				●													
Quality	Separate testing			●							○														
Purchase	Black-box engineer.								●	●			●												
After sales	Service/maint.			▨					○	▨	○														
	Upgrading								●																
	Recycling			●			●					●											○		
●=9 ▨=3 ○=1	**Weight of Driver vertically summarised**	22	4	43	9	9	27	27	32	34	18	27	16	9	4	18	10	9	9	18	9	9	19	9	15
	Module candidates	√		√			√	√	√	√		√											√		

FIGURE 48. An example of Erixon's Module Indication Matrix (MIM) presentation [Erixon 1998 p. 108]

The following phase in the MFD is the categorization of elements with shared motivations for modularity and potential decision-making on the merging of elements, as shown in the figure below:



	Function carrier Module driver	Fan	Noise absorbent, fan	Electric motor	Damper	Noise absorbent, motor	Chassis	Bag	Filter	Triristor+knob	Switch+knob	Housing	Wire+contact	Grip	Rear wheel	Front wheel	Accessories	Bumper	Cover	Indicator	Seal, cover	O ring
Design and Development	Carry-over	●		●						●	▨		▨			●	○			●		
	Technology push							●	●													
	Product Planning																					
Variance	Diff. specification	○	○	○					○	○	○		▨									
	Styling									●	●	●		●	○				●			
Manuf.	Common unit	▨	▨	▨	●	●	●	●	▨	▨	▨		○		▨	●	●	●		●	●	●
	Process/Org.	●		●			●	●				●										
Quality	Separate testing			●							○											

FIGURE 49. Parts including the same motivations for modularity can be combined. [Erixon 1998 p. 110]

The experiences of the MMD methodology have proved that it easily leads to a large number of small modules and a situation in which the discrepancies between the motivations cause the analysis not to yield a functional result. Apparently aware of this, Erixon introduces “The House of Modular Function Deployment” matrix tool shown in the figure below. This tool also evaluates the effect of the different motivations on each other. A couple of empty rows are reserved for the case-specific reasons for modularity. For assembly, an optimal point is sought for the number of elements that together form the product, with the minimal elements and the sum total of the work hours in assembly (“Target number of modules” in the figure). In this figure, Erixon rather awkwardly resorts to functional structure -based thinking and presents subfunctions instead of element entities (or something of the sort, as it says “*Sub-function / technical solution / function carrier”?*) in the table. This resorting to the functional perspective separates the methodology from the ideas introduced previously.

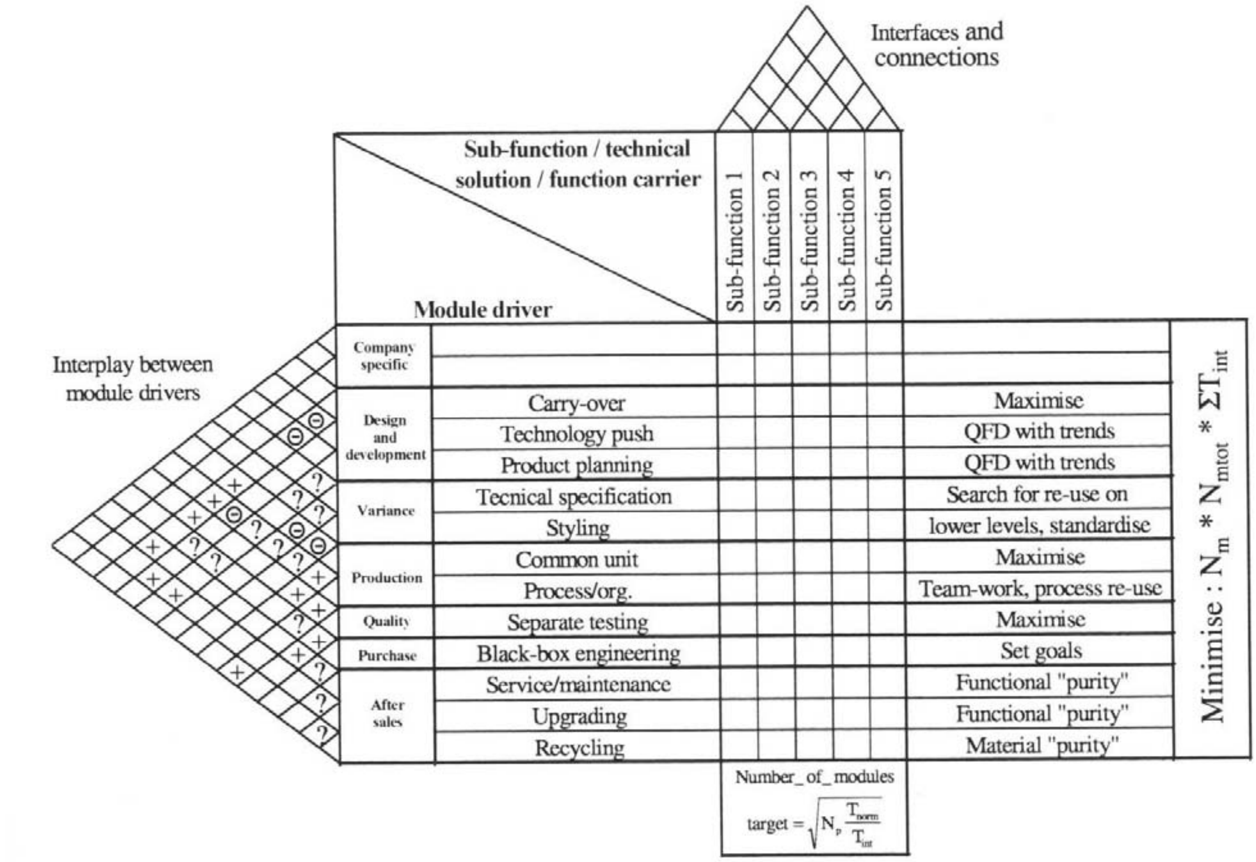


FIGURE 50. Erixon's “The House of Module Function Deployment” tool in which the functional perspective is mysteriously included as a part of the method. [Erixon 1998 p. 113]

In his work, Erixon also comments on the organizing the part structure by evaluating the interfaces. He takes the order of assembly as his starting point, as shown in the figure below. According to Erixon, there are two “pure” model types that rationalize the structure: using a basic unit and a layered structure. These ideas are somewhat based on the Design For Manufacturing and Assembly approach and they apply some of the same elements as the *plus-modularity* view. Erixon considers the retaining of the pure structure beneficial, as the interfaces between the modules remain simple. This view is not completely universal, as it does not consider the dependencies irrespective of the assembly structure.

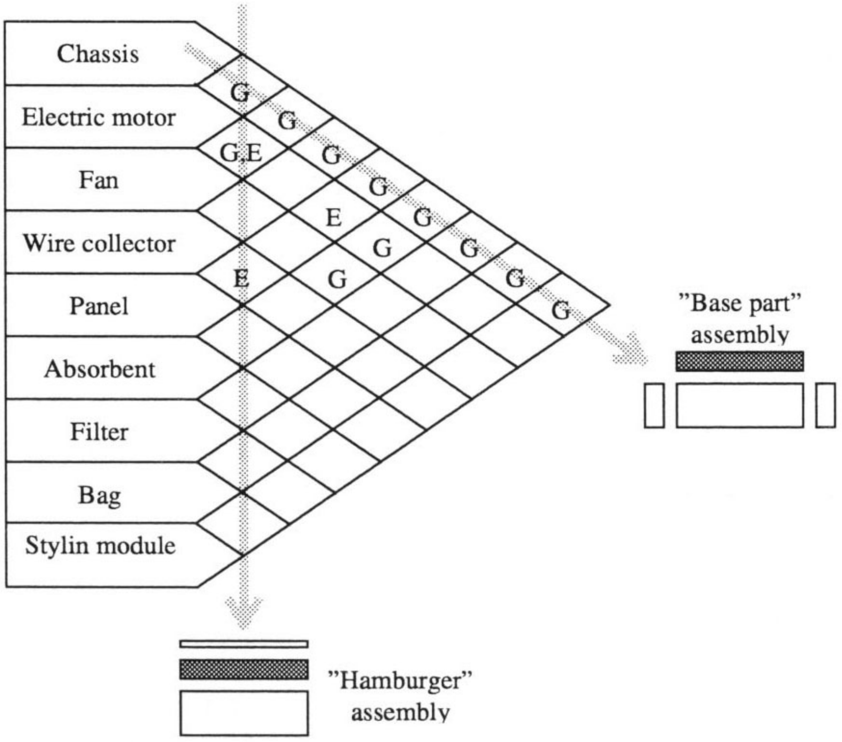


FIGURE 51. Erixon's ideas on limiting the dependencies between the interfaces in a modular structure. The sample case is still a vacuum cleaner. [Erixon 1998 p. 111]

Erixon's definition of modularity is worth examining, even if it does not lead us one step forward from Borowski's definitions (except that Borowski did not use the word “module”). Defining the modules on the basis of the motivations for modularity is also an approach with an industrial relevance. The problem with this approach is the lack of a theoretical background. On what basis are the 12 reasons for forming a module chosen? They are not based on any models of mechanisms of the market or the product, but represent knowhow acquired in practice, which probably also corresponds to today's predominant views. If, for example, we think about the *“recycling”* motivation, we notice that it would not have been mentioned 20 years ago. Based on this, we may assume that in 20 years' time, new “trendy" issues may exist on the lists while some others may have been dropped out.

The value of this approach would increase considerably if a model from which the module drivers could be derived was presented. Such a model is presented in Chapter 9 of this dissertation.

5.7.3 Plus-modularity

Here we might also like to mention the approach known in Finland as plus-modularity, even though it is not based on an academic research but rather a design philosophy based on industrial experience. The approach was suggested by Jarmo Juhola and Kalle Välimaa [Juhola & Välimaa 1997][*].

In this approach, the structure of the product range is defined by a “customer need structure" in the case of a customer-oriented modular product range (customer-configurable product range). Other

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[*] This source does not name the method. Juhola and Välimaa define plus-modularity as a method developed by Innomat Oy: they primarily use it as a product name. Instead of ”plus modularity”, they speak of a “plus principle”.

factors affecting the product policy include the conceptions of sales on the development of the market and the production-related topics. Of forming the modular structure, it is suggested that "In creating the modular structure, we must aim at a minimal number of modules with which all selected customer needs are fulfilled. With this principle, no previously selected customer need ought to be removed when a new customer need is added." The idea is to place all independent customer needs in a designated module. According to these principles, a product is created that it has an unchanging basic element on which the module alternatives can be attached without removing any items of the basic unit for configuration. The customer requirements are limited to one module, which makes configuration an easy task.

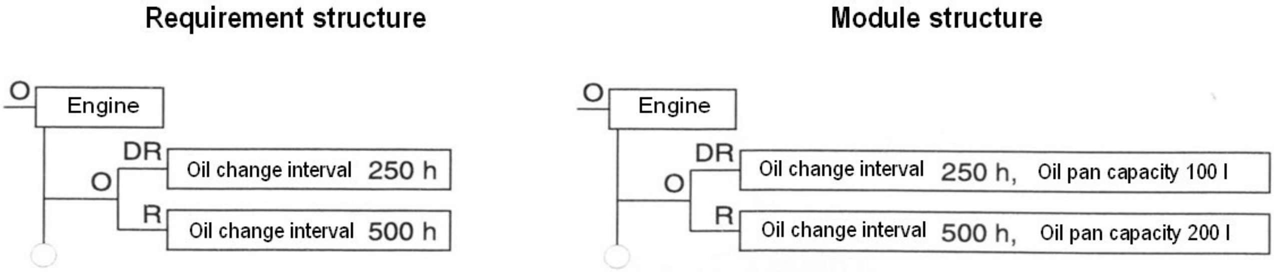


FIGURE 52. An example of configuring a customer need structure into a module structure according to the principles of plus-modularity [Juhola & Välimaa 1997 p16]

This approach is not universal. The principles of structuring the products are such that no good modular structure can not always been created in the current market situation. In these cases, the design method leads via duplicated structures to increased weight and costs and potential poor performance. On the other hand, in some cases the method has suited the product and the market situation perfectly. In the case of the Ponsse forestry machines to be presented in this dissertation, a solution is suggested that comes very close to these ideas.

5.8 Summary of the research of modularity

In this chapter, we have discussed the key sources considered in the research as starting points in defining modularity. In addition, methods and even suggested industrial practices have been discussed. Certainly, there exist plenty of other methods in addition to these, but they focus on developing tools and applications from the premises mentioned in the above sources. These research projects will be revisited in Chapter 12 in which the results of this research are compared to other scientific research projects.

As we have seen, the best-known definitions of modularity are not specifically comprehensive when examined in the light of the industrial history of modularity. *They cannot thus be based on empirical observations* (Erixon exluded). If, then, the idea of functionality as the basis for modularity is valid, a justification for it must be found in the theory of design. Here we enter our next research question.

Does the functional structure show the modular structure for a new product when the process of systematical design is applied?

Answering this question will simultaneously prove the validity of Hypothesis 1: Are the requirements arising from functionality above the other requirements?

5.9 Proof of Hypothesis 1

Hypothesis 1 is proved with a theoretical example from the book *Practical Studies in Systematic Design* by Vladimir Hubka, Morgens Myryp Andreasen, and Ernst Eder. The sample case derives from the leading researchers in the field of Design Science and it can thus be presumed that the methodology is correctly applied and justifications may exist for generalizations of the results.

The sample case to be discussed is case 8 in the book [Hubka & al 1988, p. 123-136], illustrating the design of an oil drain valve. According to the systematical design method, a functional structure is created for the valve. After this, solutions are developed for the functions, which are all entered in a morphological matrix. At the same time, the organs carrying out the functions are listed. The relations between these are examined in the matrix, and the organ structure is drawn on the basis of the findings. After this, the design work proceeds by drawing various concepts, and eventually evaluating and selecting the ones to be used.

The mentioned structures appear on the levels of the domain theory as follows:

Function domain – the functional structure
Organ domain – the morphological matrix, the organ structure
Part domain – the concepts

The most important things for this dissertation are the diagrams on the function and organ domain level. Do they show the module structure that is characteristic – maybe even ideal – for the product? The latter phases of design on the part domain level remain outside our scope of interest, as they *do not bring anything completely new to the functional structure.* In addition, it is evident that the module structure lies particularly on the part level in most products.

The figure below shows the functional structure of a valve as a block diagram. The blocks and the combinations in the diagram might be natural modules for the product.

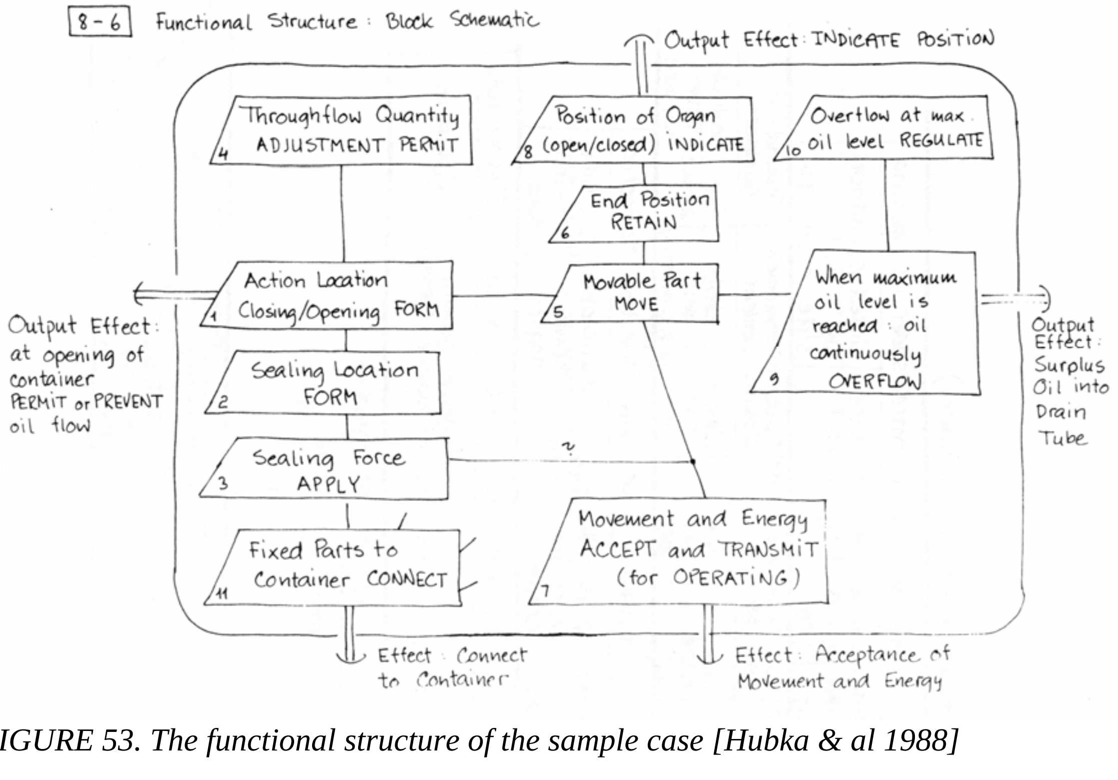


FIGURE 53. The functional structure of the sample case [Hubka & al 1988]

As the design work proceeds, an *abstract* organ structure is drawn for the valve. At this point, we must bear in mind that this dissertation focuses on the design of a *new product*. This means that in drawing the functional structure and the organ structure, we try to avoid presenting/favouring any one method of implementation. Instead, subfunctions are sought that are necessary for the overall transformation. Similarly, abstract solutions are sought in the organs. This structure already answers the question of how to implement a function; after all, the other name for this organ is a *function carrier*. In the organ structure, the relations between the organs are indicated with lines and arrows. If the functional structure defines the module structure, the division into modules must be presented in the picture. In this way, certain divisions become apparent.

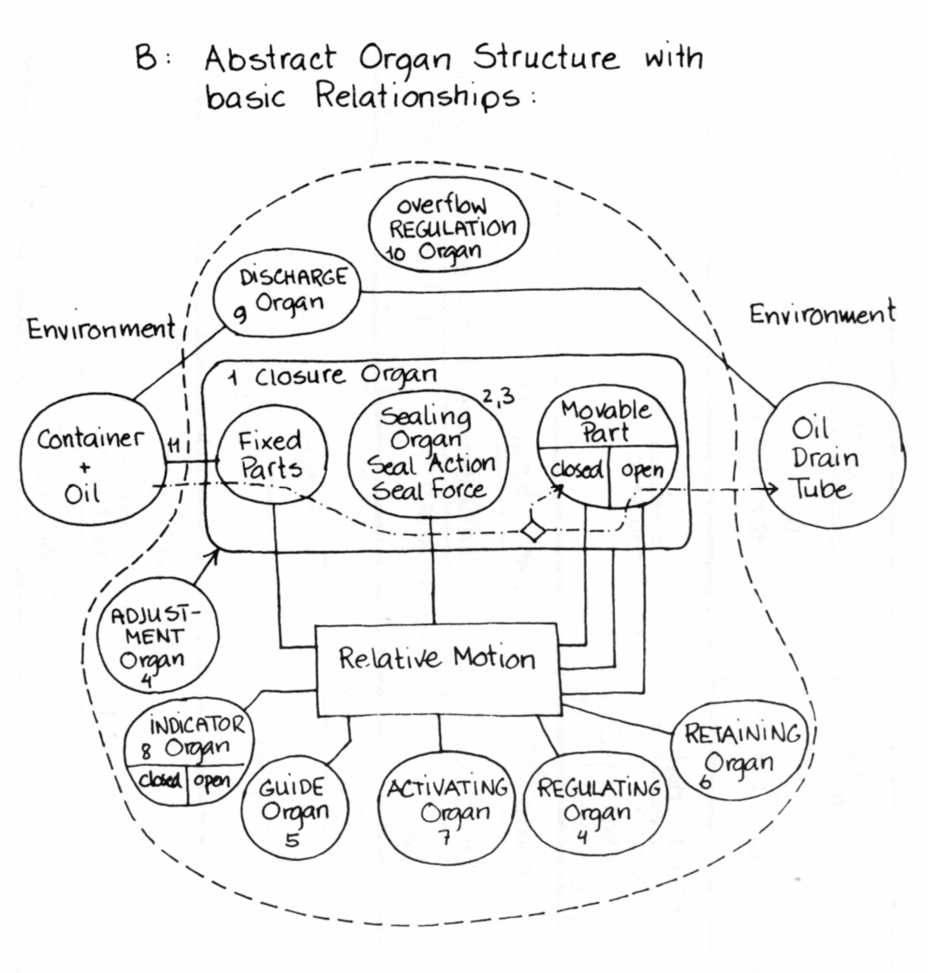


FIGURE 54. The organ structure of the example [Hubka & al 1988]

Finally, we write the five drafts of a valve, shown in the figures below.

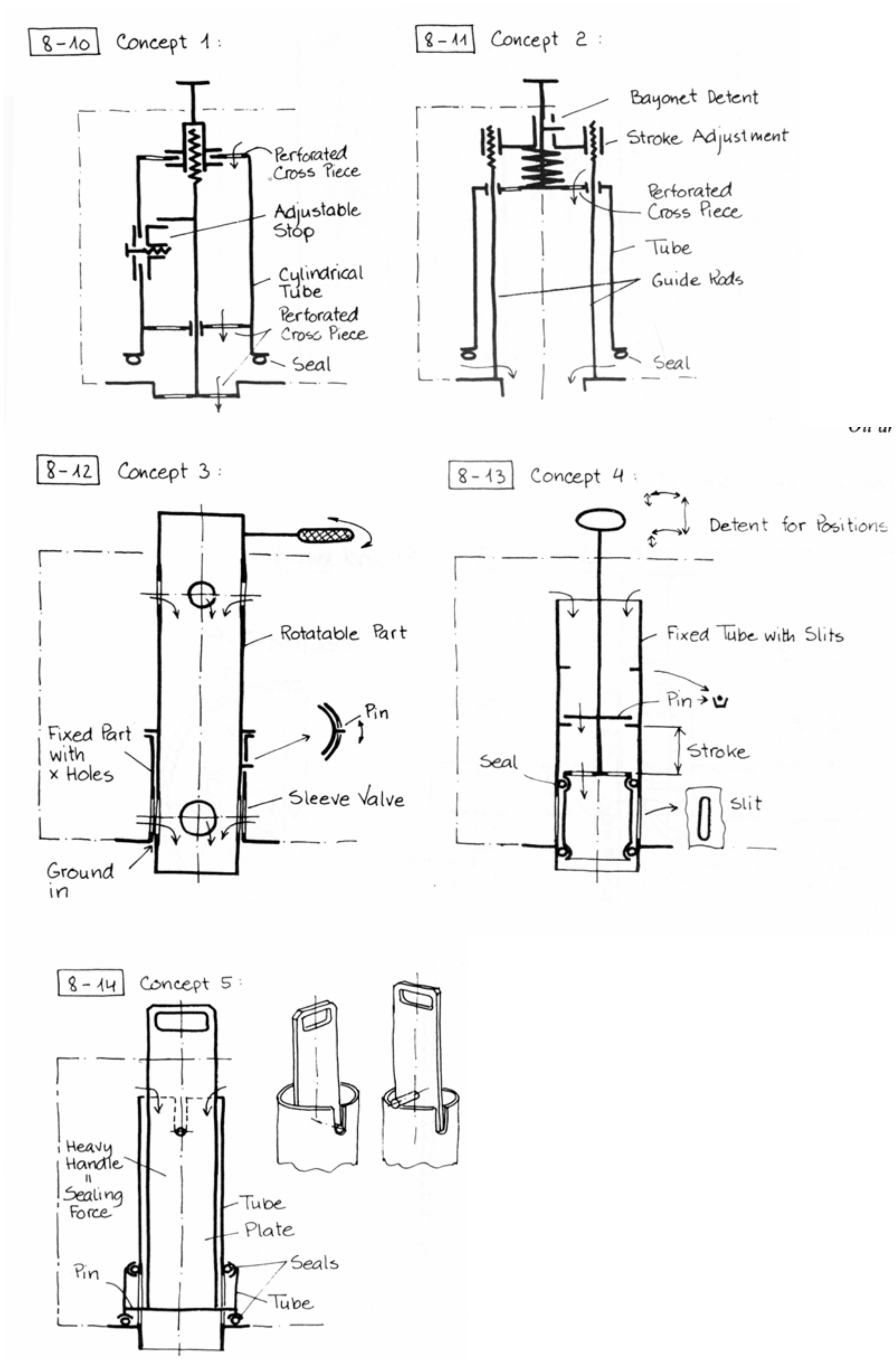


FIGURE 55. The five drafts of the example [Hubka & al 1988]

In some concepts – for example, in #1 – modules seen in the organ structure can also be found in the part structure. Some concepts have hardly any division as defined in the organ structure. Here we can see that the functional structure was able to show the division into modules in some implementations, but not in some other technical implementations.

Let us revise this once more on the general level by following the process of systematical design shown in the figure below. We will estimate which design tasks and results belong in which phase from the viewpoint of designing a modular structure.

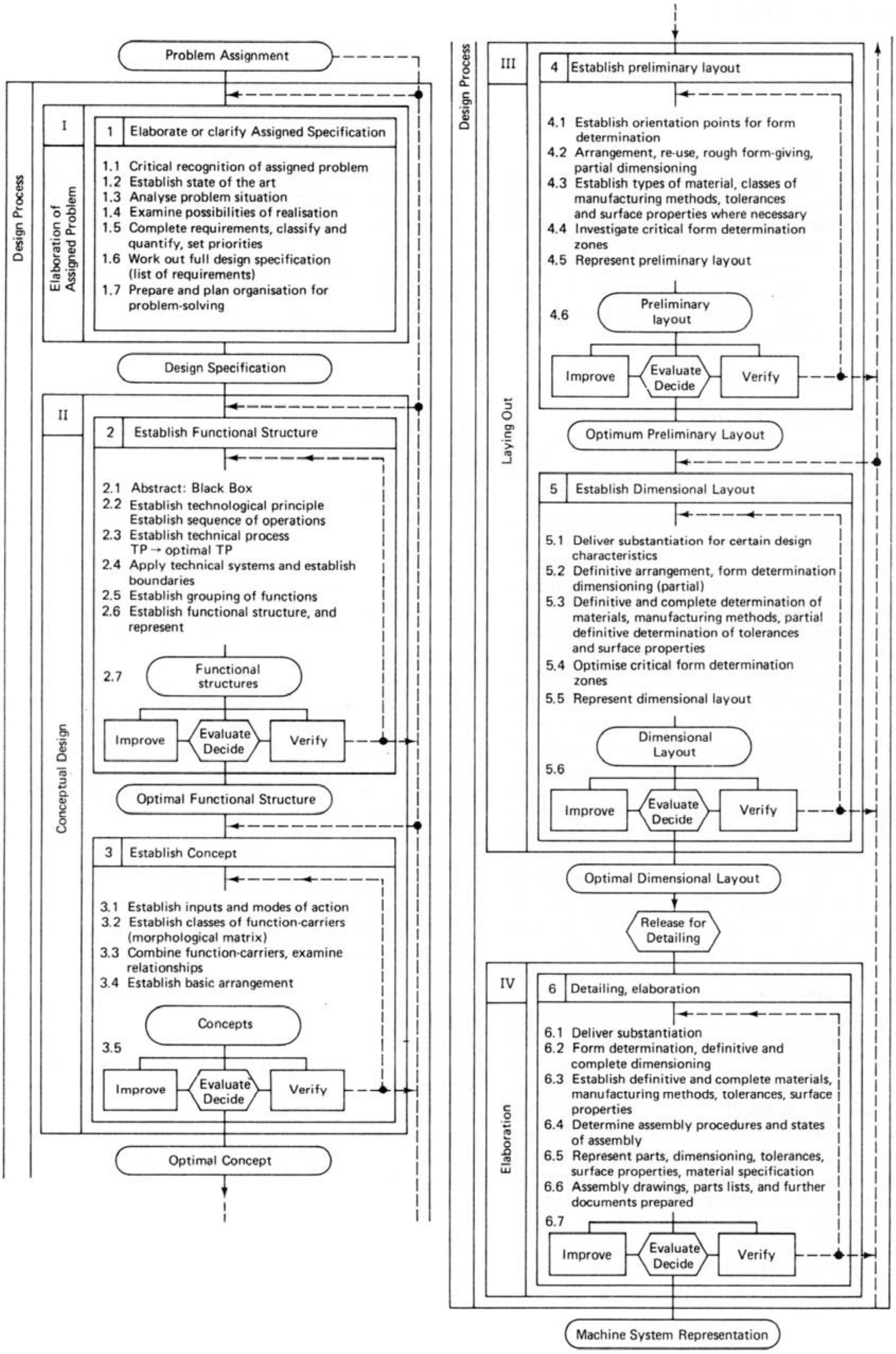


FIGURE 56. Systematic design process (according to Hubka). This illustration is included in a number of sources, but it originates in the same book as the example text. [Hubka & al 1988]

In phase 1, “Elaborate and Clarify Assignment Specification”, the goals of the modular structure must be set, or define why (and how) the product must be modular. Factors affecting modularity are often not product-internal requirements but related to the business and production processes. These are not often considered as belonging to product design. Chapter 9 discussed the issue in greater detail.

In phases 2 and 3, “Establish Functional Structure” and “Establish concept”, the layout issues of the product are not much discussed. As shown in the example, no fixed estimates of the modular structure can be presented on these levels of abstraction. As is visible in the process description in the figure, *tasks related to the organization of the part structure to be created later are not included in the design tasks.*

In phase 4, “Establish Preliminary Layout”, the most critical design decisions concerning the implementation of the module structure is made. The concepts either enable or exclude possible module structures. *In this design phase, the opportunities of implementing a certain module structure are definitively decided.*

In phases 5 and 6, “Establish Dimensional Layout" and “Detailing, elaboration”, either the part structures enabled by modularity are implemented also on the detail level, or decisions are made that fix conceptually independent entities as integral elements from the viewpoint of modularity. In these design phases, more preconditions for modularity can be created, but *usually it means adding elements and dividing individual parts into a number of parts, which does not yield as good a modular structure as one created on the draft level* .

Thus, the most important phases for the design of modularity are 1 and 4. The key issue is to discover the goals aimed at with the modular structure and to ensure that the selected draft structure is able to meet these requirements. Phases 2 and 3 – of which the former refers to the defining of the functional structure – do not include critical design decisions in terms of the module structure. *The process of systematical design does not determine the functional structure as the basis of the modular structure.* Therefore, no justification proper exists for the argument that is included in, for example, the second edition of Pahl and Beitz on page 438: ”*The establishment of function structures is of particular importance in the development of modular systems. With the function structure – that is splitting up of the required overall function into subfunctions – the structure of the system is already laid down, at least in principle.”*

The above issues provide an answer to the question posed at the beginning of this chapter: **the functional structure does not indicate one ideal division into modules in designing a new modular product. No such “principle” exists.**

It is not justified to assume that an oil valve would be an exceptional design object and therefore a special case. Corresponding cases are shown in the industrial examples of this dissertation. Even though the functional structure is an important starting point in the design of a technical system, it is not used as a basis for any such design decisions on the product layout that would primarily determine the division into modules.

Hypothesis 1 is thus valid, as it is reasonable to argue that “*the functional structure is a primary starting point for a technical system, but secondary for a modular system. The functional structure does not directly show the modular structure in the design of new products that include a physical assembly.”*

Now we know what modularity is *not* based on. However, in this dissertation, we promised to answer the following question:

"*How product modularity should be understood that it would be possible to develop better teaching und design tools applicable to non-expert users for new product development*."

To answer this, we will need to examine the phenomenon of modularity in a wider context.

6. Models of business operations and modularity

The history of using modular structures and the research related to modular structures were discussed in the previous chapters. Another important dimension is that of the strategies of using modularity. In such a case, methods of operation are linked to the modularity of the product. Two well-known examples are systematical product variation, known as configurable product paradigm, and the use of product platforms.

Delivering systematically variable products, is a currently much-used model for business operation, based nearly always on applying modularity. Configurable product paradigm is one way of implementing *mass customization*. Mass customization refers to delivering a customer-adapted product via means of mass production. Joseph Pine [Pine93], among others, has written on the properties of mass customization. Pine suggests for example the following are features of business environment situation (competitive landscape) that require a mass customization business paradigm:

- Competition based on time
- Increasing variety
- JIT production (“Just In Time”)
- Regional marketing
- The policy of continuous improvement
- Shortening product life cycles
- Market-driven quality thinking
- Globalization
- Networked organizations
- Micromarketing
- Increasing customization
- Lean production
- Shortening the cycle times
- Comprehensive quality control (Total quality management)
- Flattened hierarchies (in organizations)
- Computer-integrated manufacturing
- Process re-engineering
- The increasing importance of services
- Fragmented markets
- Quick response
- Flexible manufacturing systems
- Marketing methods based on databases (e.g. direct-mail advertising)

The 22-item list illustrates the approach applied in the research conducted in the US: it is very close to industrial consulting. The lists are long and full of interesting issues more or less related to the actual theme. Pine suggests that the method of mass customization produces an increasing number of variations for increasingly smaller target groups in a flexible and rapid manner over increasingly shorter times-to-market. Whether this will lead to networking, the lowering of organizations, a more comprehensive quality control, or a host of other issues on the list remains outside the scope of this dissertation.

6.1 Configurable product paradigm (CPP)

Configurable product paradigm, or systematical product variation, is one method of mass customization. It is often just called “configuration” on “configuring” [e.g. Brown 1998] which however is quite confusing taking account that these are also used as a noun and a verb in this same topic. That is why the full name of paradigm or an acronym “CPP” is used in this dissertation. Contrary to mass customization itself, CPP can be rather specifically defined. CPP is a corporate method of operation, and an essential part of it is the defined order-delivery process. The aim is to separate design and delivery so that all customer deliveries are carried out via configuration (process). This is achieved via offering a modular product family and the fact that there exists a configuration rule set for forming the variations to be delivered. By following the set rules, the product variation to be delivered can be defined either via a systematic configuration process or even automatically using a configurator (software).

Configurable product paradigm is thus not an inseparable part of modularity, and in another era and under different models of business operations it might not be as important a factor for modularity. According our observations, *it is currently the single most important reason for using modular product structures.* CPP plays an important role in applying modularity in industrial use. **For this reason, it is well justified to discuss CPP in detail in this dissertation** – in much more detail than necessary from a mere research viewpoint. Knowledge of the nature of the configurable product paradigm makes it easier to understand the deductions from the industrial examples to be presented later in this dissertation.

The definitions and views related to CPP presented in this dissertation are based on the results of the *Konfiguroitavien tuotteiden tuki* KONSTA project, funded by Finnish Funding Agency for Technology and Innovation and conducted in 1997-1999 [TEKES99]. The *DFC Design for Configuration manual* was written on the basis of the results of the research project; it was, however, never published. The following summarizes the contents of this configuration manual. **In addition to the author's contribution, the texts in the book are written by Juha Tiihonen (Licentiate of Technology), researcher Antti Pulkkinen, and researcher Tero Juuti.**

DFC

T-LEHTONEN J-TIIHONEN T-JUUTI A-PULKKINEN A-RIITAHUHTA

JÄRJESTELMÄLLINEN
ASIAKASMUUNTELU

- MUUNNELTAVAN TUOTTEEN SUUNNITTELU ASIAKASTARPEEN
POHJALTA

FIGURE 57. An unpublished configuration manual, the key results of which are discussed on the following pages

In the Konsta research project, the configurable product paradigm was defined as follows:

1. Each delivered product is an individual that is fit to meet the requirements of the customer.
2. A product instance (individual) only consists of predesigned elements.
3. Only systematical routine design is needed in the order and delivery process, such as the selection and compatibility-testing of the predesigned elements
4. A predesigned general product structure corresponds to the product instances to be delivered. Variations of the generic product structure are made to the estimated market.

David Brown has sought to define the systematical routine design to be carried out in configuration so that design only consists of the task of selecting components, creating the relations between the components, and evaluating the compatibility and the conformity to the requirements. With certain limitations, he also accepts the arrangement of the components [Brown 1998]. This means that layout design is included in the configuration task. In our research, we have limited the scope so that free layout design is not a routine design task and therefore not suitable for a configuration process. Our solution is to draw ready-made layouts and thus change the task into a selection.

A product family that is made according the configurable product paradigm, thus meets the requirements of the Baukastensystem. If free layout design is excluded from the configuration, a systematically configurable product always has an existing structural design - a *Bauprogram.* A modular structure is not an absolute requirement for systematic configuration, but in practice the method involving configuration usually requires it. In CPP, it is not necessary to define a product instance at one go, but the definition can be specified up to three times in the order-delivery process. The order-delivery process of configurable products is shown in the figure below:

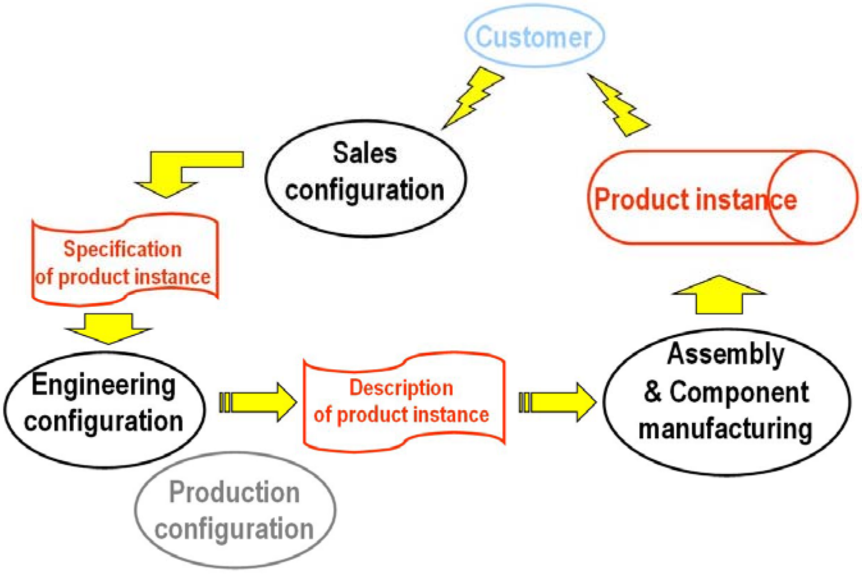


FIGURE 58. The order-delivery process when delivering configurable products

The definition of a product instance may be specified or changed three times during the process. In sales configuration, the product is assembled to correspond to the customer's requirements as much as possible. In engineering configuration (Tiihonen & al call this a “logistics center”), the sales specification is converted into a production specification. In some companies, it is not until the production phase that the decisions are made on which alternative elements are used to make up the final customer delivery. In such a case, a delivery-specific product specification is written only after this third round of configuration.

6.1. Two approaches

The purpose of systematic configuration is to create products that meet the customer-specific requirements in a profitable way. Configurable product paradigm is a way to manage the varying customer requirements without shifting into customer-specific design proper. Configuration is considered to contribute to the following issues:

1. Meeting and managing customer needs
2. Speeding up delivery times
3. Managing costs
4. Achieving uniform quality
5. Managing the product range
6. Creating a corporate brand/image

The priority of these issues varies depending on each case. The factors improving the profitability of a business idea based on product configuration and the birth mechanisms of the benefits are radically different, depending on whether the company is shifting to configuration from mass production or whether customer-specific project deliveries have been made in the past. The figure below shows the two paradigm shifts. The vertical axis indicates the cost-efficiency and the horizontal axis the range of customer configuration enabled by the method of delivery. The figure shows that configurable product paradigm is a compromise between standard-product delivery and project delivery.

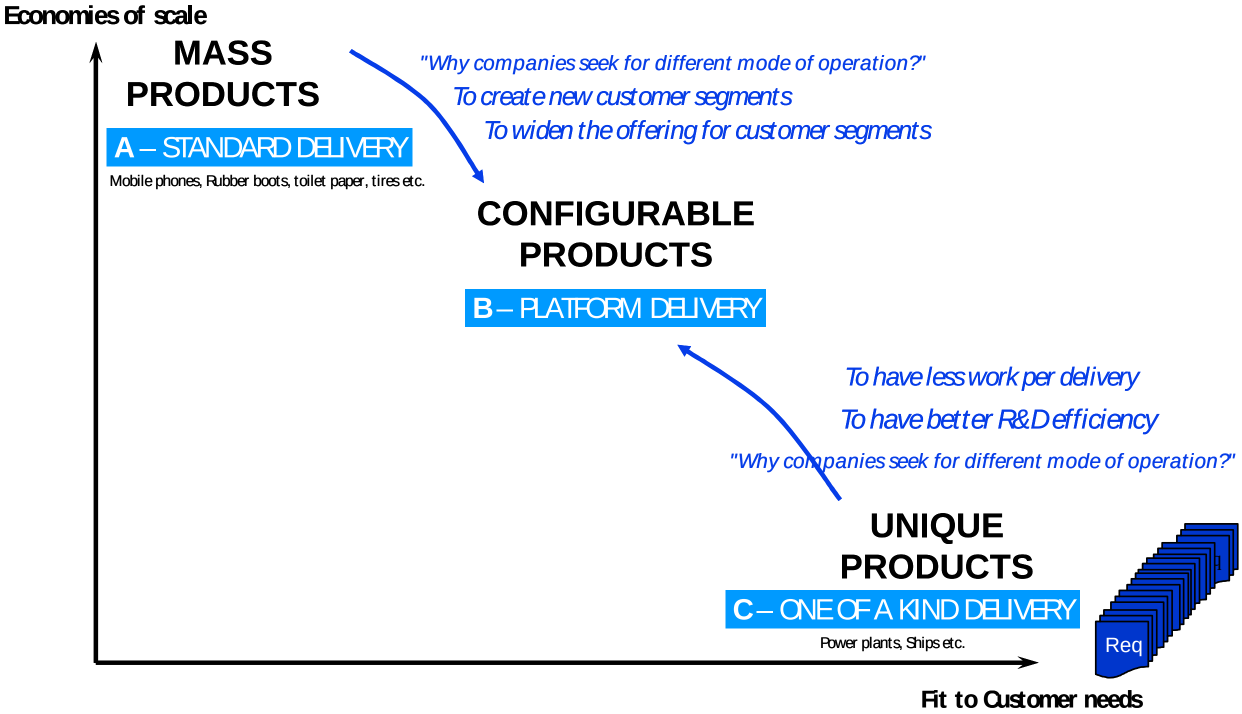


FIGURE 59. The shift-over to configurable product paradigm. CPP is a compromise between delivering standard products and project deliveries. Companies shift over to configuration from serial (mass) production or from project deliveries. According to Juuti, forming a product platform is a consistent way of developing a configurational method of operation. [Juuti & al 2006]

6.1.2. The aims of CPP when shifting over from product goods [Tiihonen abridged from DFC-manual manuscript, 1999]

As was shown in the figure above, companies shift over from project deliveries to configurable products primarily to improve their economic efficiency. The table below shows the effects of configuration as achieved or pursued by companies using configuration or those interested in using it. This was discovered in a research on configuration performed at 10 companies [Tiihonen & al 1996]. However, this presentation is not comprehensive. Some of the effects may be directly stated as aims, while others are effectual mechanisms via which the actual goals can be achieved. After the table, the effects in each phase will be discussed in the text.

Table 1: Observations of the use of systematic configuration in Finnish companies. A plus sign refers to a reported positive effect and a minus sign to a negative effect.

Effect	**Requirement satisfaction**	**Speed**	**Cost**	**Quality**	**Controllability**	**Image**
Clarification of product policy	-	+	+	+	+ -	+ -
Shortening of delivery time	+	+	+		+	+
Quality improvement		+	+	+	+	+
Eliminating customer-specific design	-	+	+	+	+	
Reuse of design		+	+		+	
Fragmenting the product definition	+ -	+	+ -	+ -	-	+
Moving customer order point later in the process		+	+		+ -	
Improving the controllability of production		+	+		+	
Standardization			+	+	+	
Improving and managing the data flow	+	+	+ -	+	+ -	+
Facilitation of sales	+	+	+	+	+	+
Improving modularity		+	+ -	+	+	+

The clarification of product policy

The product policy determines the types of products the company wishes to sell and is willing to sell. Often, companies wish to serve all interested customers by producing product instances that are customized to a great extent. This is questionable from the economic point of view, as an added price presumed by the costs caused by the changes is not always received in return.

When manufacturing configurable products, the product policy must dynamically steer the sales towards the opportunities provided by configurable product. For this reason, when approaching CPP from the direction of project products, fewer sets of customer needs can be fully satisfied, as the offered supply is more limited. If, however, the product supply is correctly defined, a sufficiently large proportion of the needs can be fulfilled satisfactorily. The method of selling is also important. Are free-formulated customer demands accepted, or are the solutions in the product range actively offered.

The shortening of delivery time

The shortening of delivery time is caused by the elimination of, or at least a considerable reduction in, customer-specific design, and the opportunity to manufacture element entities beforehand. Production may for some parts and in some products change from make-to-order to assemble-to-order. Product instances increasingly resemble each other, which enables better learning also in production and via this, more rapid manufacturing. Savings may also arise in the set-up times.

In addition keeping and predictability of the delivery times may be improved. This is primarily caused by easier manageability and the elimination of uncertainty factors in the design.

Quality improvement

In configurable products, the basic structure is standard or changes only within the designed or tested limits. In addition, only predesigned components are used. In this sense, they are essentially more real industrial products and less prototypes than project products.

A number of factors affect the improvement of quality. Some of these – such as learning in the manufacturing – are also discussed in other parts of this dissertation. Sales specifications often lack in quality: it is not uncommon that some of the orders are inconsistent in practice. Configuration as a method forces us to look into this issue, as well as into the changes taking place after an order is placed .

Eliminating customer-specific design

Eliminating or remarkably reducing customer-specific design is due to the fact that in the product development phase, the design of the product family has already been made along with its components or modules. This speeds up the order-delivery process and reduces or eliminates the delivery-specific design costs. Quality is also improved, as it is possible to concentrate more on product development than in designing a corresponding product for an individual customer.

The released design resources could be reallocated to boosting research and development. This may in time considerably affect the company's competitive edge, particularly if time-based competition occurs in the field in which time-to-market is a key factor. If, on the other hand, the resources in customer-specific design are a bottleneck for the delivery capacity, it is possible to reach larger delivery numbers and to speed up the deliveries.

In *partly configurable products*, the product instances involve design that is related to the components or system design to be performed customer-specifically. In system design, a customer-specific system is designed, based on one or more configurable or standard products. The work may also include the designing of the customer's production process. For example, a data network based on configurable computers, a power plant designed around diesel engines, or the interior design of an office are typical products that need system design. It is often difficult to systematize system design as configuration proper. Occasionally, some components must necessarily be designed customer-specifically, or this is profitable as the solutions to be offered are not known beforehand or it is impossible to standardize the products. For example, an optimal propeller in the propulsion system of a ship depends not only on the propulsion system to be configured, but also on the geometry of the ship, which is not standardized today. Due to its great importance, it is worth designing the propeller separately for each delivery. Sometimes the design of a customer-specific system based on the configurable product also remains a customer-specific task.

Reuse of design

In configurable products, the same design is constantly utilized. The modular product architecture in configurable products also supports the reuse of design data over the product generations. In the following section 6.2., an example will be presented on the effects of design reuse.

Distributing the product instance definition

A configurable product enables moving the definition of the product instance from a centralized unit (e.g. an order centre, a logistics centre) to sales offices or networks. Partly configurable product may also enable the distributing of the product instance definition.

In distributed configuration, the customer receives the desired configuration and the price more rapidly, and there is no need for a contact to the centralized unit. A direct customer contact minimizes errors caused by the misunderstanding of the customer's needs. At the same time, the entire order-delivery process speeds up. If a configurator is used, the finished configuration and the offer based on it can be finalized during the customer contact.

Moving the customer order point to a later phase in the order-delivery process

As was stated before, finished or half-finished components of the configurable product, can be manufactured as desired and regardless of individual orders. This speeds up deliveries and improves the management of lead-times. It may also reduce costs by enabling the use of more economic batch sizes in manufacturing.

Improving the controllability of production

The controllability of production is facilitated and improved, as a rather small number of recurrent components or modules are controlled instead of customer-specific components. The effects caused by the potential changes in the manufacturing method were discussed above. In some cases, the production planning may even be fully eliminated as separate manufacturing instructions do not need to be delivered for each individual product.

Standardization

Configurable products support standardization, as an entire product family, or the configurable product, is designed at one go. In this case, so-called *commonality*, or standardization between variations of the product family, automatically emerges and can be created (see ”Danish research” in section 12.1). Compared to project deliveries, a configurable product has most likely more things in common as the number of customer-specific specialties is reduced.

Improving and managing the data flow

To succeed, configuration requires good data flow and management. A rigorous documentation and long term management of configuration models are required. This is an important requirement that also causes costs and is not easy to manage. On the other hand, the manageability of delivered product instances is improved, as they have less or no unique, product instance specific components. The benefits are especially numerous for managing the service operations. Convincingly managed product knowledge and the improving quality also positively affect the corporate image.

Facilitation of sales

The ready-made design of configurable product makes the product more tangible than genuine individual products, which also means that making the product description is facilitated. Configurable products are thus more tangible sales articles than project deliveries. Pricing is significantly easier than with project deliveries, as the components to be used are known beforehand. It is sometimes even possible to use property-based rates. In such a case, defining the price is not necessarily based on the technology, but the customer purchases separately priced properties.

Clearly presented alternatives guide the selections towards the available alternatives, which may control unnecessary customization. It is also easier to manage the order-specific customer needs, as the configuration model determines the data with which the product instance can be defined. The product range can be divided into deliveries carried out according to a process of a different type by using the so-called ABC division. Here, an ABC division refers to a fully configurable and systematically deliverable product (A), a delivery (B) that involves slight customer-specific variation, and a delivery (C) that is carried out as a full project delivery. The documentation of a configurable product must include material with which the salespersons are clearly instructed on what to sell in each process.

Improving modularity

The method of configuration soon reveals whether the module division of the product corresponds to the requirements of the market. Often, a part of the product structure is more determined by design decisions derived from previous products than an analysis examining the current situation.

Redesign of the order-delivery process

In addition to previous, configurable products enable the redesign of a business operations process. The order-delivery process can be considerably simplified, as configurable products do not require customer-specific design. Systematizing the definition of product instances belonging to the order-delivery process is sometimes said to have the same effect, which combines the facilitation of sales and the elimination of or a remarkable reduction of customer-specific design mentioned above.

Increasing market share

Configuration boosts the company's economic efficiency and improves production capacity. It provides good prerequisites for increasing the market share, assuming that the limitation set by configuration do not limit the customer base.

6.1.3. The aims of CPP when shifting from standard products [Tiihonen abridged from DFC-manual manuscript, 1999]

As is shown in the figure 59, companies that used to manufacture standard products seek a better ability to meet the customer needs via configuration. The aim is thus not to reduce costs but to add to the value offered to the customer. For this reason, the perspective considerably differs from the above project-delivery perspective. The following presents the effects of configuration on companies that used to deliver standard products. Some of the effects may be directly stated as aims, while others are effect mechanisms via which the actual aims can be achieved. The most important negative effects are also identified.

The better fulfilling of customer needs

Configurable products may create a considerably wide product selection in an efficient manner. Managing large numbers of variations as configurable products can be easier than providing a corresponding selection as a product family consisting of standard products. With a very wide supply compared to the delivered numbers of one product model, implementing the supply as a configurable product may be cheaper than as individual products. In this case, this approach also (exceptionally) seeks economic savings. Most often, however, it is a question of a situation in which the supply is widened along with the configuration.

Higher costs and a longer delivery time

From the customer's viewpoint, the biggest drawback of configuration is the letting go of the ”off the shelf” method. The product is manufactured and/or assembled on the basis of a customer order, and the customer considers it a product made to order. Sales operations become more difficult compared to standard products, as the product configurations must be flawlessly performed. This naturally also increases costs. Delivery times may be delayed in comparison to standard, ordered products, as each product instance needs to be assembled or even manufactured to order. In most cases, the possibility of keeping a storage for ready-made products or a storage for the distribution channel is removed.

If final assembly is easy or it can be made easy, it can sometimes be moved to the distributor or even the customer. In this case, the delivery times are not necessarily increased. For example, some patient monitoring systems apply modularity so that modules performing different measurements can be added as plug-in units. In such a case, the local distributor can perform the assembly in addition to the factory. Even the customer can move modules from one device to another.

Standardization

Configurable products support standardization, as was the case when shifting from project products. When shifting into configurable products, plenty of commonality is naturally created between the variations. These very advantages could also be reached via designing corresponding stand-alone products at one go.

Image

Configuration usually requires a differentiation strategy of the former provider of standard goods. On the image level, this must be related to flexibility and/or products that meet the customer needs exceptionally well or achieving the sense of individualized solution. This may be used to justify the longer delivery times and higher prices.

Manageability

Management of the configuration models is a new and demanding task. This means more work for the product development process. The keeping configuration models up-to-date and providing the necessary training for salespersons are also challenging management tasks. On the other hand, the lacking culture of customer-specific configuration is a benefit: salespersons are no used to being able to promise drastically customized products, as is the case when shifting from project products.

Manufacturing, or at least the assembly processes, and usually via this also the data systems must be able to manage the customer-specific product structures and product instance named to a specific customer, and to convey the necessary delivery specific information. This causes changes in the methods of operation and possibly also in the data systems. A need for managing the product deliveries as individuals ("As Configured", "As Delivered", "As Maintained") is created.

Some of the differences related to the specific market areas can be controlled via configurable products so that properties corresponding to the different markets are separated in their own modules, of which the most suitable ones are selected.

The decreasing of invested capital

It is possible that the capital invested to inventories is reduced, as big finished product storages are minimized or eliminated. At least final assembly is only performed to order, in which case it is sufficient to store a set of modules of which the customer's product instance is assembled. Typically, there are fewer modules than end-product variations, and individual modules are cheaper than the end products.

Competing with properties, not price

Configuration enables differentiation with product properties instead of competing with price. For some companies, this enables specialization and moving out of the mass market. An improved seeing to customer needs and specialization via it are the most important factor to justify shifting from standard products to configurable products.

6.1.4. The effect of corporate-internal views on the product and configuration

It is well known that the various corporate operations such as sales, production, and manufacturing do not share views to the product. This is particularly apparent in the manufacturing of configurable products. The modular division in the product and the support systems to be used define which function is most burdened by the stress caused by configuration, and in what form the stress emerges. The following presents the views of the various operations on a general level. All the observations presented do not necessarily apply to all products, but a number of discrepancies are based on the order-delivery model and the product life cycle, which means that they can be generalized. These are also discussed in [Lehtonen & al 2003 (2)].

The advantages and disadvantages of sales

Sales naturally consider customer-specific operations important. For this reason, offering alternatives is a good solution – especially when shifting from standard products. Sales, however, do not favour systematical configuration, as it restricts alternatives. An added value is brought about by systematical customer-specific configuration if standard products were offered previously. In other cases, advantages must be found in the price, the delivery time, the delivery reliability, or easier sales operations. The company must be able to explain to the customers the diminishing flexibility caused by the shift from standard products to systematical configuration. The division of the product is seen as following the functions desired by the customer, as ***function-based modularity***, which may lead to a conflict with production (cf. the domain theory in section 3.3.).

Savings from design

Systematical configuration minimizes the need for routine design and thus releases resources for product development. At the same time, product development and the delivery process can be separated, which simplifies the operations and the responsibilities in the delivery. This sets increased requirements for documentation, and product development becomes more challenging. Similarly, the requirement for discipline increases, the designs must be reusable and thus also to be understood by others than its creator. Modular product architecture reduces alternatives and may lead to stiffening. This is particularly true when using a closed modular system.

Threats to production

Production often needs to patch things up for lacking flexibility when delivering configurable products that are not very configurable in reality. This often leads to a negative attitude towards configuration. The configurable product paradigm may, however, also lead to streamlined production. the most important effects may include the limiting of the number of different components, the routine production of variations, and the elimination of design work and fitting on the floor of the assembly hall. Production hopes for **assembly-based modularity**, which may lead to a conflict with sales. To conclude, we must bear in mind that variation does not facilitate production. Production profits most from as late variation as possible.

The view of after-sales and service

The weight of the view of after-sales and service varies according to the nature of business environment. In traditional, production-oriented operations, it plays a lesser role. The importance is defined by the related interests in the sales, renewal, and maintenance of used products. In some applications, the operational safety limits to be achieved or the requirements for use may also play an important role.

To facilitate service, each component could be a surface-assembled module. Testability and the diagnostics requirements guide services to support function-based modularity. On the other hand, reparability and replaceability would require assembly-based modularity. For service, an ideal systematically configurable product applies modularity according to Ulrich's ideas (see Chapter 5).

6.1.5. Conclusions of the configuration as business paradigm

As can be seen from the above, configurable product paradigm brings whole new dimensions into modularity. As was mentioned, a *platform-based modular product structure* supports configurations. In the following, we will proceed to examine the platform. **In Chapter 8, ”A theory of the development of modular product structures”, we will revisit these issues and discuss how these models of business operations ought to be understood in the context of modularity**.

6.2. DIFFERENT PLATFORM TYPES

Platform based product is another model of business operation that can be associated with modularity. However, we must bear in mind that a platform is not necessarily based on modules. A product platform may be set-based, consisting of a set of components, or assembly-based, as presented further in the text.

Again, it is interesting to examine whether product platforms have existed already before they have appeared in publications and papers within research. Knut Asland feels that this is the case [Riitahuhta & Pulkkinen 2001 pp. 39-48]. Asland presents examples from the US vehicle industry and, in particular, General Motors in the 1950s. At that time, the General Motors Group, following the ideas of Harley Earl, raised vehicle design as the most important issue. Comfort came second in the priority, and the key element was the use of automatic transmission. Other issues related to technical design were much less examined. [Wagner 1997] This lead to an increasing common use of technical components in the various makes of cars owned by GM: Chevrolet, Pontiac, Oldsmobile, Buick, and Cadillac. An important factor was also the knowhow and understanding of the principles of mass production and on applying centralized and decentralized management in a big organization, acknowledged at General Motors as early as in the 1920s [Sloan 1963]. If, however, we consider here that the reason for the common use of the technical components was that companies were not willing to use precious development work on such issues, we can state that calling the case a platform would be looking back in hindsight. Also, common use of technical components was implemented to a rather small extent – the vehicles had a number of elements based on the same design but differing in minor details.

A method of operations that comes close to the platform approach already existed decades ago. The method called group technology sought to design a product range of elements assembled by using similar working methods. The purpose was to boost production and save production costs.

Plenty of discussion on platforms has taken place in research. However, a general set of terms of definitions have not arisen. A good summary on the issue is Arnar Kristjansson's summary on the definition of a platform in the various sources [Kristjansson & al 2004]. Kristjansson seeks to chart the area by classifying the aims of the platforms on the operative-strategic axis. Similarly, he divides them into those with a narrow scope (component platforms) and a wide scope (comprehensive approaches). The platforms presented spread around the area examined, as shown in the figure below.

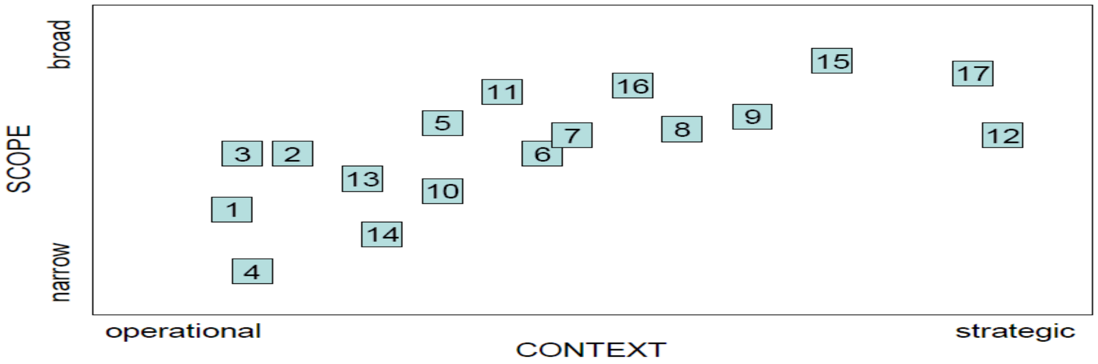
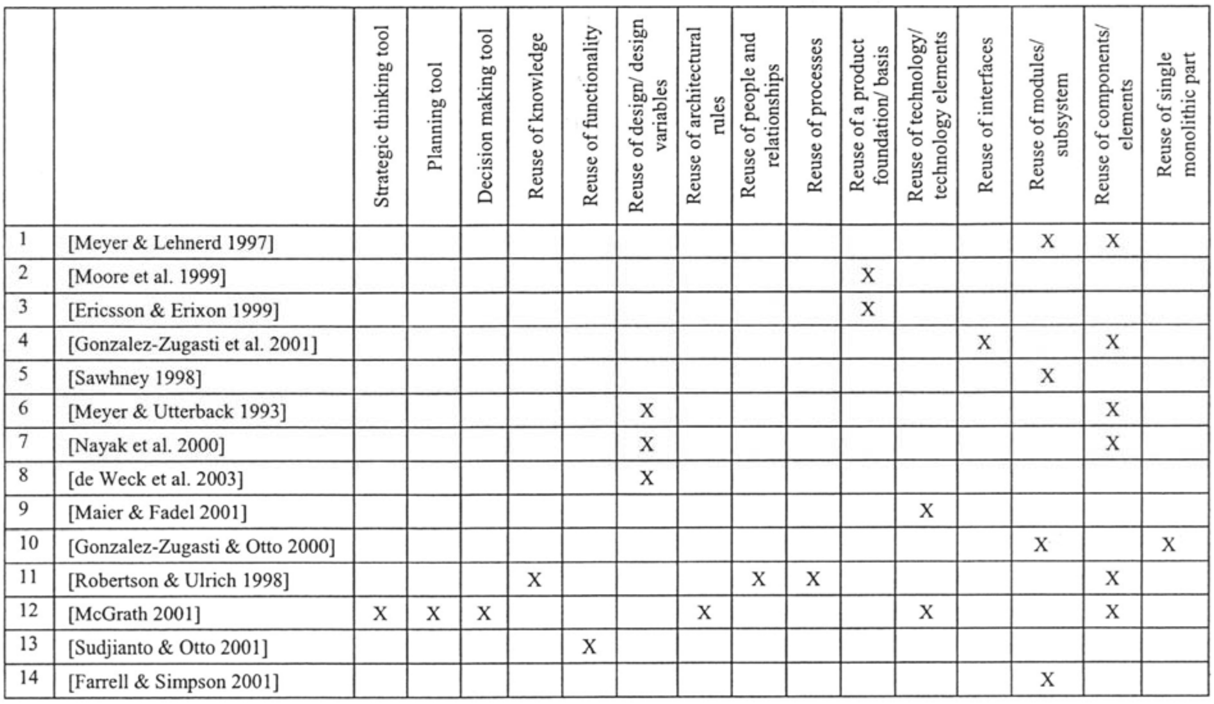


FIGURE 60. When examining the scope of the use of platform (the scope under review being that of components -product ranges) and the importance of the platform to a company (operational, for example, as the one applied in purchases; strategic as the grounds for partner selection in a

corporate network), we find that the definitions and the application spread to cover such a vast area that it is not relevant to think of an individual phenomenon here. A list of cases is in the original source. [Kristjansson & al 2004, conclusion by the author].

A host of views, differing in aims and scopes, exist in research literature on the issue of platforms. Kristjansson summarizes the definitions of the methods presented in the figure above in a table as follows:

Table 2: A summary of the definitions of platform within research [Kristjansson & al 2004]. (Some semantical considerations in the original paper have been removed from the table)



		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		

The same spreading of views is also seen in the general definition for a platform, formulated by Kristjansson:

” A platform is a collection of core assets that are reused to achieve a competitive advantage”

On the basis of research literature, we can thus state that platform is related to *design reuse.* Outside this definition, alternative views are found aplenty. For this reason, it is reasonable to explain in more detail what is meant by a platform in this dissertation and how it is considered to affect the delivery process and via that to the business operations.

6.2.1 Platform

Platform is a word used in many meanings and to refer to a host of different things. At its most modest, platform may be an elaborate name for systematic standardization. In such a case, a platform refers to the set of elements presumed to be the basis for the product. This is sometimes also called the component platform. A more advanced platform consists of assembly or functional modules. Differences also exist depending on whether the elements in the platform are design bases, ready-made modules, or something in between. A well-functioning platform enables assembling product instances to be delivered to the customers via means of systematical product variation (configuration) from the ready-made modules on the platform according to the existing product architecture.

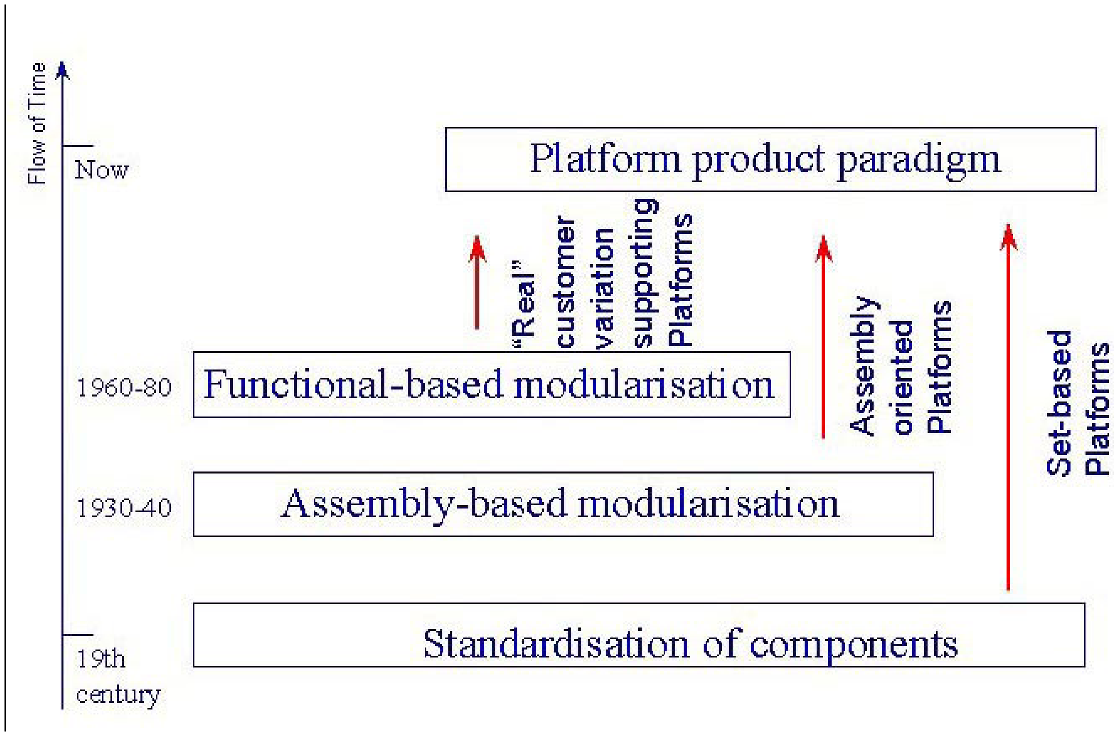


FIGURE 61. A platform can be formed on a variety of bases. At its simplest, it is used to refer to a standardization of components that is organizationally controlled (set-based platforms or component platforms). The flow of time on the left indicates the time when related ideas were developed (and not to their introduction in the industry).

6.2.2 Platform way of working

Should the definition of the actual platform be vague, platform way of working can still be defined unambiguously. The figure below indicates how reuse takes place in design in parallel and successive projects (according to Jandurek).

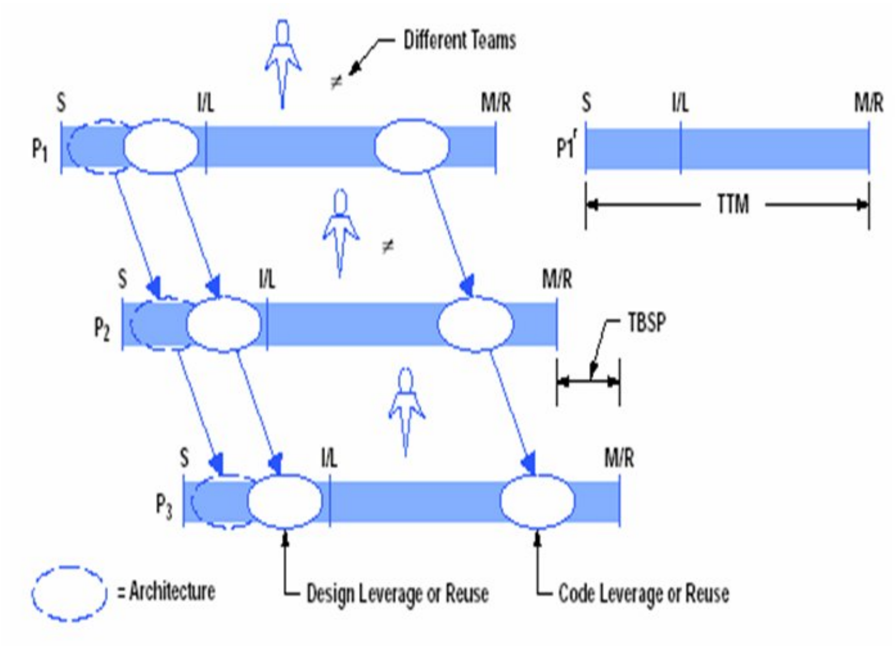


FIGURE 62. In serial delivery, reuse takes place in design, but it is not handed over to following projects. [Jandurek 1996]

The solutions applied in the first delivery of the series are reused as possible in the following deliveries. The success of this depends on, among other things, whether the team of implementors has remained the same or whether the implementors have changed. In successive deliveries (a product series), the rate of reuse may rise high. This method of operation, however, the solutions are designed only for this particular series of products (in the worst case, the first product only). They are not necessarily very reusable (design for reuse). In addition, the design is freely configured every time it is implemented, which means it is not necessarily the same as in the first product of the series. There is no version management, unless it is a question of an entity handled itself as a ”product”. There is no organisatory arrangement to convey the design data as the initial data of the next project, unless it is conveyed by the participating employees. No matter how many the repetitions, a platform is not created as such on these premises for the reasons stated above.

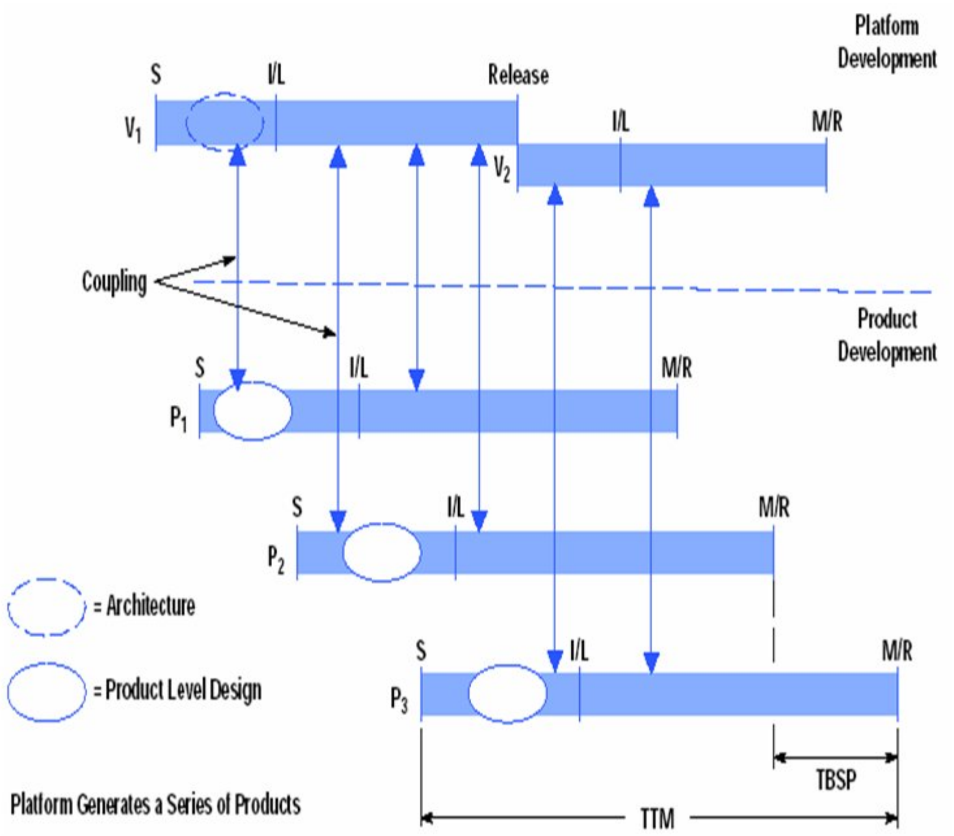


FIGURE 63. In a platform method, there exists an organisatory organ that controls design towards design for reuse and offers the existing design data as design by reuse. Version management can be implemented, for example, by dividing platform data into versions [Jandurek 1996].

In a platform method, design reuse of organisatorily controlled. Design data may again be data on component selections (standardization), design bases, ready-made modules, or everything in between. What is essential is the fact that there exists a method of operation which is used to accept data as part of the platform and design is controlled towards utilizing the existing design data in the platform as much as possible in the deliveries and, in new design, towards being fit for use in a number of deliveries. The platform method is visible in the organizations, in the instructions for design control, in the arrangements of the product data management, and eventually in the attitudes of the designers. Shifting to the platform philosophy and retaining the previous method of operation is a challenging task for an organization. These issues are discussed in a greater detail in [Lehtonen & Juuti 2002] and [Lehtonen & al 2004].

6.2.3 The effect of design reuse

The business and product structure strategy called platform can be used for a number of purposes. For this dissertation, an important goal is the shortening of the time-to-customer via design reuse and the cost savings in the delivery. In the following, we will examine the study conducted in the electronics industry on the effect of the platform.

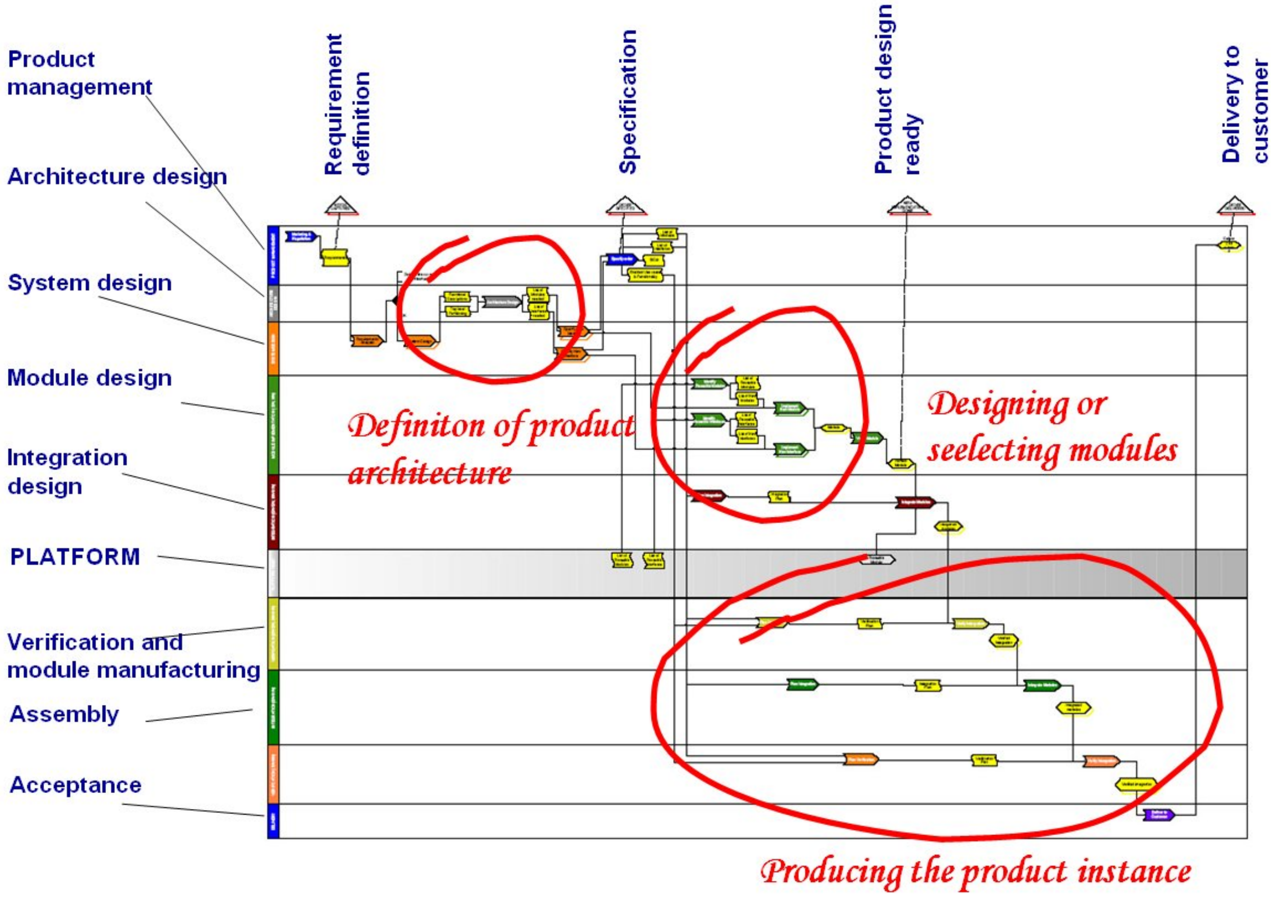


FIGURE 64. An example of the phases of a delivery process of an electronics product. Time runs from left to right. The tasks are divided on the horizontal rows according to the type of design task, which is not relevant for the scope of this dissertation. The milestones of the delivery are indicated as triangles on the top.

The figure above describes a process in which a project product is delivered to the customer and in which design reuse is not much utilized, let alone the production of a new product instance via means of systematical product variation or configuration. However, the figure shows a platform, as the platform method may support reuse in a wider or a narrower frame. In its narrowest sense, platform refers to a collection of individual components that supports the purchases (the so-called set-based component platform mentioned earlier in the text).

When shifting towards increased design reuse, the product can be delivered on the basis of a generic architecture, in which case the delivery time-to-customer is shortened by the circled ”definition of product architecture” task. If the level of systematical product design is achieved with the product, the entire ”module selection/design” section changes into a routine selection task. The effect on the delivery time follows the figure below.

FIGURE 65. The delivery process of a delivery carried out as a project product compared to a delivery process carried out via means of configurable product paradigm.

In this case, real calendar time in the delivery is in proportion to the shortening of the schematic diagram. The most important changes are:

- Time from the definition of requirements to specification was eliminated.
- Time from product definition to manufacturing definition was also slightly reduced.
- In this field of industry, the effect on costs equaled that of time.

Delivery time as experienced by the customer was reduced, as a large part of the product existed at the time it was sold, as shown in the figure below.

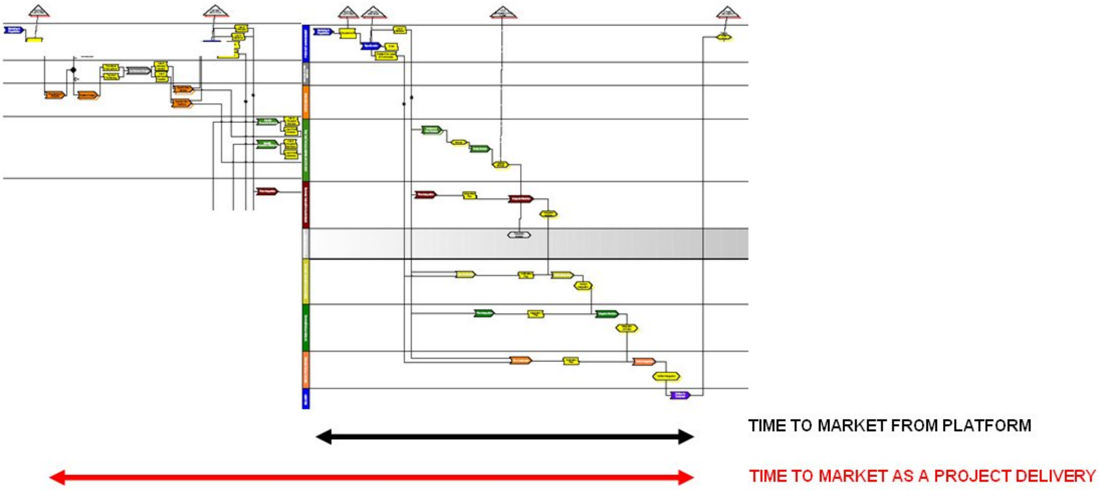


FIGURE 66. In this case, design made before the moment of order is utilized, which means that some of the process phases are removed from the time-to-customer delivery time.

To summarize, the main features of a platform that aims at design reuse can be listed as follows:

- In the platform method, the delivery is much more ready-made at the time of ordering than in the project design phase.
- The important time-to-customer is shortened.
- In the first delivery, the design in the platform is made just before delivery and it does not affect the real amount of work or time.
- The first delivery is rapid but not cost-effective.
- The real cost advantages of the platform show in the second delivery.
- The more the platform is used, the bigger the financial gain.
- We are not talking merely savings in the design. Repetitions boost the operations throughout the process.

6.3 Summary of the models for business operations and modularity

Two models for business operations were presented above that are strongly bound to modular product structures. In a number of sources, for example, the properties of configuration are presented as general properties of modularity (e.g. Ulrich, Pahl & Beitz). They cannot, however, be considered as general properties of modularity, as modular structures can exist without configuration and a platform, and, with certain limitations, vice versa.

Modularity, as it appears in these methods of operation, can be regarded as modularity of a special type. This idea will be further developed in Chapter 8 in connection with the development of modular product structures.

7. How to define modularity?

7.1 Modularity aiming at configuration, the definition of M-modularity

As was explained above, various types of assembly or system element can be called a module. In this dissertation, however, we cannot draw conclusions or estimate the value of the results unless we delimit the scope of the work. For this reason, we will define what is meant by a module in this dissertation. The definition is based on the following fundamental premises:

1. The idea of modules as blocks is generally accepted in the field, and it serves as the starting point already in Borowski's Baukastensystem. The existence of interfaces is also a prerequisite for being able to examine the independence of the modules. Therefore, we must start from the assumption that a module has an interface.
2. In European research, Borowski's Baukastensystem is often regarded as a starting point for modular structures. With this, our definition will include a requirement of a module belonging to a modular system.
3. The type selection of the meta-models of Borowski's Baukasten systems is based on the idea of constructional elements of two sizes. As was stated before, this refers to selecting a two-level solution level, which would be an arbitrary solution. For this reason, we ought to select the types of interchangeability (Abernathy-Utterback-Ulrich) occurring in the US research on modularity as the basic types of the modular system instead of Borowski's models.
4. We cannot proceed any further than this in the definition regarding the industrial history of modularity as a starting point (Chapter 4). In actual fact, even including Borowski's requirement of interchangeability excludes a couple of industrial examples.

As we see in the fourth premise, the definition does not apply to all possible modularity but only modularity that involves configuration. Of course, it would be most systematic to stop using the standard-language word "module" altogether. In his previous publications, the author has called the modularity to be defined in the following "M-modularity" and the corresponding modules M-modules, in which the letter M refers to the Finnish word for configuration, *muuntelu* [Lehtonen & al 2003]. On the other hand, there is no contradiction between the definitions of M-modularity and the standard-language term. M-modularity only separates the subset of issues generally understood by modularity, which means that M modules are always also modules as understood in standard language. Hereafter in the text, we will not divide modules into ”ordinary modules” and M-modules. The hypotheses and conclusions presented by the author automatically refer to M-modules. When discussing previous research and the industrial examples, it is mentioned to what extent the modules presented correspond to the definition of M-modularity.

In M-modularity, a module is defined as follows:

A block (any assembly of the product or part of the system) is a module if it has an assigned interface and it is a part of a modular system.

In the definition, a modular system is defined as follows:

A modular system is a system consisting of blocks which involves the interchangeability of the blocks.

Interchangeability refers here to the use of interchangeable modules in the same place, the use of one module in several product variations, or using a bus-type structure or a structure with a free layout. The interchangeability types of Abernathy-Utterback-Ulrich are accepted as the definition of interchangeability.

References also exist in which the modular boundaries are presented as movable or the modules overlap in part in the system. The starting point of this dissertation is that *a modular system only has modules on one level*, that is, modules do not consist of modules. This is not the case in, for example, large system products. In such situations, however, it is a question of having a number of modular systems on different levels in the product. The cabins of a ship may be internally modular, but they show as one module in the overall modules system of a ship. In principle, it is possible that the same lamp module occurs in the cabin and as an independent module elsewhere on the ship. This is not, however, a good method for building a data model, as the hierarchy is nor unambiguous after this. If, for example, a lamp is the only part of a cabin that is also used in the module system of the level of the entire ship, how is the cabin module described: a cabin inclusive of a lamp module, or a cabin exclusive of a lamp module and with a rule that it always comes with a lamp module. What if we replace the cabin lamps by ones that are not used elsewhere on the ship? Now we have two different cabin modules that behave differently in the data model: a fully-equipped cabin and a cabin that requires a modular lamp. We will not discuss this problem in any more detail in this dissertation: it suffices to state that the module systems to be discussed are one-level Borowskian Baukastensystems that only exist on one level of examination (Auslösunggrad) at a time.

According to Borowski's view, the purpose of a Baukastensystem must always be to have a set of various assemblies (in this case, products) that carry out a certain set of functions. The configurable products paradigm, a model of business operation that is strongly based on modularity, also contains this idea. It is, however, not taken as an absolute indication of a module in this dissertation, as modular structures have also been manufactured for other reasons in industrial history. Therefore, it is not justified to exclude these cases from modularity, as even the theoretical grounds for this are poor, as was proved earlier in this dissertation.

7.2. Modularity related to the life cycle of the product (non-system-based modularity)

Some industrial sample cases introduced in the examples of this dissertation remain outside the definition of M modularity. In these, modularity is related to the life cycle of the product – not the configurations of the product range. Three type categories can be detected of such *life-cycle-based modularity*:

1. Modularity based on reasons of manufacturing
2. Modularity based on reasons of maintenance
3. Modularity based on logistical reasons

An example of modularity based on reasons of manufacturing is presented on pages 25-26. It is a case of German submarine yards in which a standard-model submarine was divided into assembly modules for decentralized production. After the manufacturing phase, modularity was not utilized in the product. This case is shown on the top row in the figure below.

An example of modularity based on reasons of maintenance is presented on pages 26-27. It is a case of the ”Dash-2” locomotive series by the Electro Motive Division in which the usability of the locomotives was increased by grouping critical electrical steering systems in replaceable rack-type modules. This case is shown on the middle row in the figure below.

We will discuss modularity based on logistical reasons in connection with the industrial example of a passenger ship in Chapter 10. An example of this could be the interior design of a ship restaurant to be implemented at Merima Ltd: it is constructed and even assembled in part at the production facilities of the company. In the next phase, the entity is disassembled to be transported in modules and delivered to the ship with assembly instructions. Finally, the restaurant is assembled in the desired location on the ship, which is performed rapidly and with a small number of people compared to actual on-site construction (for more information, see [Taneli 2007 p. 73-75]). For example, pipe systems and pump houses for ships are delivered in a similar fashion. Entire process plants have also been delivered in this way. This case is shown on the bottom row of the figure below.

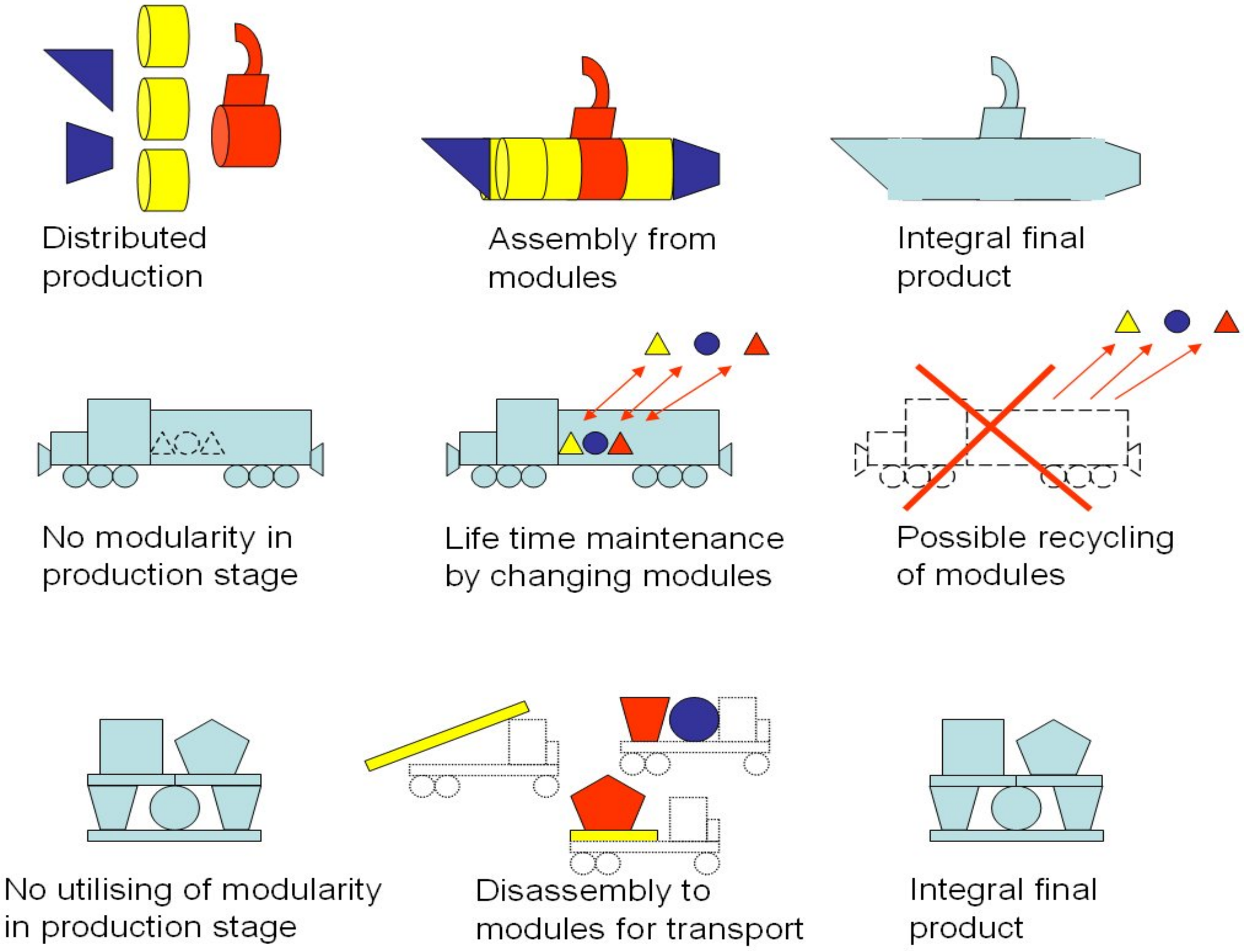


FIGURE 67. Types of life-cycle-based modularity: modularity based on reasons of manufacture, maintenance, and logistics. In the figure, the modules are indicated in bright colors in the phases of the life cycle in which their modular structure is utilized.

These are existing cases of using modularity that are nevertheless excluded from configurable modularity, as they do not feature configuration. This limitation is justified by the different purpose of use. In a life-cycle modular product, there is no variation in the product structure, but the situation is completely static. ***A modular system is thus not needed, and in most cases it does not***

even exist. For this reason, designing life-cycle modularity is a completely different task than designing a product family that contains variation. In life-cycle cases, the mere definition and managing of the interfaces suffices for modularity.

The situation changes if new goals are added for modularity. If, for example, the Electro Motive Division decides to include the updating of the control system modules into using a new technology or including new properties as part of maintenance, the modularity becomes M-modularity. Now we have a modular system (of the bus modular type: a locomotive is a bus) in which both new and old modules fit. Limitations may arise for the configuration, for example, all combinations of old and new modules cannot be used. Similarly, the situation changes, for example, if standardizations are sought between the various deliveries in the sample case of Merima Ltd. If we wish to achieve this via means of modularity, it is no longer a question of dividing the delivery into parts for the duration of the transport, but of creating a modular system that enables a number of variations. (This perspective is discussed in more detail in [Taneli 2007 p. 68-76].)

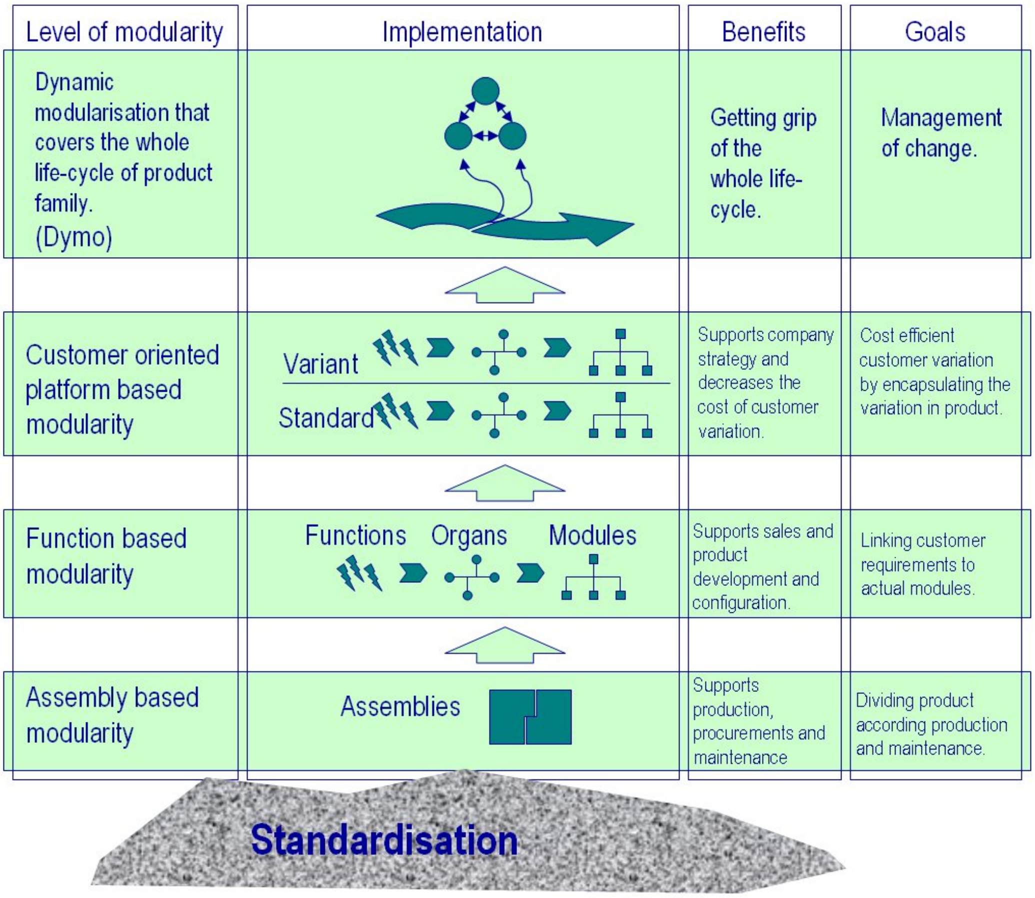
7.3. Summary of the definitions of modularity

The definition of M modularity is thus not arbitrary. M-modularity is system-based modularity that enables product variation. It excludes life-cycle-based modularity that does not enable variation. The design principles of this latter form of modularity are evident (although they may be challenging to implement), which means it is not a theoretically challenging issue for the scope of this dissertation. A function-based structure ought not to be included in the definition of modularity. Its effect has not been generally detected in the empirical data, and it is based neither on a systematical design process nor the creation mechanisms of new design (the order of design decisions, see section 5.9).

8. The theory of the development of modular product structures

In Chapter 4, we discussed the industrial history of modularity. If we compare this history to the theories presented in the research of modularity (Chapter 5), we see that there exists a clear development path in the utilization of modular structures in which the increasing internal structurization of the product has been used to reach ever-growing benefits. The idea of a historical trajectory visible in the development of modular product structures was first presented by the author of this dissertation in 2003 [Lehtonen & al 2003] (also in [Lehtonen & al 2005]). This theory examines the methods and the aims of modularity and sets them in a chronological order. As we find in addition that this order is also the order of complexity, it is well justified to argue that this is a systematical development. Marco Cantamessa [Cantamessa 1998] and Kevin Otto and Kristin Wood [Otto & Wood 2001] have used a corresponding historical perspective in their studies. In these examinations, however, the focus has been on the general design development.

The figure below shows ”The development of modular product structures”. The element at the bottom is standardization that forms an industrial prerequisite for the introduction of modularity. On top of it, assembly-based modularity is presented as the most fundamental form of modularity. In this form of modularity, the modules are physical assemblies. The modular division is often performed from the viewpoint of production or service and to support these operations. A modular division of this type is natural and in most cases easy to implement. It is the form of modularity that has been used for the longest time and in the widest scope of applications.



Level of modularity	Implementation	Benefits	Goals
Dynamic modularisation that covers the whole life-cycle of product family. (Dymo)		Getting grip of the whole life-cycle.	Management of change.
Customer oriented platform based modularity	Variant Standard	Supports company strategy and decreases the cost of customer variation.	Cost efficient customer variation by encapsulating the variation in product.
Function based modularity	Functions Organs Modules	Supports sales and product development and configuration.	Linking customer requirements to actual modules.
Assembly based modularity	Assemblies	Supports production, procurements and maintenance	Dividing product according production and maintenance.

FIGURE 68. A theory of the development of modular product structures

The next development phase, function-based modularity, contains the idea of a design process based on functions that lies at the core of Design Science. However, we can also end up in function-based modularity from the industrial and the business perspective. In a customer-configurable product, configuration often applies to the functions that the customer wishes to carry out with the product. (See section 6.1.4. *The effect of corporate-internal views on the product and the configuration*). For this reason, a natural product division in these cases would be based on the function carriers or functional entities which are very often not assemblies. An old belief on the ”bloating” effect of modularity on the product is precisely based on the belief of forming, for example, assembly modules by adding parts to functional modules. However, this is not the case in the light of our present understanding; instead, the functional module may be a system physically located all around the product that cannot be separately sold or manufactured. Of course, this sets increasing requirements for product data management, but on the other hand it provides strong support, for example, for the delivery of the products to be configured. This division is also closer to the design view of the product, and it also provides support for development of the product and product family during their life cycle.

The product platform approach presented in Chapter 6 is the next improvement in modular structures. All the various platforms are not related to modularity, as discussed in section 6.2. A platform concept related to the development of modularity is a platform that is based on functional modularity. This differs from function-based modularity in that the product is divided into variable elements and a stabile standard element. In this case, this standard element together with the product architecture of the configurable elements form the platform. An interesting question is that of the relative size of the standard element and the configurable element. How big must the standard element be to allow for referring to the formation of a platform? If no limits are set here, all bus modular products are automatically platforms. Also, how large-scale configuration is necessary for the product to avoid the approving of any product including alternative modules as a platform? Otherwise, all products of the ”component swapping modularity” type would be platforms by nature. This dispute, however, is not relevant for the scope of this dissertation, and we can pass it without further definitions.

The platform approach is most often associated with the idea of an open system. In practice, the ”Open system” idea means that new functionalities can be designed and added within the architecture during the entire life cycle of the product platform. As mentioned above, an idea is often not spoken out loud and its implementation is therefore also arbitrary. The idea of including the life cycle of a product in the product platform seems to be the next step in the development of modular structures. Riitahuhta and Andreasen have introduced one theory on this issue in 1998. In their paper ”Configuration by Modularisation”, they define the features of the approach they call Dynamic Modularity. These are as follows:

”Dynamic modularisation is the novel Modular Engineering process, which allows bringing in a dynamic way new more merited modules to the system and leaving out the old ones. This process is based on the definition of the encapsulation, similarities and the description of interfaces as well as modular management system. All different stakeholders’ views should be taken into account; other dimensions will be very similar to those defined for modularisation.” [Riitahuhta & Andreasen 1998]

The idea of Dynamic Modularisation has been further developed, and one model of industrial practice has been presented in 2003 that meets the criteria set [Lehtonen & al 2003]. The key idea in the process is to divide product development on two levels. The collecting and the management of the requirements takes place on the top level. On the basis of this data, a product architecture is developed that is estimated to meet the requirements in the future. This is strategic work. Often, all requirements cannot be included in one architecture, and thus we are forced to select between starting several product ranges or limiting the target market segment. Most of the product development work is carried out in module development projects. The modules and thus also the product development projects are defined on the basis of the selected product architectures. Roadmaps are important tools: they are used to define the types of properties are available in the development area of each module in the near future.

The creation of a product to be delivered takes place on a lower level in the Dymo process. A product project is a process of integration in which the desired modules are selected on the existing module development lines, and thus a product that meets the requirements is created. In the ideal model, no new parts are designed at this stage. This method enables rapid product launches. It involves ready-made mechanisms for managing the life cycle of the product and optimizes the reuse of design. The set business goals are shortening the design time and increasing the productivity in product development.

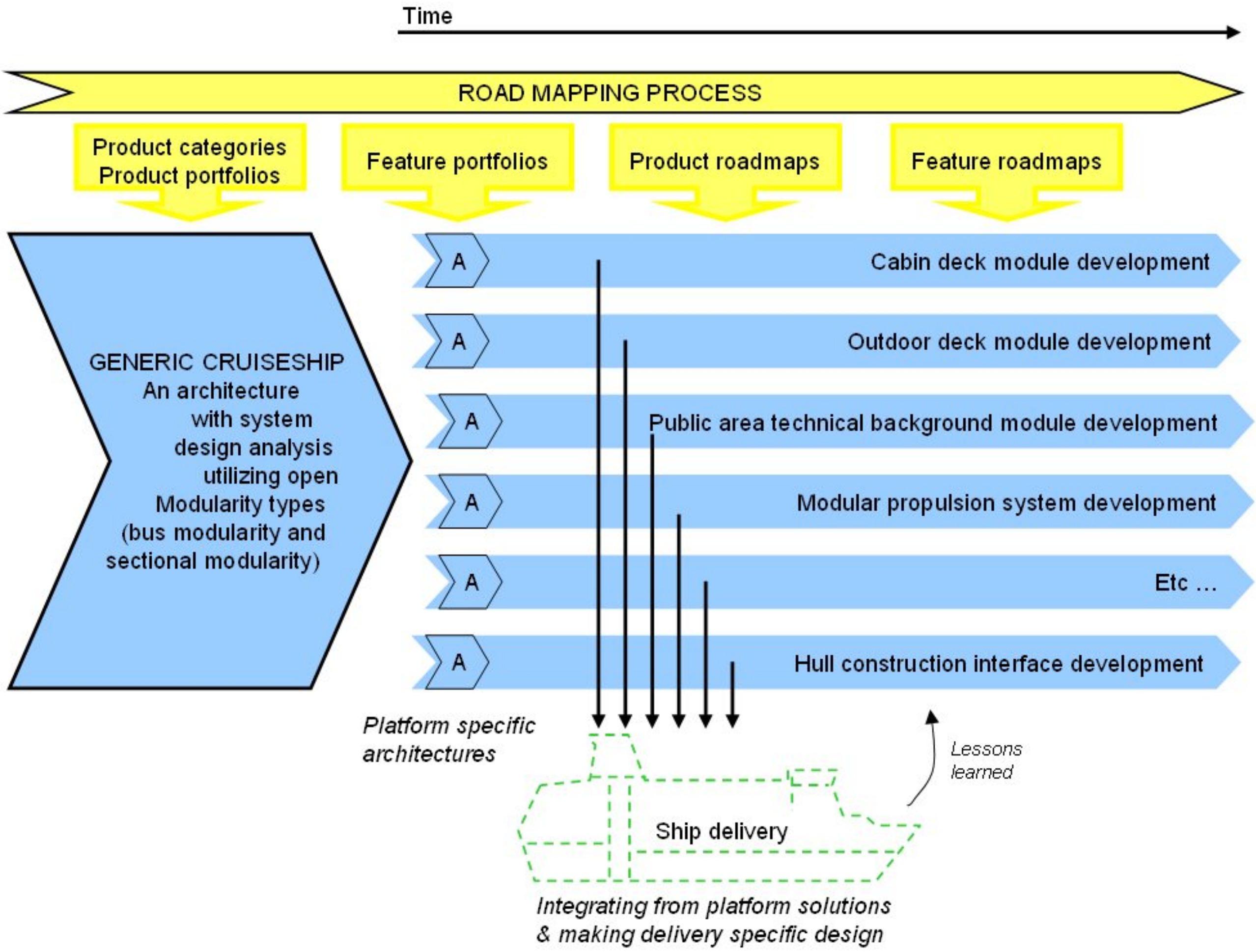


FIGURE 69. An example of applying the Dymo process in the construction of cruise ships

Even though we have presented an example of operations following the Dymo definitions, we can not yet speak of a finished paradigm. It is evident, however, that this is one of the most likely future development steps in the history of modular structures.

8.1 Conclusion on the importance of modularity for Design Science

In the previous chapters, we have discussed modularity as an industrial phenomenon and an object of theoretical development. We have examined models of business operations based on modularity and presented a theory on the evolution of modular structures. This wide scope is, however, only one perspective to the issue, one that is limited by the scope of modularity. The figure below shows standardization as the starting point, which guides our thoughts to longer historical cycles and developments. If modularity is understood as the standardization of design entities, we can set the development of modularity as a milestone in the history of industrial production, as shown in the figure below.

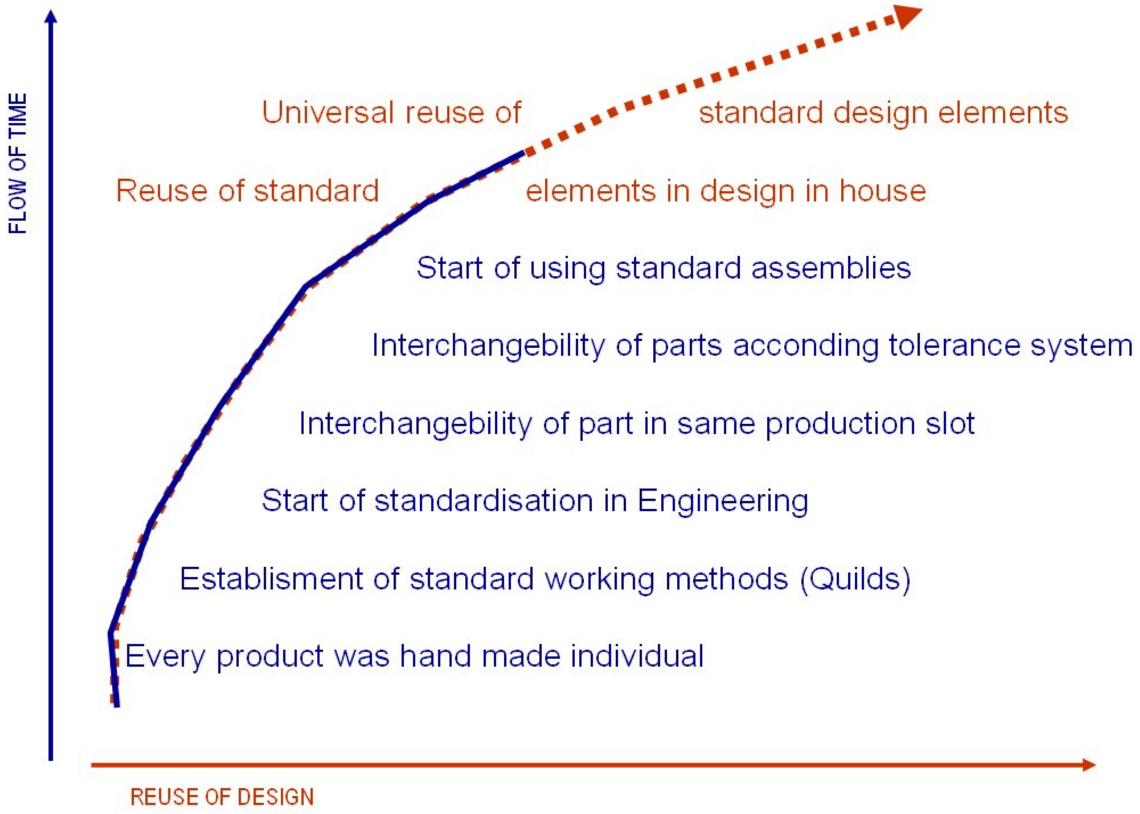


FIGURE 70. A rough sketch of the history of industrial production

From this viewpoint, we can state that the standardization of screw threads at the beginning of standardization in the figure was not only an improvement in the industrial practice, but also an early example of the reuse of design. Throughout industrial history, reusable elements have constantly grown in size and their use has become more varied. According to this view, using modularity will in time lead to the wide use of standard solutions. As the next stage, we could think that a certain type of product architecture might be established for certain products, which would lead to opportunities for using dynamic modularity within that field of industry.

The increasing internal structurization of the product along with the use of modular structures is a direct continuum in the development of industrial operations. Therefore, it can be presumed that in the future the importance of modularity will rise to a self-evident ground level, so that products that have proceeded to a static phase in the technological development are no longer even considered for implementation unless an established, dominant module structure is used. Signs of this have been detected, for example, in computer production. The getting grip of the synthesis of modularity will be the great challenge for the near future of Design Science.

9. A framework model following Hypothesis 2

Hypothesis 2 argues that *the key issues for the division of the module structure arise from the business environment and the production environment, and the relations emerging from the technical implementation ought to be examined only in regard to these product requirements.*

Hypothesis 2 ought to be examined in the light of the *development of modular product structures* presented in Chapter 8. According to this theory, the oldest form of modularity is assembly-based modularity. This is modularity that exists physically in the product. Function-based modularity, presented as the next level of development, corresponds to the traditional design Science view of a modular product. The modular structures are not mutually exclusive, but they often lead to conflicts. According to Ulrich's view (see section 5.6), modularity ought to be define according to how well these two structures correspond to each other. In any case, the two levels are well known in the industry and research. There exist good tools for comparing the assembly modular structure and the functional modular structure, such as the dependency matrix of design (see section 5.7). If, however, we consider the proof of Hypothesis 1, we can question the importance of functionality. As functionality does not clearly point at a certain structure in new product design, is it too highly valued compared to the other reasons for forming modules? If we think of Erixon's motivations for modularity (see section 5.7), would not functionality be the thirteenth module driver?

When proceeding in the development of modular structures to platform-based modularity, we step outside the traditional product structure views. A product platform is a strategic choice for a company, and a part structure examination in the Baukastensystem spirit does not provide any instructions on which parts of the product ought to be standard and which systematically configurable. The situation remains the same on the level of dynamic modularity, only the number of variables increases. In addition to the product structure and the functional structure, the requirement of configuration enters the picture. Theory-based tools do not recognize this variable. Gunnar Erixon's method considers it, but does not seek to describe the synthesis of a modular structure.

Today's technologies provide rather bifocal methods for developing a platform-based modular structure. Methods based on functional structure and the theoretical background of modularity are blind to the important goals on this level. Erixon's Module Indication Matrix, on the other hand, remains neutral on the issue why the selected reasons for implementing the module are important and what is their mutual order of priority.

To conclude, we can state that examining modularity within its internal mechanisms may be barely sufficient on levels one and two of the theory of the development of modular structures (see Figure 68). On level three, it is already clearly insufficient. For this part, the hypothesis thus seems to be valid.

To obtain an overall picture, we must examine the elements in the business environment and the relations between them. Modularity is not related to the product, but it exists in relation to the business goals and via that to the corporate processes, the value chains in the business operations, and the business environment. The framework model to be presented in the following is based on the ideas of researcher Tero Juuti on the status of product structure in the entire corporate operations. The author's contribution to the development of the framework model is that this dissertation is the first study in which a model created as a theoretical idea is refined as a tool which has enabled the description of tangible cases of product structure development (as will be shown in the following chapter).

The framework model – Company Strategic Landscape (CSL) [Juuti & al 2007] – defines the elements related to the product development operations and the production of the company. The figure below shows which relations between these elements are dominant and thus important. In research aiming at the development of operations, measures must be directed to the management of the guiding relations, as these guide the entity in reality. Elements related to funding (investment capitals etc.) are not presented in the figure.

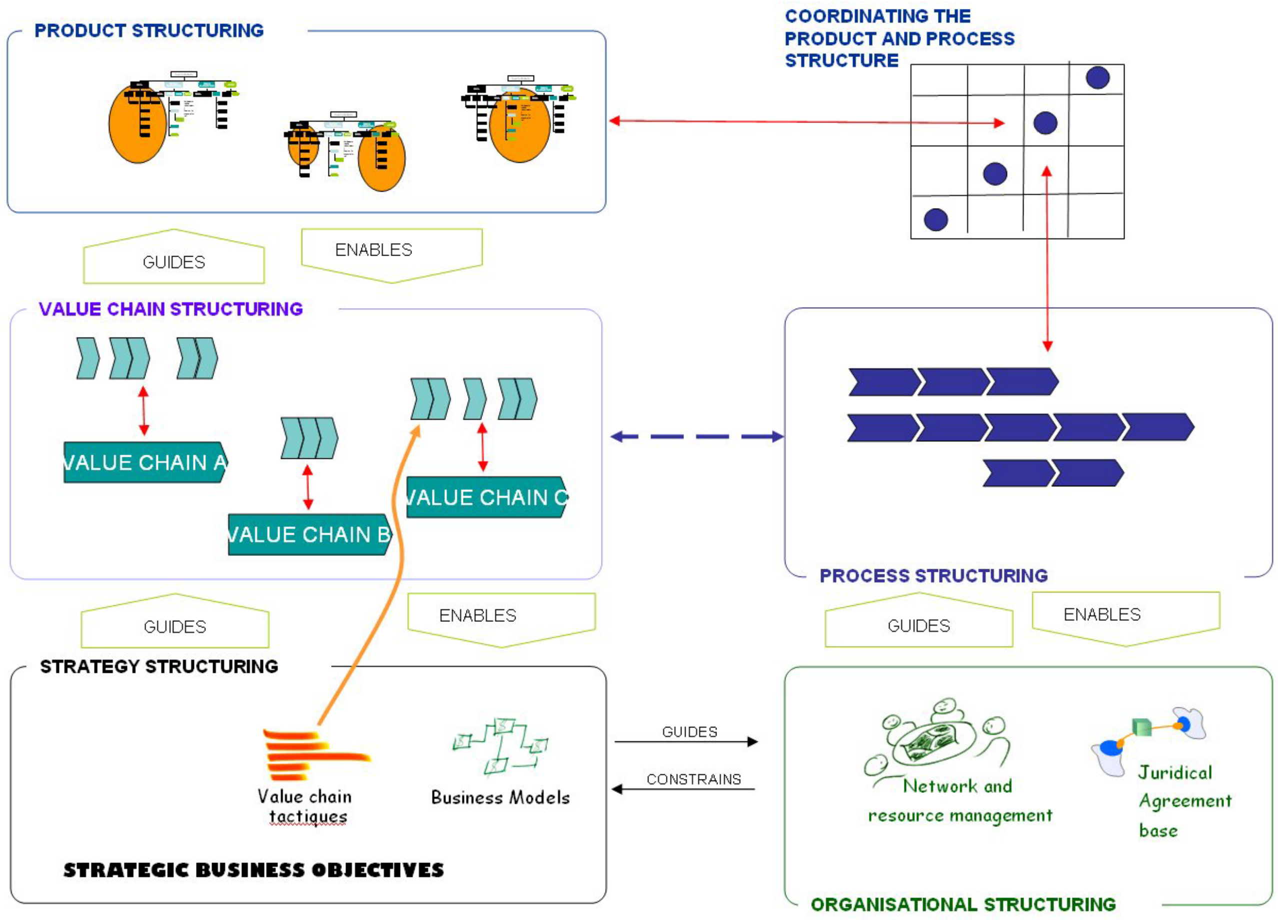


FIGURE 71. In the company strategic landscape framework, business operations are seen as an entity of which, for example, the product structure cannot be separated to be examined and developed individually. The importance of the strategic goals is emphasized and the solutions selected in all areas must support them. In addition, the solutions in the different areas must be compatible and, in ideal cases, support each other.

The CSL-framework model describes the key issue entities for the structuring of the product and the contents of the relations between them. The product structure itself is in the top left corner. In this figure, the ”structure” of the product does not refer to the mere assembly structure and a list of parts, as a product assembled of the same parts may be divided differently from the viewpoint of product structure management. The structuring of the product is guided by a value chain (the structuring of the value chain) in which the product must operate. On the other hand, the properties of the product structure also enable and limit the number of the possible value chains. The value chains, in turn, are determined according to the business goals (the structuring of the strategy).

The sales, design, and production processes of the products and services to be delivered are shown in the middle on the right-hand side. In their background, we can see the structure of the internal resources and the network (the structuring of the organization) and the selected methods (operative interfaces). The structuring of the organization and the business goals exist in a reciprocal guiding and limiting relation to each other.

The key idea in CSL-framework model is the relation between the internal structure of the product and the delivery process. In principle, the product structure and the delivery process can be selected separately and are usually examined one at a time by approving the other as a static background data. When optimizing the operations, these two are no longer seen as separate, but they must be synchronized. The points in the table on the top right corner indicate the product structure/delivery method pairs that are ”good points” or combinations in which the operations are carried out rationally according to the *selected goal*. In the figure, the points are located on the diagonal line merely as an example. As will be seen in the following section, the points do not necessarily form an unambiguous vector – good points are not necessarily found at all. We must note, however, that the ability of the various delivery methods to support the set *goals* differs drastically. Let us interpret the figure: a certain process defines the product structure that supports it. This, in turn, only enables certain value chains that only correspond to certain business goals.

Verification with industrial examples

If the CSL-framework model presented above is valid, the key factors affecting the product structure are the requirements arising from the selected value chains and the ability to adapt to the process models used. This would fall in line with Hypothesis 2. It is not theoretically possible to verify this. For this reason, we will verify it by presenting a number of examples and examining the validity of the argument in relation to empirical observations.

The examination is carried out as follows. First, we will describe the sample case in its context. After this, the grounds for the modularity implemented and the results achieved are evaluated in the context of the reference frame. The dominance of the product functionality in the structure is evaluated. If functionality is not considered to be the most dominant qualifier, we will determine to which area the key requirement belongs. Finally, we will evaluate whether the success of product modularity correlates to the observations made. Finally, we will determine the truth value of Hypothesis 2 on the basis of the material presented.

10. Industrial examples and the proof of Hypothesis 2

In the spirit of Borowski, the following sample cases are not presented as corporate-specific special cases. Instead, we will discuss the eight different industrial products as representatives of their species. We aim to generalize the cases by also examining the operations of other manufacturers when data is available. The criticism voiced previously against Borowski's examples – that they are only valid when using a certain method at a certain time – cannot be fully avoided here, either.

The other research problem is related to the fact that the present dissertation discusses the design process of a new product. Has a new product been developed according to the definition in the cases to be presented? In most cases, this data does not exist. For cases of which we have data, the answer is negative. Are, therefore, the examples relevant for this dissertation? This cannot be proved with a positive argument; we will present a negative one instead. No individual issues can be pinpointed on the analyses to separate them from the context of new product design, *if we define that a market and thus a market situation also exist for the new product*. If we do not accept this definition, the sample case 2 (the truck) must be considered irrelevant for the dissertation, as the Dominant Design on the market emerges among the requirements of the product structure.

The products to be presented are

1. A tunnel drilling rig
2. A truck
3. A diesel locomotive
4. A passenger ship
5. A safe box
6. A machine tool
7. An ambulance
8. A forestry machine

We have collected the sample material from research since 1997. At that time, the Tampere University of Technology conducted a large research on configurable products together with the Sober-IT research centre (called the TAI research centre at the time), funded by the Finnish Funding Agency for Technology and Innovation. In the Konsta research project, we worked in co-operation with 10 companies: Sandvik-Tamrock, Kaso Oy, Tunturipyörä, KCI Konecranes, Ponsse, Valtra, WDPP (Wärsilä Diesel Power Plants), Rocla, Neles, Datex-Ohmeda, and Hydrovoima. The author has become familiar with four companies when M.Sc. theses or teaching research, or development work have been carried out in co-operation with them: Fastems, Kvaerner, Nokia Mobile Phones, and Profile. In the Merimo project carried out in 2004-2007, the author was introduced to the Finnish marine industry cluster. In addition, two sample cases (Scania and Valmet) were included based on the existing material, even though the author has not worked in co-operation with these companies.

10.1. A TUNNEL DRILLING RIG

Research related to the modularity of a tunnel drilling rig was conducted at Tamrock Oy in Tampere during the Konsta research project in 1997-99. The participants were the author, researchers Antti Pulkkinen and Juha Tiihonen and research assistants Sami Järventausta and Jani Malvisalo. Sami Järventausta wrote his M.Sc. thesis on the issue and was given an excellent mark.

During the project, we examined a number of Tamrock product families, but mostly worked with the Jumbo tunnel drilling rigs. A tunnel drilling rig is a mobile machine on rubber wheels the purpose of which is to drill more or less horizontal holes on the back wall of the tunnel as locations for the bursting charge. The figure below shows the process of drilling the tunnel on a hard rock.

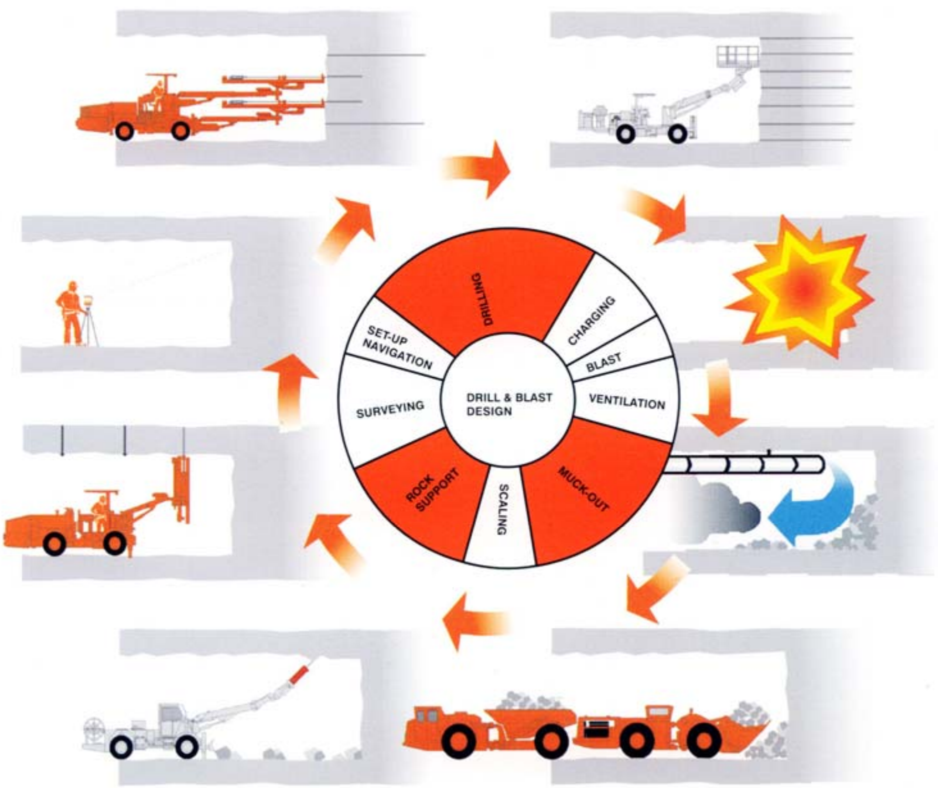


FIGURE 72. A tunnel drilling rig does not drill tunnels but blast holes (the phase on the top left corner). This process is used when drilling a tunnel in a hard rock. [Tamrock 1999].

In different parts of the world, different practices exist on the phasing of the work and on whether the back wall is straight or whether an intermediate level is made. The phasings bring about different requirements for the equipment of the drilling rig. The number of drilling booms in the machines of that specific model line was one to three, and in addition to these, there was the boom supporting the chargerman's hoisting cage. We must further add to these the customer's wishes and the willingness to invest in expensive or more simpler but cost-effective accessories. In addition, the size of the machine also varies considerably and mostly depends on the size of the tunnel to be drilled.

The work process of a tunnel drilling rig is as follows. The rig is driven to the drilling location. The diesel engine in the machine produces power, and the transmission is hydrodynamic. The driver usually steers the machine from the cabin. The rig is steered with a steering wheel in the manner of a normal frame-steered wheel loader, and hydraulics is used to turn the articulated vehicle. In some size ranges, however, there is no frame steering but turning wheels. When the rig enters the drilling location, its outriggers support it. It is attached via a cable to the electrical system of the pit, as the diesel engine is not used during the drilling. The necessary hydraulic pressure is generated with electric motors. This causes variation in the machines, as the electric systems of pits vary considerably even in within one country. In addition to the voltage, also the frequency may vary, which means that the changes in the electrical system are not minor. The booms, the ends of which hold the feeding devices of the drills and the drilling machines, are used via hydraulics. Hydraulic power is taken to the booms via flexible hydraulic hoses that are collected into bunches. During the drilling, the borehole must be rinsed with water. Water comes to the pit from the water network of the mine to which the rig is also plugged. There is a big hose reel for the water hose at the rear of the machine. At the time of the research, the available drilling control methods were a direct hydraulic manual control or several electronic and automatic control systems. The equipments of the machines varied considerably according to the target country. At its simplest, the cabin consisted of an open canopy, and a separate control panel existed for each drilling boom from which three employees operate the machine simultaneously. At the finest, the cabin was completely closed and air-conditioned, and the operator of the machine merely programmed the drilling task into the machine and the task was performed automatically. In bigger machines, it was possible to order the cabin with a hoisting mechanism so that the operator could better see to the location. This option was not applicable for a machine with direct hydraulic steering. The selection of tunnel drilling rig models in 1997 is shown in the figure below.

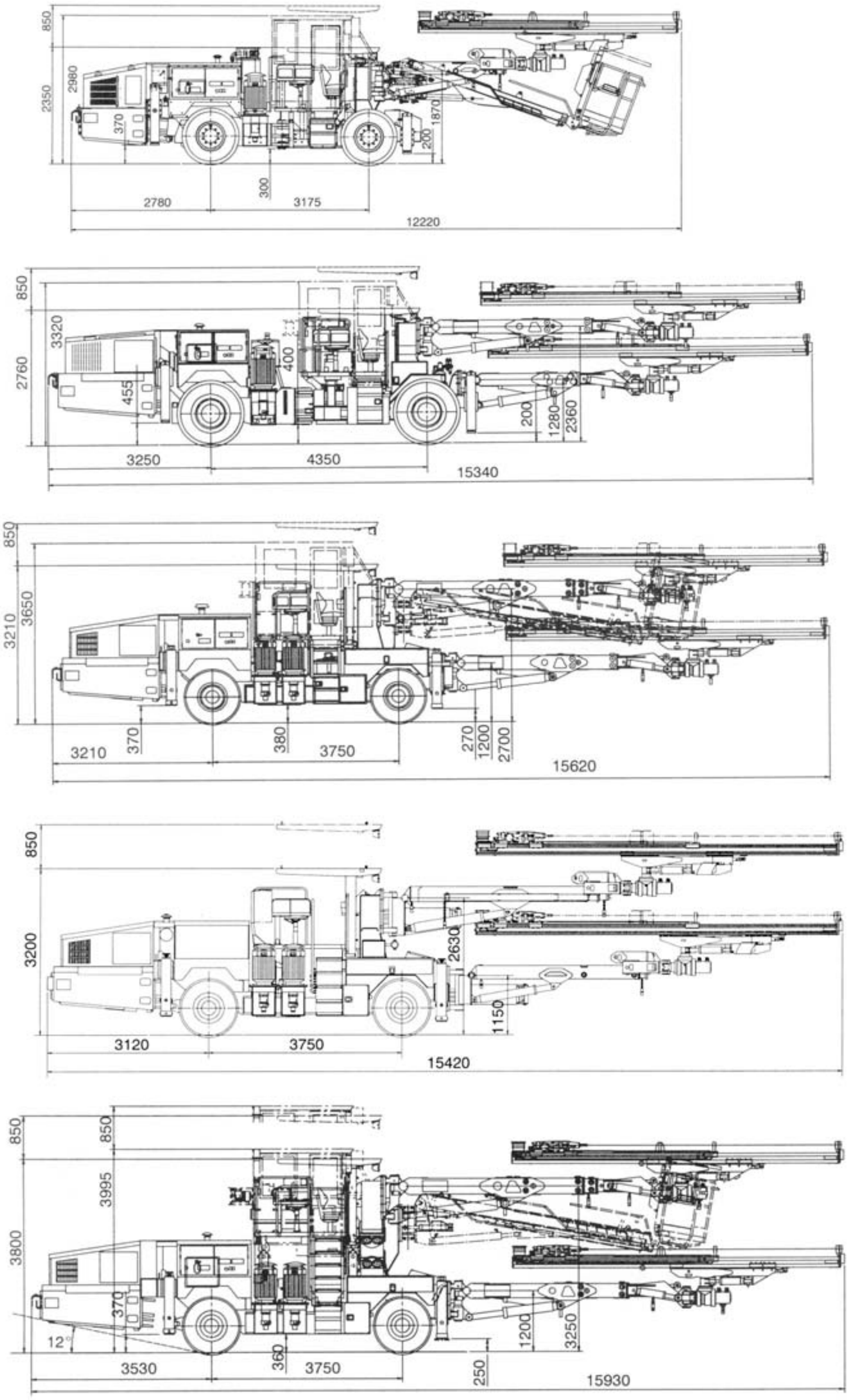


FIGURE 73. Tunnel drilling rigs in the model line of the late 1990s. On top, Mini 206 DB equipped with a hoisting cage intended as the working area of the chargerman. It is followed by Para 316 - 90, Maxi 316-120, Super 316 G, and Titan 316-150. The control system versions are not shown in the figure, but products equipped with an electrohydraulic THC 500 control system acquire the suffix –matic in their name (e.g. Paramatic). Machines equipped with computer-controlled automatic drilling control have the prefix Data in their name (e.g. Datamaxi 316 T). In total, 20 different product versions were available in this product family. [Update sheets to the Tamrock salesperson's folder 13 December 1994 – 8 January 1997]

Thus, there exists a great deal of variation in a tunnel drilling rig even within the basic model line. In addition to the basic machines, there exist special products such as drilling machines to be fitted on a crawler-mounted frame car of a digger, but these remained outside the scope of this dissertation. All machines are order-based, and the production numbers of individual models were not big. The delivery time was often critical in devices to be delivered to construction sites. In these, the way of working involved several contractors submitting an offer for the contract. The contractor invites tenders for the tunnel drilling rig from selected suppliers as the basis of his pricing. An order on the machine is placed only if the contractor wins the contract. At this point, the actual machine delivery is urgent, as the work must be started. In addition, the site manager decides some of the requirements for the machines; site managers are often only hired after the contract is won, which means that the original machine offer will have to be made on an estimate. For this reason, the remaining alternatives for Tamrock were project deliveries or systematical product configuration. Of these, the selected strategy was the latter one, and the purpose of the research was to discover the most economical product structures for this particular method.

In the research, we started with applying functional modularity. For this reason, a functional structure was drawn of the tunnel drilling rig that described the implementation used at the time. The structure was created in a highly pragmatic manner. The figure below features power input on the left and the machine control on the right. The presentation was large in size, and it is not possible to present it in the page format of a dissertation. The figure below will, however, provide an idea of the size of the modelling.

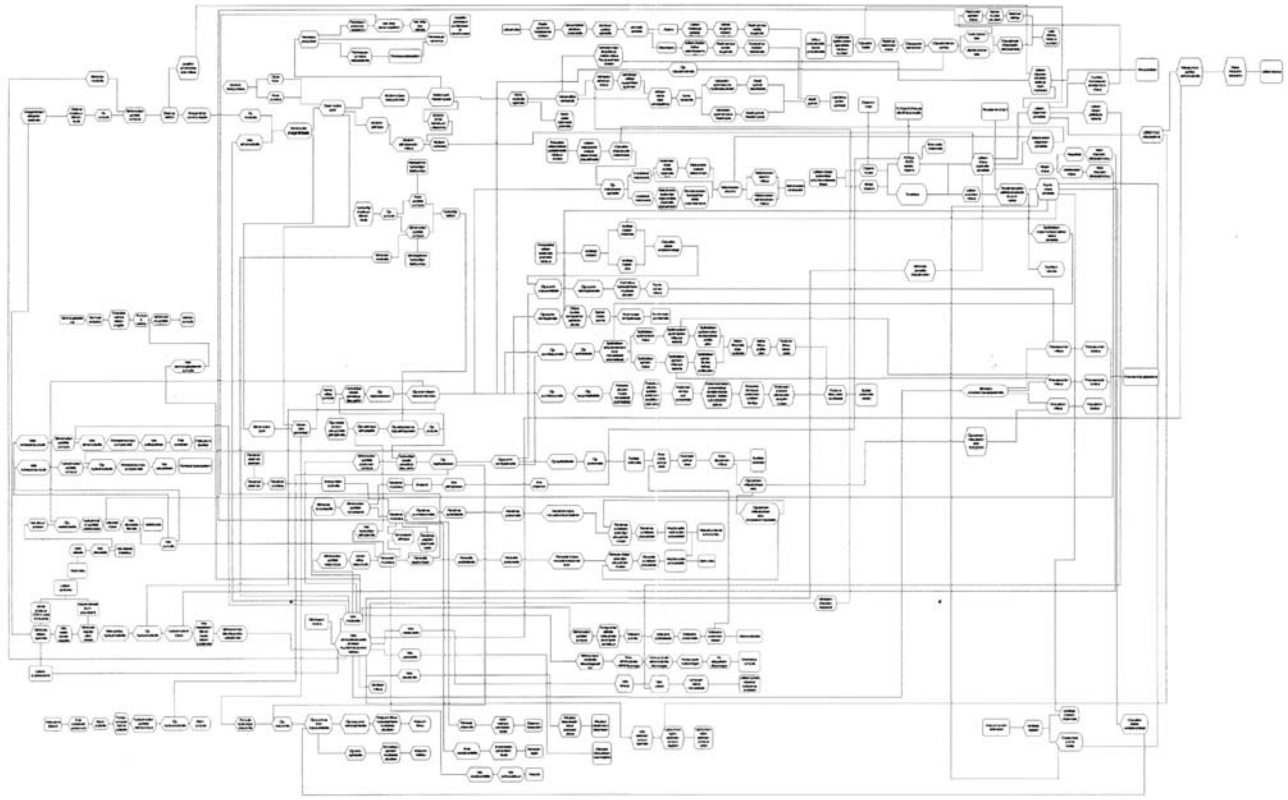


FIGURE 74. The functional diagram of the Jumbo as an "as implemented" model. Power input comes from the left and the machine control from the right. The figure does not indicate the mode of operations, but all functions in the moving and the drilling mode are drawn in the same diagram.

The diagram was used to recognize functional modules. However, the work did not yield results. The modules to be outlined in the diagram could not be implemented in practice in the assembly structure, and they did not yield a necessary level of variation. **This empirical observation is the same that we deducted with the theoretical example in Chapter 5**.

After this, we proceeded with the work by moving on to matrix methods. Due to the large number of variations of the tunnel drilling rig, the first test research was conducted by using a surface drilling device of the Ranger series as an example. This machine that moves on the ground is a much simpler device and the variation it contains is more related to its equipment. The figure below shows the configuration model of the Ranger by using the modelling language originally developed by Timo Soininen and Juha Tiihonen at the TAI research institute, the use of which was further developed in the research project [Tiihonen, Lehtonen & al 1999].

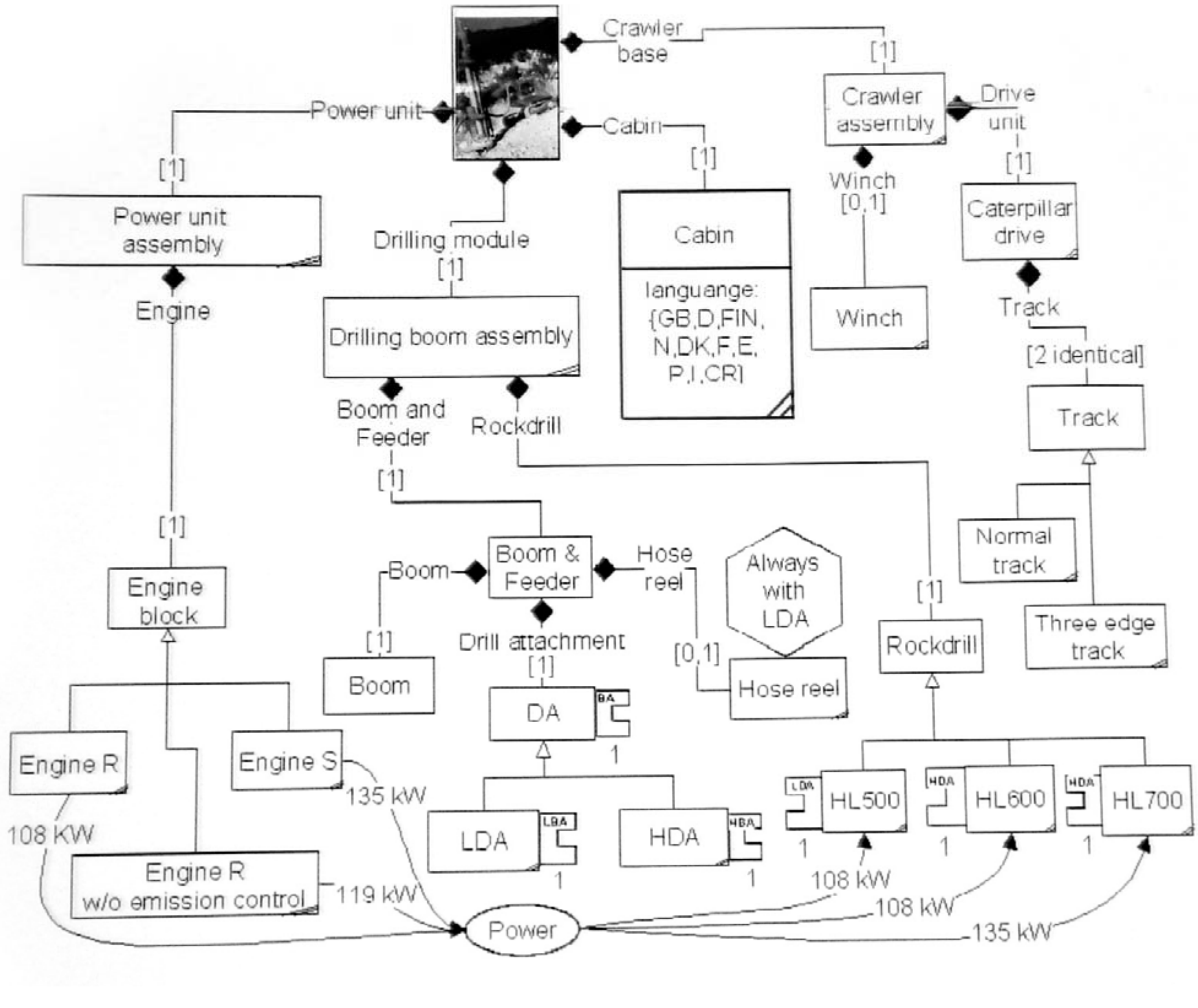


FIGURE 75. A configuration model for a Ranger surface drilling device. The modelling language used in the figure is explained in [Tiihonen, Lehtonen & al 1999], and the goals of the modelling language are explained in greater detail in [Soininen & al 1998].

Slightly over 160 items were listed in the dependency matrix of the Ranger. Their dependencies are shown in the figure below. The matrix is undirected, and the strength of the dependencies is not estimated. There are over 160 elements in the Ranger dependency matrix, and it seems difficult in terms of configuration. There is a host of dependencies with large-scale effects. According to the M.Sc. thesis of Järventausta, ”*We can see in the matrix that the configuration of a product family is difficult to manage. ... The retaining of product specificity in the structure forces us to retain a* *large number of dependencies to achieve unambiguous structure management. ... The matrix has 7,063 dependencies that represent compatibility or incompatibility .*” [Järventausta 1998]

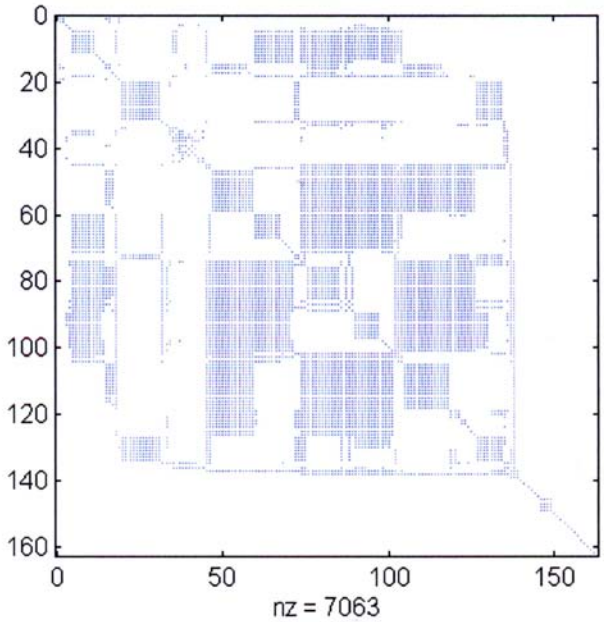


FIGURE 76. There are over 160 elements in the Ranger dependency matrix, and it seems difficult in terms of configuration. [Järventausta 1998 p. 96].

After this, trivial entities that can in any case be added directly on top of the structure were removed from the matrix. These included, for example, country-specific plates and labels. Still, a big submatrix of 101 sub-entities remained in the matrix that contained 3,160 dependencies, which is 98.9% of all the remaining dependencies, as shown in the figure below.

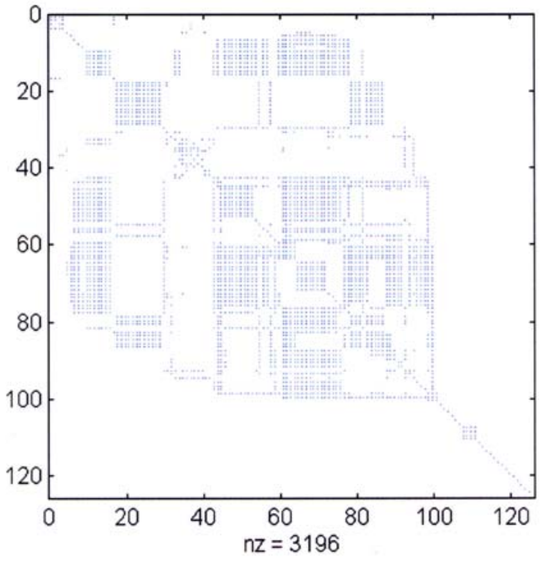


FIGURE 77. The Ranger dependency matrix, when trivial elements for product assembly are removed [Järventausta 1998 p. 97].

We tried to further improve the structure; large elements were divided into smaller ones to tear down the dependencies. A total of 35 new elements were created, and the number of items on the matrix again neared 160, as shown in the figure below.

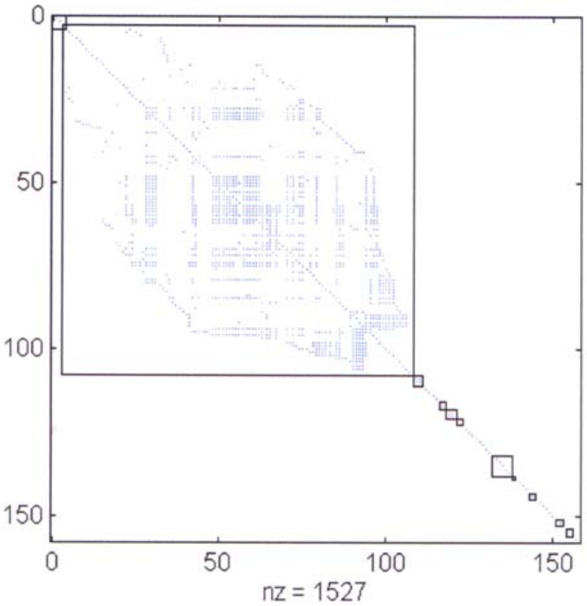


FIGURE 78. A product family specific dependency matrix in which the submatrices are indicated. [Järventausta 1998 p. 100].

As a conclusion, the study said, *"the results presented indicate that basic product dependency is an obstacle for efficient configuration."* The mentioned "basic product dependency" was the term used in the study, referring to a product structure strategy in which the product variation consists of the basic (product) modules automatically belonging to it, and in which customer-specific configuration is carried out by choosing alternative modules and adding freely insertable options. When this approach was discarded, 61 modules were left in the product family, of which 33 are selected directly according to the product family. The final product structure is shown in the figure below:

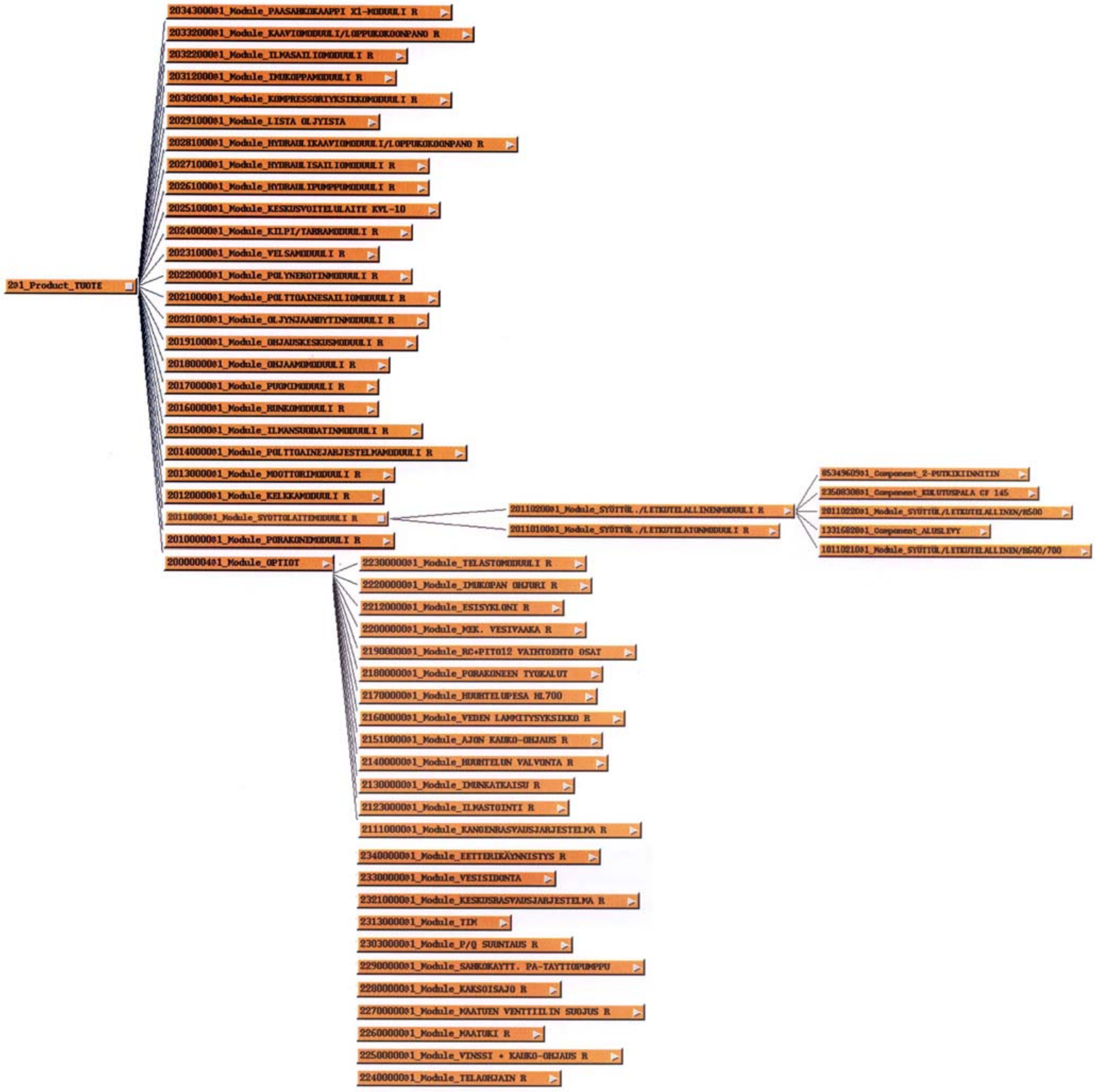


FIGURE 79. The new product structure for Ranger [Järventausta 1998, compiled from pages 114, 116, 117]

The change in the product structure was not estimated as easy. For example, the new divisions did not follow at all the existing draft divisions. Even though results were reached in the case of Ranger, it was stated that ”...*we can, however, estimate that it will be difficult to form other products modelled in a corresponding way.*” This result must be evaluated in the light of the issues discussed in Chapter 5 ”Problems of the matrix methods”.

Next, the author set out to draw an ideal structure for a tunnel drilling rig together with research assistant Jani Malvisalo. Earlier, a rough draft of the modularity had been made with Sami Järventausta. Now, the business goals of the modular structure were determined. The following presents these in the order in which they appeared in the author's notes in 1999:

- As large base-unit as possible (=the standard element shared by all products)
- Configuration as late in the process as possible
- No parametric components as spare parts
- The delivery time must be shortened by enabling the early start of the assembly
- Customer selections on the top of assembly

When analyzing the list of requirements written down in a meeting, we realize that a number of them are actually solution suggestions for the very requirement. In further considerations, however, we noted that the requirements, excluding the item on the type of spare parts, were related to two issues: managing customer configuration and its relation to the phasing of production and assembly. As was explained earlier, these issues were emphasized in case of contracting devices due to the special features related to this trade practice.

Inspired by the article written by Kos Ishii [Ishii & Eubanks 1995], the author developed an analysis method that has later been called the *Late Point Differentiation analysis*. [Lehtonen & al 2001 (1,2)] The initial data of the analysis are:

1. The relations between the sales selections and the modules
2. The order of the time sequence in production and assembly
3. The order of the sales selections (confirmation)

On these basic data, an *Inter-Domain* matrix is created, in which an analysis of the *alignment* type is performed (according to Malmqvist's classification). The sales selections are on horizontal rows in their order of confirmation. The vertical columns of the matrix show the modules in the order of which they are executed in the manufacturing or assembly. The effect of the sales selections on the modules is marked on the matrix. After this, a diagonal line is drawn from the top left corner to the bottom right corner, which represents the progress in the manufacturing of the product. The location and the form of the diagonal line are determined by the time sequence of production, as shown in the figure below.

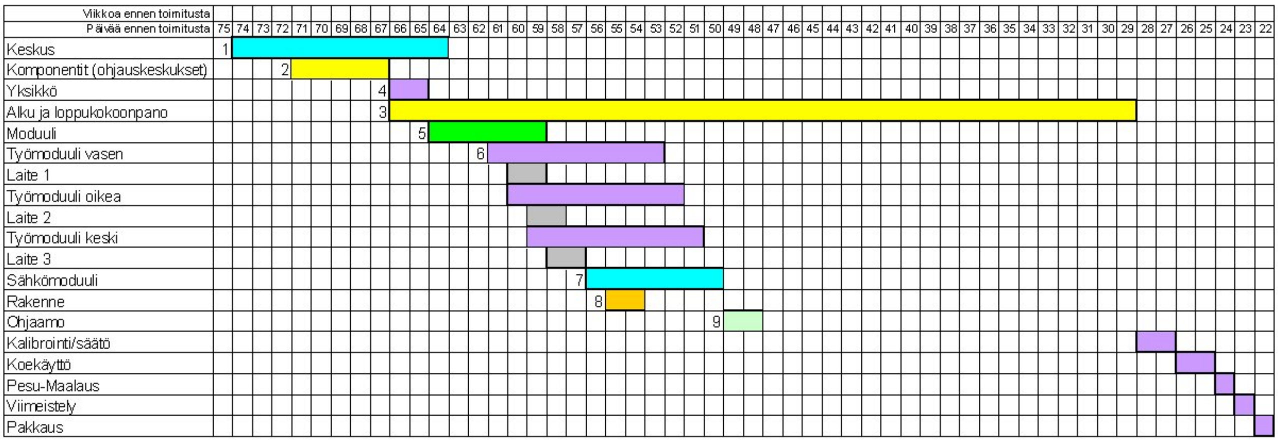


FIGURE 80. The time sequence of production in the sample case. The long, undivided assembly phase caused the long projection in the diagonal line shown in the next figure below.

The final analysis matrix is shown in the figure below. The relations on the left-hand side of the diagonal line are harmless and do not cause problems. The ones on the right-hand side, however, are issues that are confirmed in the sales too late in the current structure. The purpose of the analysis is to direct attention to the redesign of the structure for the problematic issues. A number of issues emerged proved to be rather easy to fix: these were often later additions to the product. This phenomenon is probably best explained by the fact that these problems were eliminated in the old features along with product improvements as a result of learning from earlier deliveries.

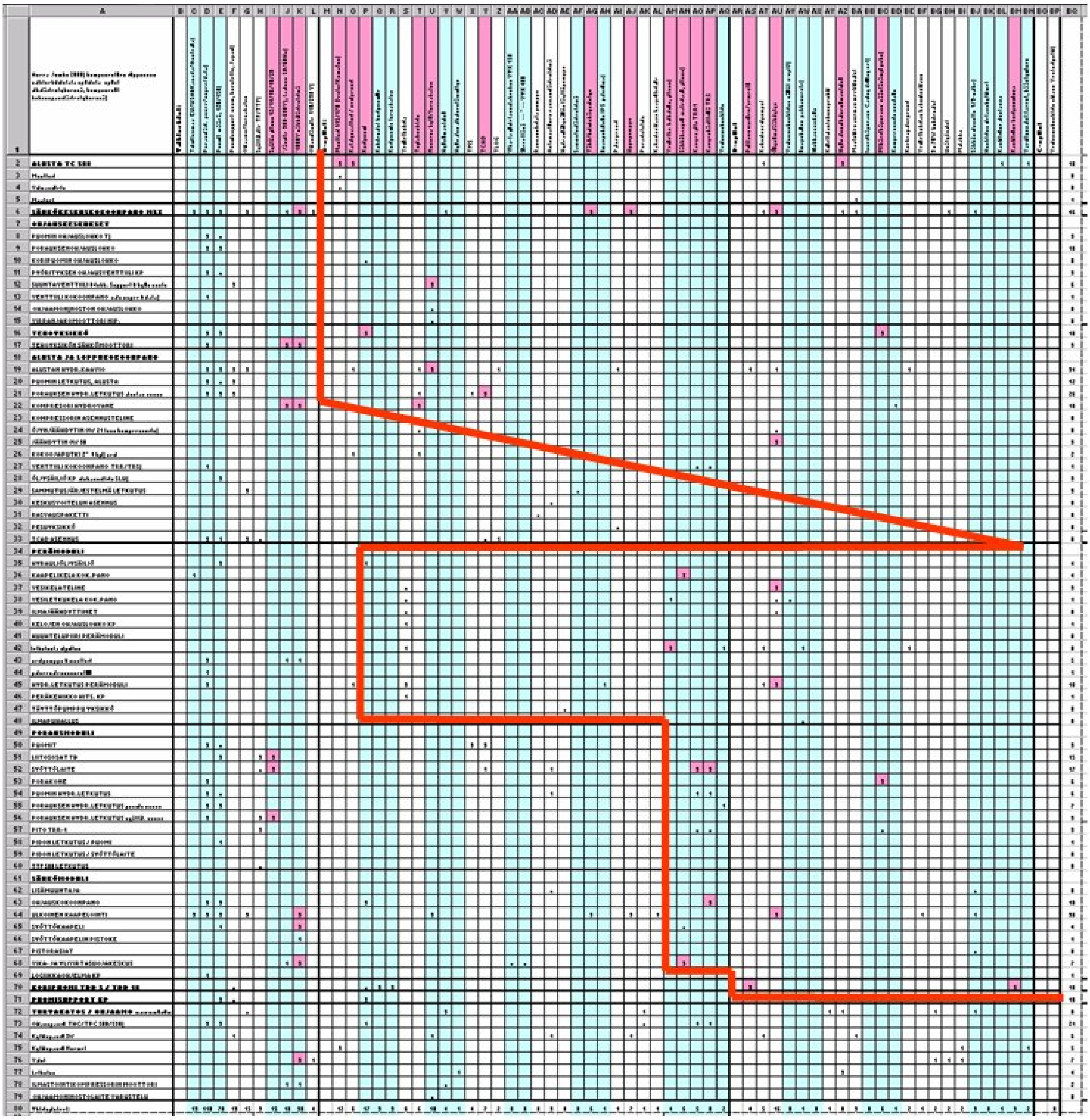


FIGURE 81. The Late Point Differentiation analysis matrix. The horizontal rows present the sales choices and the vertical columns the modules/element entities. The line indicates the proceeding of production. The relations on its right side are problematic.

Conclusions of the tunnel drilling rig

Applying the company strategic landscape framework model introduced in Chapter 9 in this dissertation would have forced us to evaluate the requirements arising from the value chains (that is, the special phasing of the order and delivery chain) and the matching of the product structure and the delivery process already in the beginning. Late Point Differentiation was used as a tool to seek the synchronization point of the product and process structure. The research conducted solely in the product structuring domain did not yield results, as the functional structure was not a dominant qualifier for the product structure in this case.

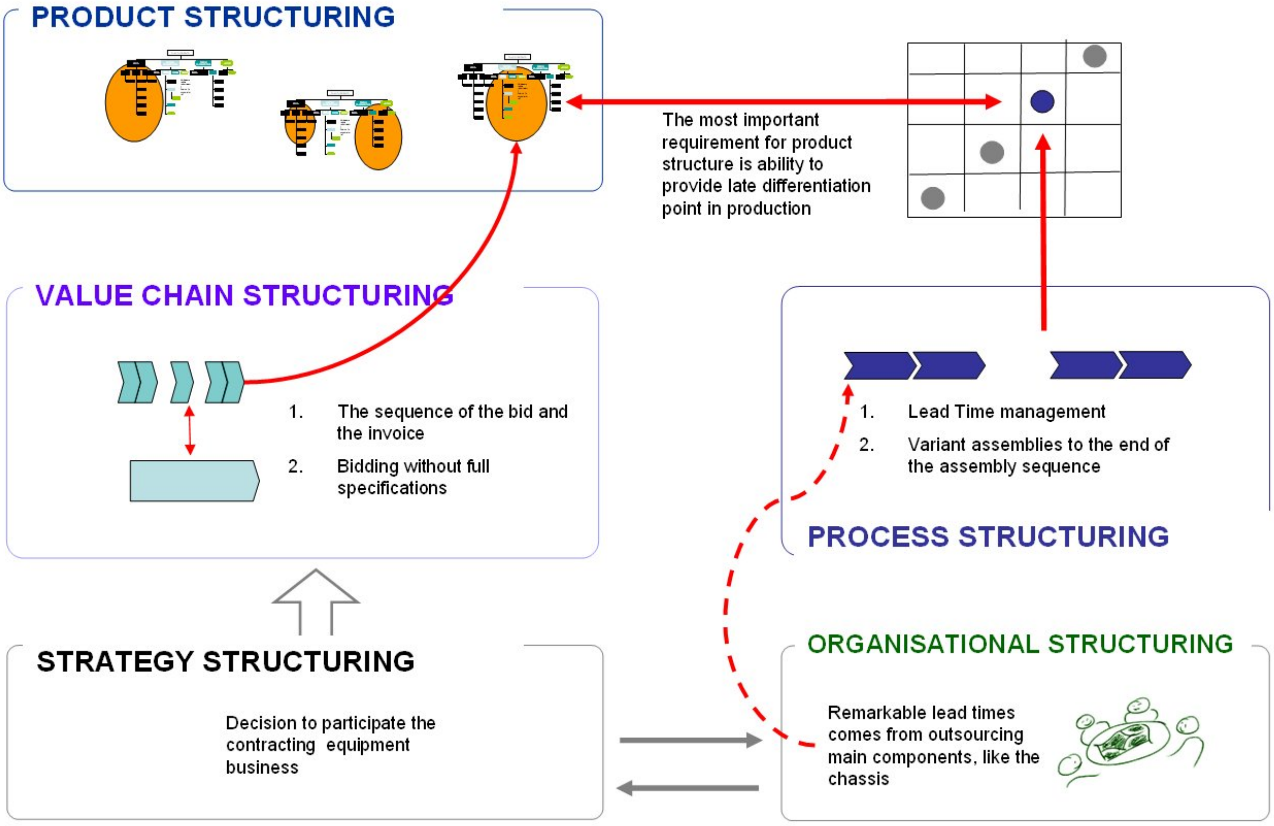


FIGURE 82. The CSL-framework model of the development of the product structure in the case of a tunnel drilling rig. The key challenge was not to divide the functionalities into modules, as the functionalities were most changed in their parameters (for example, the voltage and the frequency). The key issue was to place the variation caused by the parameters at the end of the delivery process, which required the synchronization of the product and process structure.

Using the framework model would have directed the product structure development in the right direction. Let us take another example of this. When analyzing competing products, our research team felt that synchronization of the product and process structure was also sought in the design of the Atlas Copco tunnel drilling rig. This was implemented by radically changing the implementation method of the product. As was stated earlier, the quality of the electrical current in the mine or tunnel construction site causes considerable changes in the electrical equipment used. In its Rocket Boomer, Atlas Copco had converted a number of functions normally operated on electricity into hydraulic ones. This must have increased the part costs, but it enabled the manufacturing of a bigger machine part before the order data were confirmed. In the

”Modularisering som affärskoncept och produktutvecklingsfilosofi” event in Södertälje on 14 March, 2002, Atlas Copco declared that it had reached a 50% reduction to the estimated production times. Production had been arranged as simultaneous modular and final assembly, as shown in the figure below. In this case, too, the product structure was changed to synchronize the delivery process.

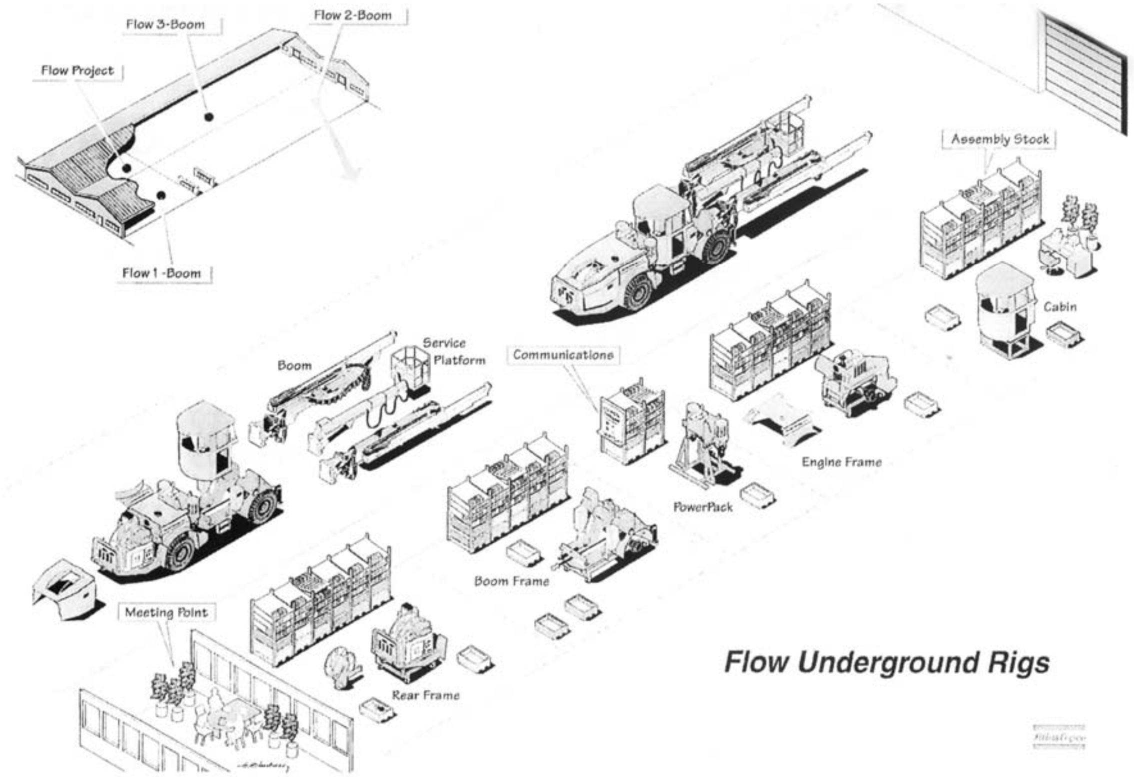


FIGURE 83. The general arrangements of the production of a tunnel drilling rig at Atlas Copco. The figure is from the hand-out material given at the ”Modularisering som affärskoncept och produktutvecklingsfilosofi” event on 14 March, 2002.

10.2. A TRUCK

In the history section of this dissertation, Scania was presented as an example of a company that has been able to utilize modularity in its business operations. It is therefore justified to examine the truck as a product primarily from Scania's perspective. Some alternative solutions will also be examined, but, as we will discover, they have not succeeded on the market.

Strategical structuring and core competences

From the historical perspective, Scania (until 1968 Scania-Vabis) is a small manufacturer that has succeeded in reaching an important position on the global market during the past few decades. For the most part, Scania operates on a one-company model. Most of the product development is carried out in Sweden, but there are some exceptions. For example, the development work of the BR116 bus chassis, launched in 1978, was carried out to a large extent in the Brazilian unit of Scania [Nordström & Nyström 1990]. Final assembly is also centralized in a small number of internally managed production plants.

Scania has a long tradition in the rationalization of production and utilizing standardization. In the late 1930s, a new engine series was designed at Scania-Vabis that is sometimes called ”Unitary”. The diesel engine series consisted of three power ranges, the cylinder capacities of which were 5.17, 7.75, and 10.34 litres respectively. All engines had a similar cylinder group with the same stroke and diameter. The engines had a number of common parts; the cylinder heads with accessories, the pistons, the bearings, even the cast exhaust manifold consisted of parts fit together with a pipe coupling so that the different size ranges used the same parts. The variation of power rating was simply carried out by changing the number of engine cylinders. The smallest engine had four cylinders; the middle one had six cylinders, and the big one eight. The corresponding powers with the rotation speed of 1,200 1/min (in the 1946 models) were 135, 160, and 180 horsepower. This innovation could be introduced, as the corporate management at the time had strong faith in the rationalization of production as the basis of success. The invention proper, however, was the achievement of one man. August Nilsson even received an inventor royalty for his engines for a while. The royalty was paid on the basis of the number of cylinders delivered, which means that the royalty was double for an eight-cylinder engine compared to the four-cylinder one. [Lindh92] Standardization between engine sizes worked in practice, too. For example, the engines D420, D610, D620, and D810 have a shared repair manual in which the control values, the tightening torques, and the tolerances are the same for all engines [Scania-Vabis 1951]. The first digit in the engine number indicates the number of cylinders. There were versions of the six-cylinder model for left-hand and right-hand traffic in which the injection pump was located on the corresponding side of the vehicle.

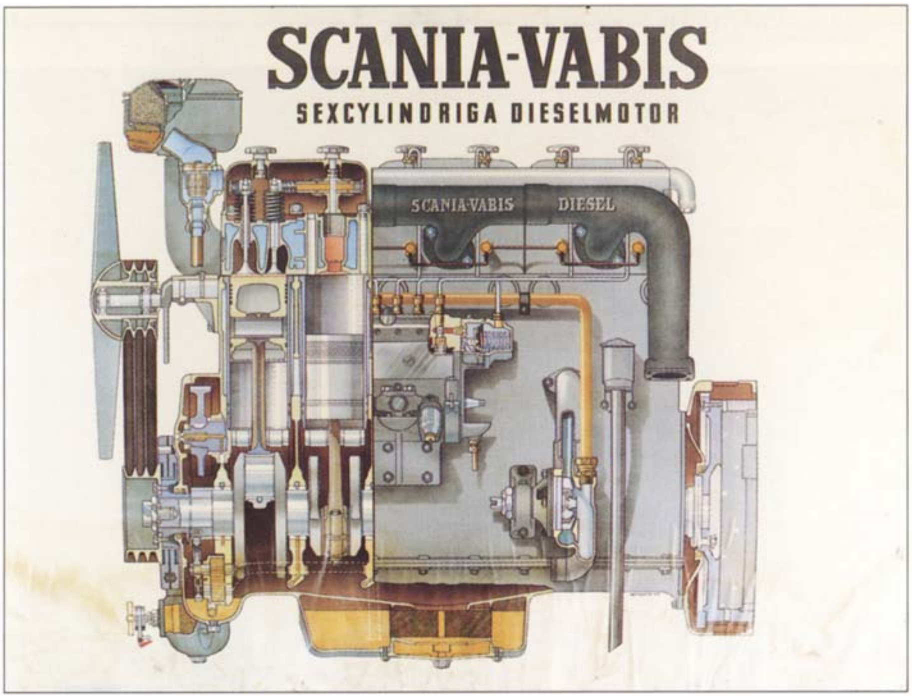


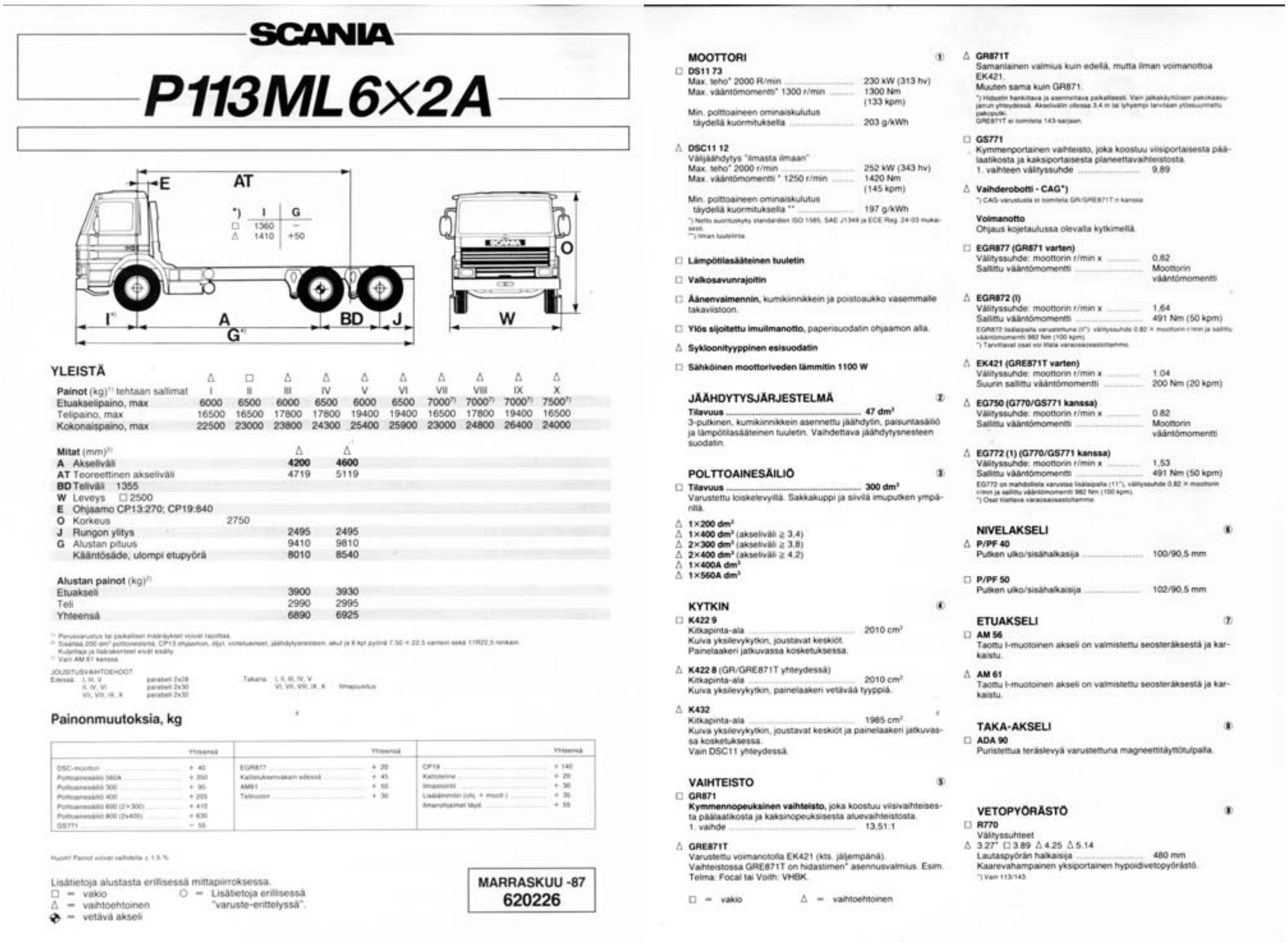
FIGURE 84. The most common engine in the Unitary series: the six-cylinder D600. The figure shows an older development version of the engine, equipped with prechamber injection. The engine in the figure is a six-cylinder model intended for right-hand traffic in which the injection pump is on the left. [Lindh 1992] In the Buldogg bus model, the driver's seat, the gear selector lever, and the control devices stand in the way of service operations, which means it is beneficial to place the injection pump on the opposite side of the driver.

As was presented in the section on the history of modularity, it can be argued that standardization and the rationalization of production have remained as the key strengths of the company. Another strength is the knowhow in engine technology. The latter has directed the entire product strategy. It is probably very difficult to manufacture efficient and durable diesel engines that would also be very cheap. This fact excludes the price championship strategy which would otherwise be a natural choice for a company manufacturing a rational product. In this way, Scania has been forced to settle in the category of the expensive so-called ”prestige” products. In this category, – particularly as it is a case of an investment product – the company must be able to provide the customers with added value. The added value provided by Scania is the customer-specific weight optimization that increases the load capacity of the truck. This is achieved via means of systematical product configuration, so that each vehicle delivered to the customer is configured as the optimum choice for its purpose of use. *A modular, systematically configurable product is thus one of Scania's key strengths on the level of corporate strategy.* This can be considered a continuum of the development work carried out since the 1930s.

The product and product structure in Series Three

In the case of Scania, the conversion of standardized and rationalized product range into a fully configurable modular line takes place when shifting from the model series three to the model series four. When examining a truck *as a product*, the view is slightly different from that of examining it as *a technical system*. In product examination, we must consider what a truck product means for the company, that is, *we will only consider those parts of the value chain that the company has decided to include as part of the product.* Scania has limited its product range as consisting of the basic truck element: the chassis without the actual load space and loading equipment, or the so-called superstructures. Service and maintenance agreements are often added as parts of the life-cycle-related service of a truck product, but we will not discuss them here as their status has only been emphasized in Series Five, which remains outside the scope of this dissertation.

The example in Chapter 4 on the modularity of the structural elements of the cabins in Series Three shows the advanced level of standardization and product rationalization in this product series. However, the product structure of the series followed the traditions of the truck industry. ”Truck models” containing certain variations were available. The model line was based on one standard model of which certain variations were available. An example of such a specification from 1993 is shown in the figures below. A square indicates the selections in the standard model and a triangle refers to the available alternatives. In such a method, product pricing is usually based on the price of the standard model and the accumulating (in some cases, abating) effect of the selected alternatives.



SCANIA

P113ML6×2A

YLEISTÄ

	△	□	△	△	△	△	△	△	△	△
Painot (kg)[1] tehtaan sallimat	I	II	III	IV	V	VI	VII	VIII	IX	X
Etuakselipaino, max	6000	6500	6000	6500	6000	6500	7000[7]	7000[7]	7000[7]	7500[7]
Telipaino, max	16500	16500	17800	17800	19400	19400	16500	17800	19400	16500
Kokonaispaino, max	22500	23000	23800	24300	25400	25900	23000	24800	26400	24000

Mitat (mm)[2]		△	△
A Akseliväli		**4200**	**4600**
AT Teoreettinen akseliväli		4719	5119
BD Teliväli 1355			
W Leveys □ 2500			
E Ohjaamo CP13:270; CP19:840			
O Korkeus	2750		
J Rungon ylitys		2495	2495
G Alustan pituus		9410	9810
Kääntösäde, ulompi etupyörä		8010	8540

Alustan painot (kg)[2]		
Etuakseli	3900	3930
Teli	2990	2995
Yhteensä	6890	6925

Painonmuutoksia, kg

Lisätietoja alustasta erillisessä mittapiirroksessa.

□ = vakio
△ = vaihtoehtoinen
○ = Lisätietoja erillisessä "varuste-erittelyssä".

MARRASKUU -87
620226

MOOTTORI ①

□ **DS11 73**
Max. teho* 2000 R/min .... 230 kW (313 hv)
Max. vääntömomentti* 1300 r/min .... 1300 Nm (133 kpm)
Min. polttoaineen ominaiskulutus täydellä kuormituksella .... 203 g/kWh

△ **DSC11 12**
Välijäähdytys "ilmasta ilmaan"
Max. teho* 2000 r/min .... 252 kW (343 hv)
Max. vääntömomentti * 1250 r/min .... 1420 Nm (145 kpm)
Min. polttoaineen ominaiskulutus täydellä kuormituksella ** .... 197 g/kWh

□ **Lämpötilasäätäinen tuuletin**

□ **Valkosavunrajoitin**

□ **Äänenvaimennin,** kumikiinnikkein ja poistoaukko vasemmalle takaviistoon.

□ **Ylös sijoitettu imuilmanotto,** paperisuodatin ohjaamon alla.

△ **Sykloonityyppinen esisuodatin**

□ **Sähköinen moottoriveden lämmitin 1100 W**

JÄÄHDYTYSJÄRJESTELMÄ ②

Tilavuus .... **47 dm³**
3-putkinen, kumikiinnikkein asennettu jäähdytin, paisuntasäiliö ja lämpötilasäätäinen tuuletin. Vaihdettava jäähdytysnesteen suodatin.

POLTTOAINESÄILIÖ ③

□ **Tilavuus** .... **300 dm³**
Varustettu loiskelevyillä. Sakkakuppi ja siivilä imuputken ympärillä.

△ **1×200 dm³**
△ **1×400 dm³** (akseliväli ≥ 3,4)
△ **2×300 dm³** (akseliväli ≥ 3,8)
△ **2×400 dm³** (akseliväli ≥ 4,2)
△ **1×400A dm³**
△ **1×560A dm³**

KYTKIN ④

□ **K422 9**
Kitkapinta-ala .... 2010 cm²
Kuiva yksilevykytkin, joustavat keskiöt.
Painelaakeri jatkuvassa kosketuksessa.

△ **K422 8** (GR/GRE871T yhteydessä)
Kitkapinta-ala .... 2010 cm²
Kuiva yksilevykytkin, painelaakeri vetävää tyyppiä.

△ **K432**
Kitkapinta-ala .... 1985 cm²
Kuiva yksilevykytkin, joustavat keskiöt ja painelaakeri jatkuvassa kosketuksessa.
Vain DSC11 yhteydessä.

VAIHTEISTO ⑤

□ **GR871**
Kymmenopeuksinen vaihteisto, joka koostuu viisivaihteisesta päälaatikosta ja kaksinopeuksisesta aluevaihteistosta.
1. vaihde 13,51:1

△ **GRE871T**
Varustettu voimanotolla EK421 (kts. jäljempänä).
Vaihteistossa GRE871T on hidastimen* asennusvalmius. Esim. Telma: Focal tai Voith: VHBK.

△ **GR871T**
Samanlainen valmius kuin edellä, mutta ilman voimanottoa EK421.
Muuten sama kuin GR871.

□ **GS771**
Kymmenportainen vaihteisto, joka koostuu viisiportaisesta päälaatikosta ja kaksiportaisesta planeettavaihteistosta.
1. vaihteen välityssuhde 9,89

△ **Vaihderobotti - CAG*)**

Voimanotto
Ohjaus kojetaulussa olevalla kytkimellä.

□ **EGR877 (GR871 varten)**
Välityssuhde: moottorin r/min x 0,82
Sallittu vääntömomentti .... Moottorin vääntömomentti

△ **EGR872 (I)**
Välityssuhde: moottorin r/min x 1,64
Sallittu vääntömomentti .... 491 Nm (50 kpm)

△ **EK421 (GRE871T varten)**
Välityssuhde: moottorin r/min x 1.04
Suurin sallittu vääntömomentti .... 200 Nm (20 kpm)

△ **EG750 (G770/GS771 kanssa)**
Välityssuhde: moottorin r/min x 0.82
Sallittu vääntömomentti .... Moottorin vääntömomentti

△ **EG772 (1) (G770/GS771 kanssa)**
Välityssuhde: moottorin r/min x 1,53
Sallittu vääntömomentti .... 491 Nm (50 kpm)

NIVELAKSELI ⑥

△ **P/PF 40**
Putken ulko/sisähalkasija .... 100/90,5 mm

□ **P/PF 50**
Putken ulko/sisähalkaisija .... 102/90,5 mm

ETUAKSELI ⑦

□ **AM 56**
Taottu I-muotoinen akseli on valmistettu seosteräksestä ja karkaistu.

△ **AM 61**
Taottu I-muotoinen akseli on valmistettu seosteräksestä ja karkaistu.

TAKA-AKSELI ⑧

□ **ADA 90**
Puristettua teräslevyä varustettuna magneettitäyttötulpalla.

VETOPYÖRÄSTÖ ⑧

□ **R770**
Välityssuhteet
△ 3.27* □ 3.89 △ 4.25 △ 5.14
Lautaspyörän halkaisija .... 480 mm
Kaarevahampainen yksiportainen hypoidivetopyörästö.

□ = vakio △ = vaihtoehtoinen

FIGURE 85. A Series Three truck specification 620226 from 1987 on the heavy-duty chassis model P113ML6X2A. The standard version is indicated by a square and the alternatives with a triangle. The figure only shows the first two pages of the four-page specification. [Oy Scan-Auto Ab]

In Series Three, the model series were built around the engine or the cabin used (bonneted models and sleeping cabins for long-haul transportation). The figure below shows the Scania 113 model assortment [Scania brochure material 1590057 fi/FI]. This is an example of a product series built around an 11-litre engine (DS11, DSC11, and DTC11). The division in the figure is not sufficient enough to separate the all available models. The example model P113ML6X2A is seventh from top in the figure. There is, however, another example of this ”general type” in the research material: P113HL6X2Z (presentation 620228). This means that there are more versions that described here, and the figure is not configuration model or a Borowskian structural plan (Bauprogramm).

Alustat	Moottorit	Vaihteistot			Ohjaamot	
P113MA4X2	320-360 hv	GR871	GR900	GRS900	CP13	CP19
P113ML/HL4X2	320-360 hv	GR871	GR900	GRS900	CP13	CP19
R113MA/MW4X2	320-400 hv	GR871	GR900	GRS900	CR13, CR13 Streamline	CR19, CR19 Topline, CR19 Streamline
R113ML/MV/HL/EL4X2	320-380 hv	GR871	GR900	GRS900	CR13, CR13 Streamline	CR19, CR19 Topline, CR19 Streamline
P113HK4X4	320-360 hv	GR871			CP13	
P113ML/HL6X2	320-360 hv	GR871	GR900	GRS900	CP13	CP19
R113ML/MV/HL6X2	320-380 hv	GR871	GR900	GRS900	CR13, CR13 Streamline	CR19, CR19 Topline, CR19 Streamline
R113MA6X2/4	320-400 CV	GR871	GR900	GRS900	CR13, CR13 Streamline	CR19, CR19 Topline, CR19 Streamline
P113HK/HL/EL6X4	320-360 hv	GR871	GR900	GRS900	CP13	CP19
R113ML/HK/HL/EL6X4	320-380 hv	GR871	GR900	GRS900	CR13, CR13 Streamline	CR19, CR19 Topline, CR19 Streamline
P113HK6X6	320-360 hv	GR871			CP13	
P113HL8X2	320-360 hv	GR871	GR900	GRS900	CP13	CP19
R113HL8X2	320-380 hv	GR871	GR900	GRS900	CR13, CR13 Streamline	CR19, CR19 Topline, CR19 Streamline
P113MK/HK/HL/EL8X4	320-360 hv	GR871	GR900	GRS900	CP13	CP19
R113HK8X4	320-380 hv	GR871	GR900	GRS900	CR13	

Figure 86.: The Scania 113 model set of Series Three is here presented as an example of a product series built around the engine. The categorization in the figure is not sufficiently detailed to separate the all available models. The example model P113ML6X2A is seventh from top in the figure. [Oy Scan-Auto Ab]

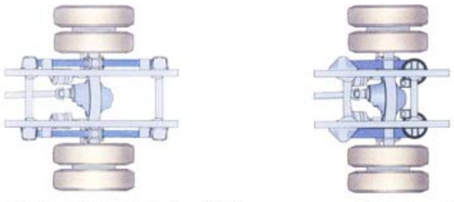
Even though the 113 model set shared an engine type, all truck types using this engine do not belong to this model set. For example, the T113 chassises with a bonnet belong to the T series that is built around the cabin. The T series is shown in the figure below [Scania brochure material MK32034 svSE 1992].

Chassier	Motorer	Växellådor				Hytter	
T93ML/HL4X2	250-280 hp	GR801	GR871			CT13	CT19
T93HL6X2	250-280 hp	GR801	GR871			CT13	CT19
T93HL6X4	250-280 hp	GR801	GR871			CT13	CT19
T113ML/HL4X2	320-360 hp		GR871		GRS900	CT13	CT19
T113HL6X2	320-360 hp		GR871		GRS900	CT13	CT19
T113HL6X4	320-360 hp		GR871		GRS900	CT13	CT19
T143HL4X2	420-500 hp			GR900	GRS900	CT13	CT19
T143HL6X2	420-500 hp			GR900	GRS900	CT13	CT19
T143HL/EL6X4	420-500 hp			GR900, GRH900	GRS900	CT13	CT19

FIGURE 87. The T model of Series Three is here presented as an example of a product family built around the cabin. This model line features vehicles in which an engine typical to the 113 series is used. [Saab-Scania Ab]

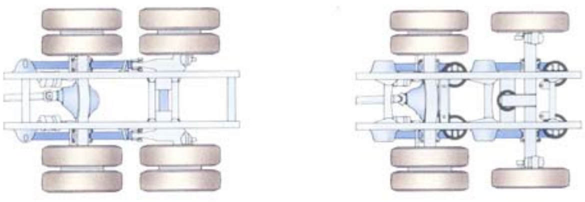
A typical feature in such a product structure is that the product features are sold one at a time. Seven ”feature-type” brochures for the product were found among the research material which only includes a random selection of the Scania material of the time: the turbo-compound engine supercharge system, the new dashboard layout, the EDC electronically controlled injection, the ABS brake system, the GR900 gear system, the decorative stripes on the cabin wall, and the high cabin model. Some of these introduce the tangible selectable component or accessory, while others present the feature in the product series (e.g. dashboard, turbo-compound). In addition to providing keeping for the unit that produces the technical material busy, this also sets a great challenge for the maintenance of the internal consistency of the product range.

Series Three uses modular thinking, and the structures are in part modular. In the 1992 truck brochure, [Saab-Scania brochure material MK32035 svXX], it says that the modules of the truck model line are the cabin, the gear boxes, and the back axle system. The back axle system is shown in the figure below, and they are reported to fit on the chassis types M, H, and E. For some reason, the bonneted model T is not mentioned. For cabins, it would seem that they have their own internal modular system, and a cabin as a whole is a part of the modular system of the truck level. If the cabin parts showed in the modular structure on the truck level, the solution level (Auslösunsgrad) would be difficult to manage due to its large scale.



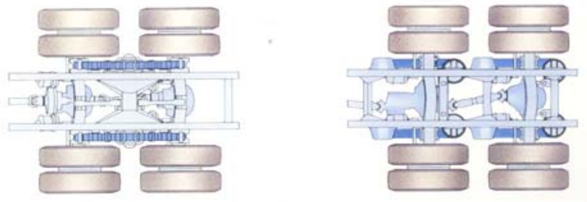
Enkelaxel med parabel- eller trapetsfjädrar

Enkelaxel med luftfjädring



Stödaxelboggi med parabel- eller trapetsfjädrar

Stödaxelboggi med luftfjädring



Tandemdrift med balansboggi och trapetsfjädrar

Tandemdrift med luftfjädring

FIGURE 88. The structure of the back axle systems in Series Three, called modules in 1992. [Saab-Scania Ab]

Product structure in Series Four

The product structure systematics of Scania's Series Four was briefly explained in Chapter 4. The product structure systematics in particular is the biggest difference between Series Three and Series Four. As has been argued earlier in this dissertation, modularity is not merely a product property. If a test was carried out in which a research team disassembled one truck of Series Three and Series Four each on the floor of a truck garage in order to find out which of the products is a systematically configurable modular product, we would probably not reach results. The model series closely resemble each other in terms of technical implementation, and the systematics of a product families cannot be deducted from individual products. Even though we will not prove this on a general level in this dissertation, the issue can be generalized: *modularity cannot necessarily be detected in the end-product*.

Instead, there is no doubt of modularity when we see the technical material of the product range and follow the manufacturing of the vehicles. In Series Four, engine-and cabin-based product series were discontinued – they do not even appear in the highly visual marketing brochures. As was mentioned, a Series Four truck is systematically variable, that is, a configurable product. A configuration based on the specific needs and wishes of each customer is created, and all vehicles manufactured on the production line are made to customer order, or in some cases, to distributor order. The truck model line is divided into four product families, created for the various recognized purposes of use. The specification of a truck starts with the selection of a correct product family. To do this, there is a simple selection chart shown in the figure below. Four questions determine the customer's chassis type: how long is the customer's annual mileage, what are the road conditions like, what is the total weight, and how much power the customer needs. The latter choice is mainly a question of costs and preference, even though it is also somewhat related to the terrain.

FIGURE 89. In Scania's Series Four, the correct product family is found with four questions. [Scania brochure 1592341 fiFI].

Three chassis types are weight optimized, and one is a G chassis for heavier transportation in which extra stress capacity is temporarily needed, such as timber trucks and oversize transports. Each product family has predesigned chassis layouts available. In this way, a difficult layout design is converted into a selection task. (For more information, see Chapter 6.1 ”Configurable product paradigm”) The figures represent the Borowskian structural plans (Bauprogramm) of the chassises of the truck series. The figure below shows the chassis layouts of the long-haul transportation vehicle product family L from 1996.

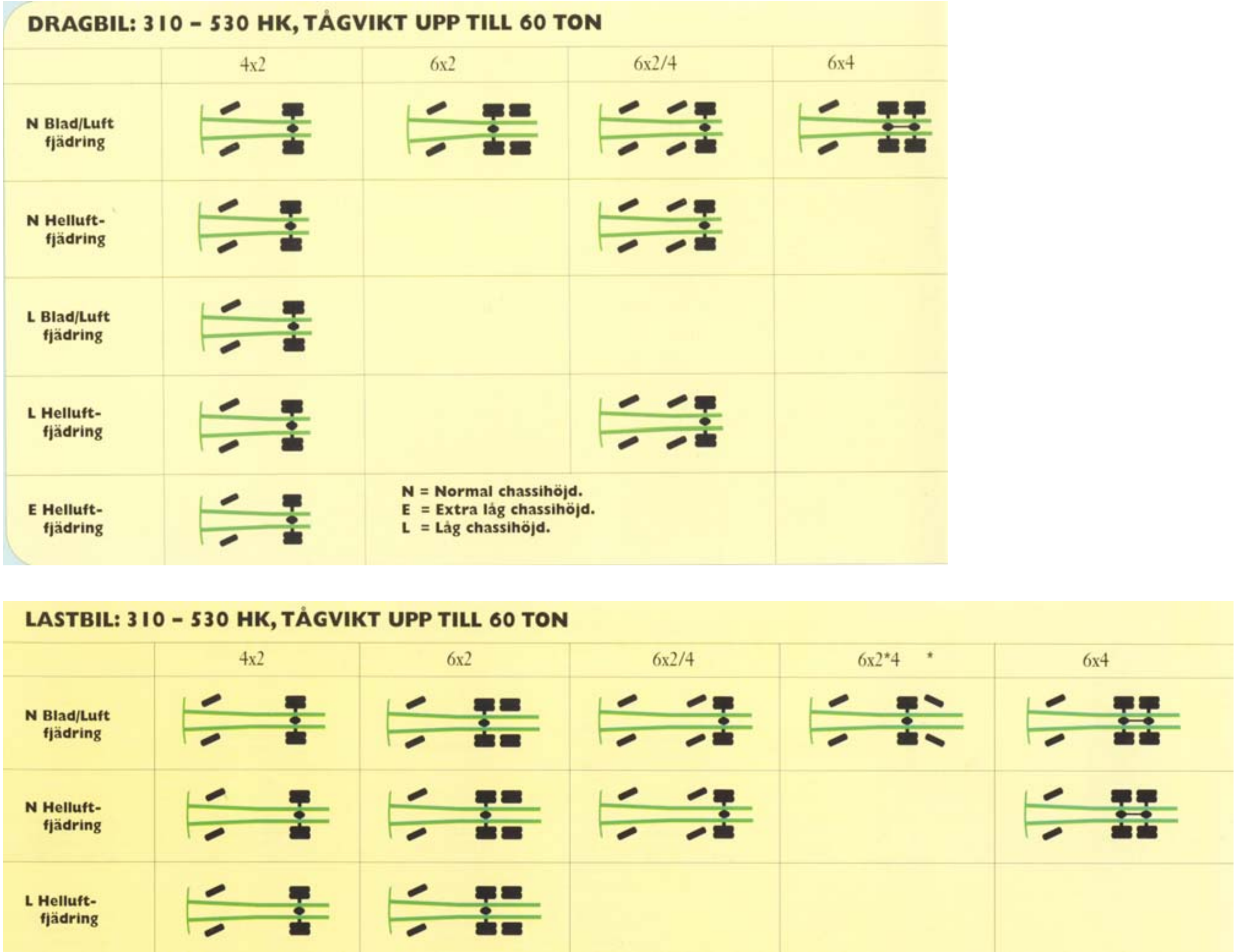



FIGURE 90. The chassis layouts of the long-haul transportation vehicle product family L in Series Four. This is a structural plan (Bauprogramm) following Borowski's idea that converts a difficult layout design into a selection task. [Scania brochure material 1591554 svSE]

In Series Four, the engines, gear systems, and drive gears are combined into a ”power line module”. The propeller shafts in the module of course change according to the length of the vehicle, but this is probably manageable via simple rule-based configuration models. This is not indicated in the figure below (the type of propeller shafts is not indicated). The figure below shows an example of four of the power lines using 12- and 14-litre engines. At the time, the total number of power lines available was 16.

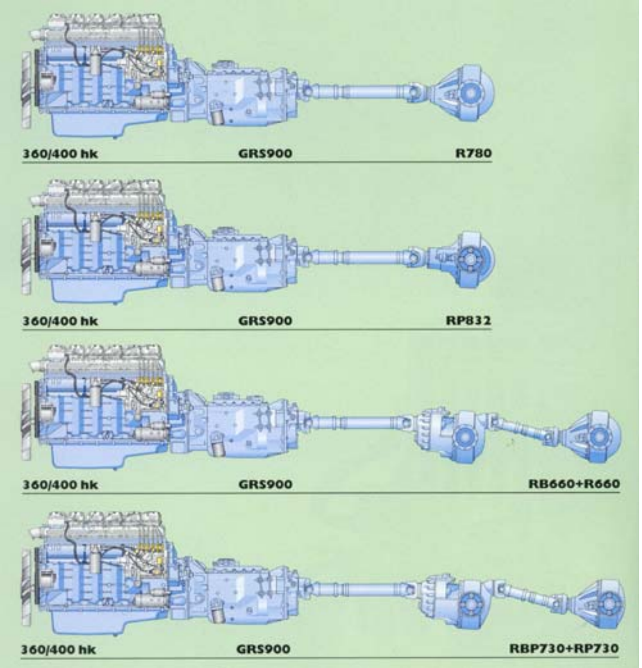


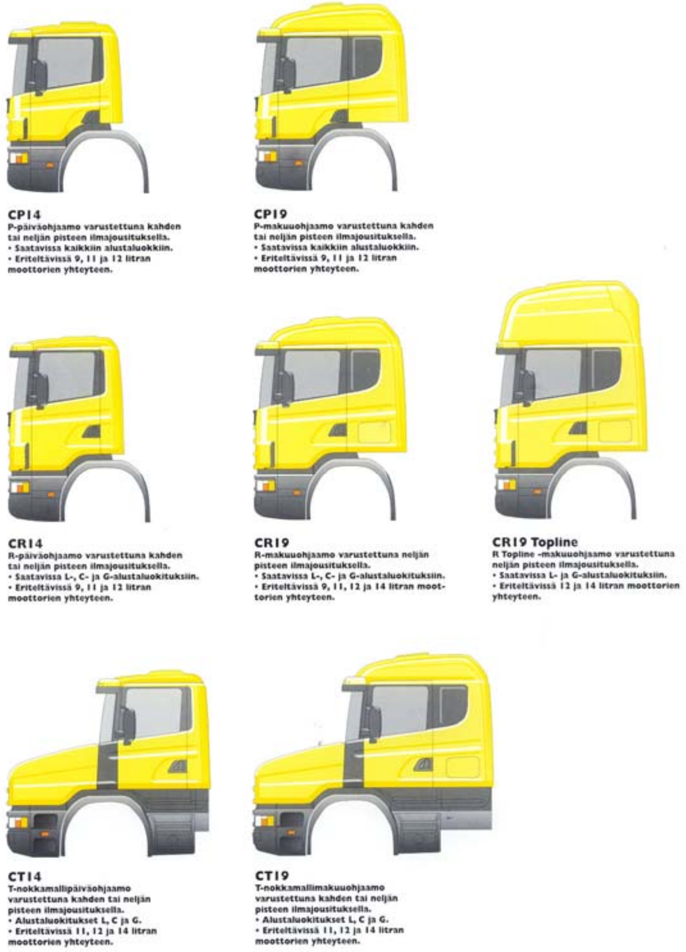
FIGURE 91. The power line modules in Series Four. Four examples of the 16 power line alternatives that use 12- and 14-litre engines. [Scania brochure material 1591391 svSE]

The last phase in the configuration of the main truck parts is the selection of a cabin. In Series Four, cabins with or without a bonnet fit on the same chassis, that is, there is no separate bonneted truck type in the series. All cabins have the same cabin frame. According to these main selections, the customer selects from a relative large supply of accessories. The accessories in the product are, however, of the plus modularity type mentioned earlier, which means it is easy to manage.

According to Scania's own report, there are 360 main variations and thousands of subvariations in Series Four. These versions are composed of approximately 12, 000 components. In Series Three, the number of components was 20, 000. A number of components are shared with the Scania bus models. The following are reported as fundamental technical and productional solutions of a modular system: [Scania 2003]

- Standardized chassis frames for the various vehicle types, regardless of cabin location
- The same basic cabin for each model (with or without an engine bonnet, a day cabin or a sleeping cabin, a high or low cabin).
- Standardized fittings for the engine, the gear system, the suspension, the cabin etc.
- Factory-made fixings for the various superstructures.
- The possibility to combine main components as necessary.
- Same-generation products are produced all around the world.

The last rather obscure statement could be interpreted as referring to the centralization of product development and developing the entire model line at one go, following the generation idea (for example, Series Three and Series Four).



CP14
P-päiväohjaamo varustettuna kahden tai neljän pisteen ilmajousituksella.
- Saatavissa kaikkiin alustaluokkiin.
- Eriteltävissä 9, 11 ja 12 litran moottorien yhteyteen.

CP19
P-makuuohjaamo varustettuna kahden tai neljän pisteen ilmajousituksella.
- Saatavissa kaikkiin alustaluokkiin.
- Eriteltävissä 9, 11 ja 12 litran moottorien yhteyteen.

CR14
R-päiväohjaamo varustettuna kahden tai neljän pisteen ilmajousituksella.
- Saatavissa L-, C- ja G-alustaluokituksiin.
- Eriteltävissä 9, 11 ja 12 litran moottorien yhteyteen.

CR19
R-makuuohjaamo varustettuna neljän pisteen ilmajousituksella.
- Saatavissa L-, C- ja G-alustaluokituksiin.
- Eriteltävissä 9, 11, 12 ja 14 litran moottorien yhteyteen.

CR19 Topline
R Topline -makuuohjaamo varustettuna neljän pisteen ilmajousituksella.
- Saatavissa L- ja G-alustaluokituksiin.
- Eriteltävissä 12 ja 14 litran moottorien yhteyteen.

CT14
T-nokkamallipäiväohjaamo varustettuna kahden tai neljän pisteen ilmajousituksella.
- Alustaluokitukset L, C ja G.
- Eriteltävissä 11, 12 ja 14 litran moottorien yhteyteen.

CT19
T-nokkamallimakuuohjaamo varustettuna kahden tai neljän pisteen ilmajousituksella.
- Alustaluokitukset L, C ja G.
- Eriteltävissä 11, 12 ja 14 litran moottorien yhteyteen.

FIGURE 92. In Series Four, cabins with or without bonnet fit on the same chassis, and the cabins always feature the same cabin frame. [Scania brochure material 1591545 Fifa]

Modular structure based on functional structure

Scania's modularity resembles assembly modularity on the main level, but in a more detailed examination, we find that all the elements are not assemblies, and the division into modules is not motivated by the assembly structure.

The product is a heavy-duty truck chassis that implements the following transformation:

> **The load on the vehicle in the point of departure -> [Transformation] -> the load on the vehicle transported to the correct destination.**

If, therefore, we discovered in our examination of the transformations that a number of different transformations were being performed with the trucks (distribution traffic, earth hauling, long-haul fixed-route transport, oversize transport), and if four different functional structures were created of these, we might well achieve the module structure presented above.

If we present the requirements in sufficient detail on the transformation level, the division into modules based on functionality may lead us to the implemented solution. However, this deduction chain is not easy or the most evident! In addition, it is more likely that following a systematical design method will show us something obvious: a truck implemented with this structure is not the best possible solution for many of the tasks in which they are used! Let us take an example: in long-haul transportation on European roads, the legislation poses limits for the length of the vehicle, and in a number of transportation tasks this in turn limits the load capacity. In the current solution, the cabin takes up a part of the precious length and thus wastes an important resource. There are no technological grounds for this. In the early 1960s, Büssing introduced a ”decklaster” truck concept that is shown in the figure below. The issue has also been revisited later on. In the 1980s, Steinwinter introduced a drawing vehicle that fit under a semi-trailer, shown in the figure below. Neither of these products succeeded in acquiring an even small market share.

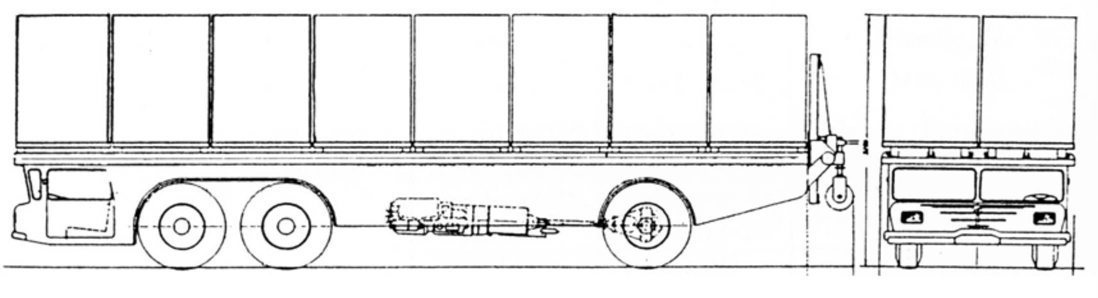


FIGURE 93. In its time, the Büssing Grossraum-Decklaster ”Supercargo 22-150” challenged the conventional truck structure [Albrecht & al 1986 p 236].

KATTOKUORMALLA varustettu Porsche: jotta Steinwinterin yhdistelmän koko pituus voitaisiin käyttää kuorman hyväksi, ohjaamo on ollut pakko sijoittaa puoliperävaunun alle. Ohjaamossa on loisteliaan urheiluauton mukavuus.

Tekniikan Maailma 5/1985 □ 23

FIGURE 94. In the late 1980s, Steinwinter developed differing ideas on the traditional truck model. His prototype raised an interest but found no buyers. [Tekniikan maailma 5/1985]

There is another example of this in the field. The total weight usually limits the load capacity of truck tankers. For this reason, for example, a self-supporting aluminium tanker truck with an integral design could take much more load than a truck tanker built normally on a separate heavy-duty chassis. The Finnish manufacturer Hollming tried to launch such a truck in 1980-82. The tanker and the trailer constructed in a similar way were able to carry 20% more load than a traditional tanker truck combination. Moreover, the truck had excellent riding qualities due to its low centre of gravity. Only 50 trucks were manufactured [Walhström & Walhström 2000].

These examples prove that a Dominant Design has been established in the field of truck industry, that is difficult to undermine. Customers expect the product to follow a certain structure, and the practices in the field support this method. In the truck industry, this structure has remained unchanged for decades, which has undoubtedly provided Scania with an opportunity for focusing on developing the product structure and the related method of operation.

Using the framework model in the case of the truck

In this case, it is extremely difficult to evaluate the benefits of using the framework model, as the initial situation and the initial data in the project of modularity development are not known. Perhaps a definitive starting point cannot even be shown: a systematical line of development stretches back over half a century. The following illustration can, however, be presented. It may be criticized for having been drawn in hindsight – this is difficult to avoid in a retrospective analysis.

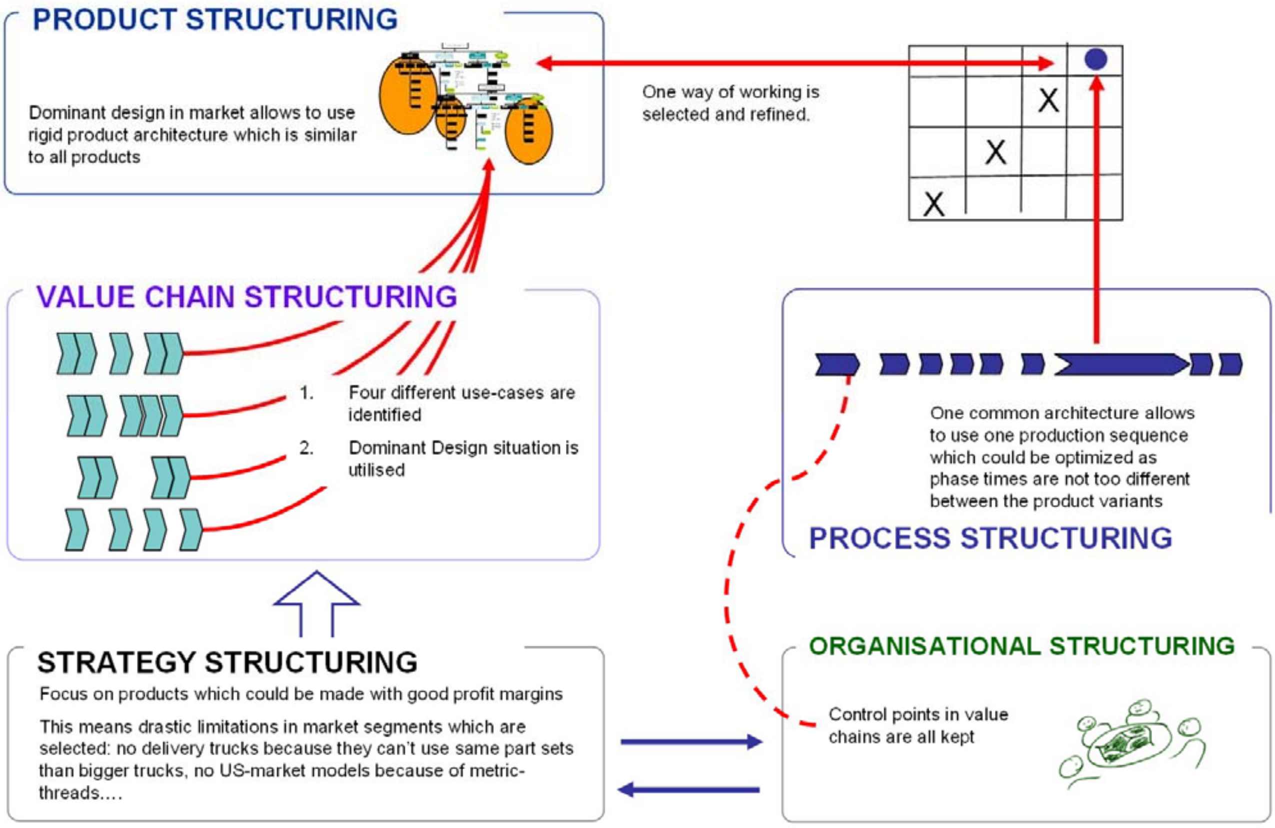


FIGURE 95. The company strategic landscape framework model of developing the product structure in the case of a truck. The model shows the key elements for decision-making.

The CSL-framework model shows the key elements for decision-making. When approaching the matter from the framework perspective, however, we need the same idea on the division into various customer usage situations as in the functional structure approach when outlining the transformations. However, if the division is very abstract in the transformations, such a division according to the customer process is natural and thus easier to grasp.

10.3. A DIESEL LOCOMOTIVE

Our diesel locomotive example hails from the mid-1980s' Finland, when the then Valmet (later Transtech) rolling stock factory in Tampere developed a new M-type diesel locomotive for the National Railways. The author did not participate in this project, but the observations here are those of an outsider.

Invitations for tender for the new, general-purpose diesel locomotive were sent in 1982. The actual agreement for purchase was made on 16 November, 1983. At that time, the agreement covered the delivery of two prototype locomotives to be delivered in 1985-86 and of a series of 21 locomotives to be delivered in 1987-1991 [Pentikäinen 2006]. These 23 locomotives were supposed to be the first batch to be manufactured in a series of a new successful product. According to the article published in *Helsingin Sanomat* and *Aamulehti* in 1986, the first series of new locomotives would replace the 18 Dr12 locomotives made in 1959-1963 that were still used, but plans were made to later also replace the 40 Dr13 locomotives from 1962-65[*]. From the very beginning, the locomotive was designed for international export as well. In 1989, as the locomotive approached the readiness of serial production, it was estimated in an article in *Tekniikka&Talous* (5 June, 1989) that several hundreds of diesel locomotives of this size range that were over 20 years old were used in the Nordic Countries.

Visa Luukkonen, a project manager at Valmet, had previously worked at Lokomo Oy. The ideas of modularity for the new locomotive project derive precisely from Lokomo's earlier locomotive projects. In 1968-1973, Lokomo had manufactured a three-axle industrial shunting locomotive C600, of which 7 were build, most for Swedish industrial plants. In earlier locomotive projects, problems had arisen from the fact that the pneumatic appliances had been located in different areas of small locomotives. In the C600 locomotive, the pneumatic appliances were collected in a frame specifically designed for this purpose. The pneumatic valves and tanks were attached to the frame that was lifted to the locomotive as a whole and then joined to the pipeline. Luukkonen remembered this solution and he thought it could be tested on a wider scale as well [Pentikäinen 2006 pp. 16-17].

The new Valmet locomotive was designed and manufactured as modular. The locomotive consisted of approximately 30 big constructional elements of which some were called modules, some elements, and some only components. The figure below shows the elements from top to bottom: the bogies, the frame, the cable element, the foot bridges (4), the preheater module, the compressor and the pipeline module, the traction motor blower (the figure shows one of the four blowers), the air drier, the starting compressor, the hydraulic pumps, the diesel-generator unit, the cabin chassis module, the radiator, the front casing, the middle casing and the exhaust pipe casing as its extension, the cabin, and the electrical equipment module. Valmet's model name for the product was an M locomotive. In the marketing material, the letter was reported to stand for ”a modular structure”, ”modern technology”, ”modifiable” and ”multiple uses”. This was a statement of the marketing material, even though other views exist on the origin of the model name[†]. At the National Railways, the type name of the locomotive was Dr16 (a diesel engine, heavy axle weight, type 16).

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[*] The press release mentions ”approximately forty” locomotives. A total of 54 locomotives were manufactured, and 41 were in the register ten years later, on 1 January, 1996 [Pölhö & Pykälä-Aho 1996].

[†] The airplane factory unit of Valmet which now manufactured locomotives has a long tradition in alphabetical model names. Even at the time of airplane production, planes designed by Valmet were named following the VL.E. pattern (Valtion Lentokonetehdas, type E = the fifth self-designed type) [see e.g. Raunio 2005]. This was also the case with the bus

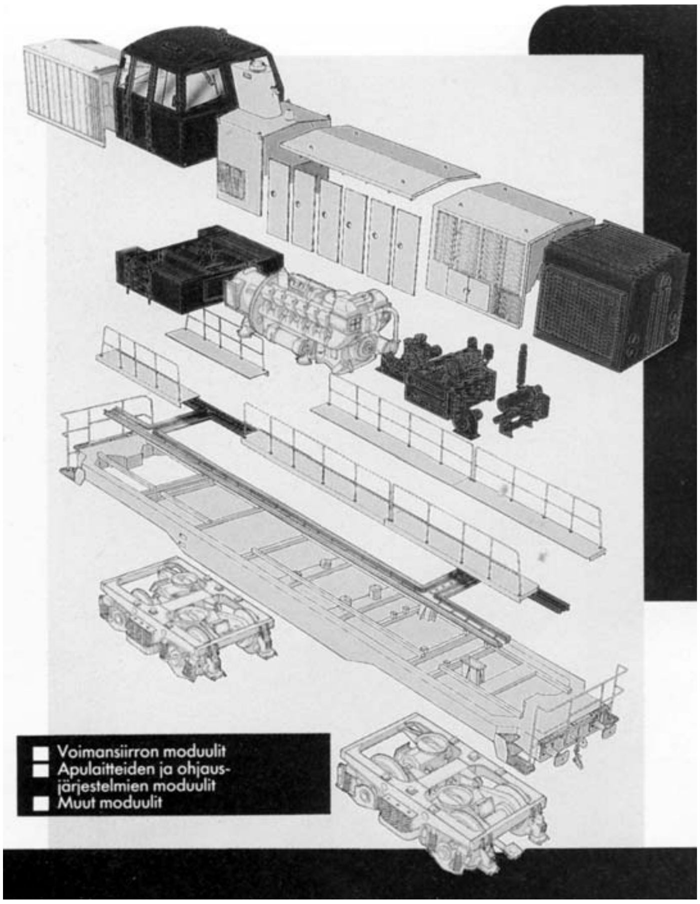

FIGURE 96. The division of the modular M locomotive into modules, according to the Valmet brochure material

Modularity was not the only novelty in the locomotive. In the locomotive delivery, Valmet co-operated with Oy Strömberg Ab that developed the electrical transmission for the locomotive (the locomotive was a diesel locomotive with electrical transmission). In this locomotive, transmission was carried out by using a computer-controlled frequency converter control in which the rotation speed of the alternating-current motors that pull the wheels was controlled by alternating the frequency of the electrical current feed. This enabled more precise steering, which in turn enabled an improved utilization of friction at startup. In practice, this means that a locomotive equipped with this control method is able to pull a heavier train than one equipped with a traditional control (direct-current motors). In addition, the alternating-current motors used require less maintenance and they are often smaller in size and lighter in weight. The M locomotive was one of the first diesel locomotives in the world to be implemented with this technology. The equipment in the frequency converter implemented with thyristors had been collected in the electrical equipment module of the locomotive.

The benefits of the frequency converter technology were mentioned above. The modularity implemented brought about benefits in the construction of the locomotive. Modularity was utilized already in the management of the product development project. A wall chart method was used in which the design phases of the modules were visible to all participants [Pentikäinen 2006 p. 66]. The cable and pipe system module assembled in connection with the frame enabled assembly in a comfortable working position. The device entities could be tested even before assembly. The

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body works manufactured: for example, DA (a diesel bus, the first self-designed type) [Lehtonen 2001]. The locomotive following the M locomotive, which was also the factory's last locomotive, was of the N type.

simple-to-assemble machine covers also speeded up assembly and later facilitated service operations. In the design, opportunities for the common use of the components were considered with the diesel-electric locomotive that was foreseen at the time. It was hoped that the cabin module could be used as such in future locomotive models [Pentikäinen 2006 pp 26-29]. The modular structure was supposed to support maintenance in general. In 1986, the savings in maintenance were reported to be 30% (according to the DI Kari Hassinen, manager of the usage division at the National Railways interviewed in *Aamulehti*). The reference point is not mentioned in the article, but if we compare the situation to the Dr12 engine of the 1950s in which all machineries are fit inside a self-supporting coachwork and we are talking work hours, the figure seems completely plausible. The modular structure was strongly used in marketing – it was the first feature to be listed as the advantages of the locomotive.

The decision to build a powerful, four-axle locomotive limited the total weight to 84 tons. The customer wanted to try the engines of two manufacturers in the prototype locomotives. One locomotive was supposed to have a Wärtsilä 8R22 8-cylinder in-line engine, and the other a Pielstick PA4 V200 VG 12-cylinder V engine. It was discovered when the first locomotive was being built that the Wärtsilä engine cannot be made lightweight enough to reach the total weight limit. Wärtsilä said that they would develop a new eight-cylinder V8 engine for the locomotive, but it would take some time to manufacture these. The prototype series increased to four locomotives, of which two would have a Pielstick engine and two a Wärtsilä engine. The engine change considerably affected the structure. For example, total length was reduced from 19 metres to 17.6 metres. In October 1986, the new Wärtsilä engine was finished, and the manufacturing of the latter two locomotives could continue. Even though the engine alternatives had come to resemble each other in their outer dimensions, they still required changes in the machinery located in front of the engine as well as in the structures at the back, as is shown in the figures below. Modularity did not, therefore, support configuration for this part.

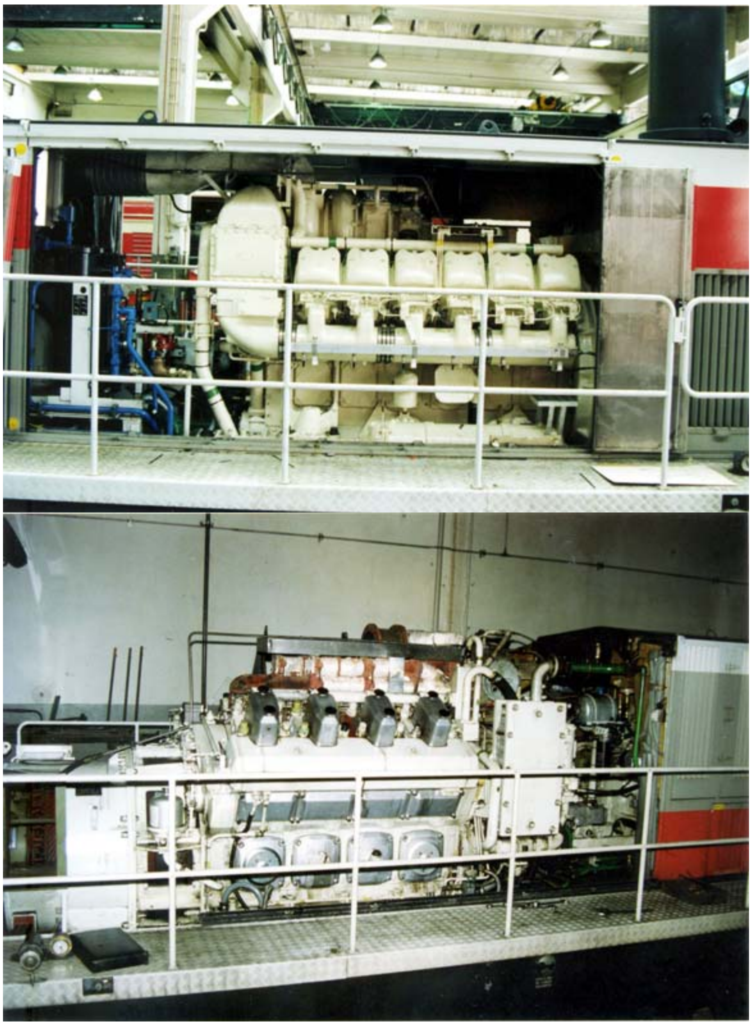

FIGURE 97. The engine variations of the M locomotive were Pielstick (top) and Wärtsilä (bottom). The locations of the equipment required by the engines differ considerably, for example, at the front of the locomotive (NB. The pictures are taken at different sides of the locomotive). [Pictures taken by the author in March 1993]

All four prototype locomotives entered test and typification runs in 1987. The test runs and tests on the locomotives were carried out over the two years that followed. By early December, the most used locomotive had run 244,600 kilometres, and the less used one 155,400 kilometres. The first serial-production locomotives were finished in 1990. At this stage, the development project was badly delayed. In addition, a dispute arose between the supplier and the customer on the poor operational reliability of the prototype locomotives. Around New Year's in 1990-91, the prototype locomotives were removed from traffic for a while. There were no problem in the serial production of the locomotives, and they were manufactured according to schedule. The last locomotive, number 23, was delivered in June 1992.

However, the locomotive project failed as a product development project. The practical operational reliability of the locomotive was poor. For example, in August 1992, nine locomotives were removed from traffic due to malfunctions (39% of the total number of locomotives). During January-October, locomotives failed on the line 23 times for each million kilometres run. The corresponding figure for the old Dr13 locomotives of the early 1960s was 17. The National Railways did not place a new order for locomotives. The M locomotive was offered for many other operators as well, including the Banverket of Sweden and the Norwegian National Railways*. New locomotive deliveries did not take place. A failed development project was no minor setback for the company: the track rolling stock production was shut down in Tampere. This brought an end to the locomotive construction that had been performed in the city uninterrupted since 1901.

Conclusions of the diesel locomotive

The M locomotive is undoubtedly a modular product. Modularity in the locomotive is obviously assembly-based. If we wish, we can also see clear function-based modular divisions in its design. The original division into modules is shown in the figure below. In some areas, the assembly-based modularity did not succeed. This was the case, for example, with the engines. Pielstick engines were chosen for the serial-produced locomotives, and the company also wanted to change the two locomotives with Wärtsilä engines to fall in with the series. In practice, the changing of the engine would have lead to replacing or changing all the equipment at the front of the locomotive, and the work would have cost approximately FIM 4 million. At the time, a new serial-produced locomotive cost 13 million, of which the engine approximately one million. [Pentikäinen 2006 pp 74-75].

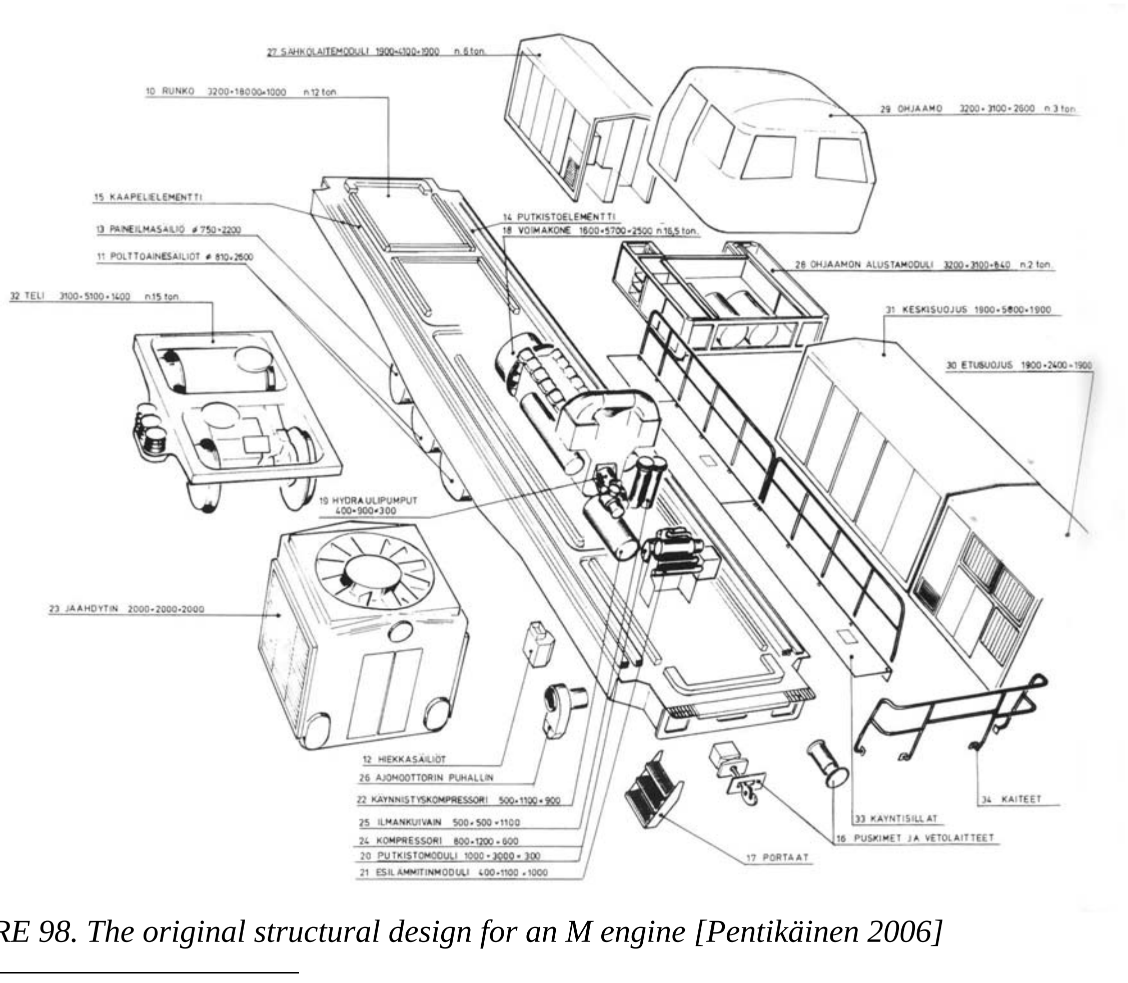

FIGURE 98. The original structural design for an M engine [Pentikäinen 2006]

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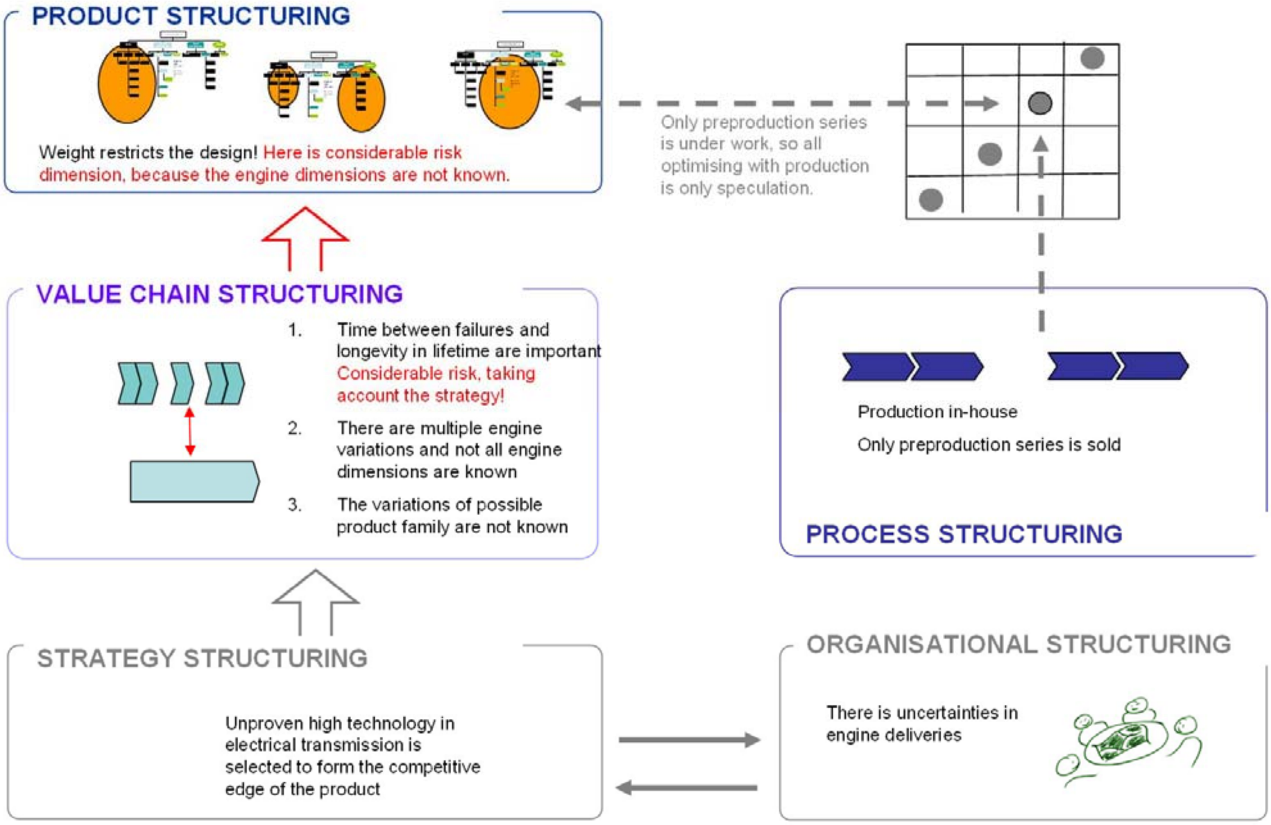
[*] Valmet's unluck in the development of the locomotive was not a one-of-a-kind event in the European locomotive industry at the time. In Norway, the winner of the competitive tendering, Siemens, had to buy back its locomotives after the Norwegian National Railways (NSB) cancelled the agreement. The agreement on the delivery of 10 locomotives was signed on 23 November, 1992. In tough price negotiations, the price of the locomotives was reduced so that the number of locomotives to be delivered for NSB increased from ten to twelve. The first of these Di 6 locomotives entered the test run phase in Norway in 1996. The problems with the new locomotives started immediately, and eventually NSB and the supplier cancelled the agreement in the spring of 1999, as the locomotives did not meet the requirements. [Næss 1999].

Modularity implemented for operational reliability did not improve the situation. At the depot in Oulu, where the locomotives were stored, it was reported that the modular structure does work in part as intended in service and repair, but in some areas the goals are not met. In 2006, operational reliability was still only barely satisfactory. The modular structures may even have reduced the operational reliability, which is indicated by the large alteration work performed on two locomotives in 2005. Part of the alteration work sought to raise the operational reliability of the electrical equipment ”by removing unnecessary connectors”. [Pentikäinen 2006 pp 125,129]

The commonality with future models was mere assumption at the time the design work was started – the product family could not have been developed any further on their basis. The existing and known variations in the form of different engines could not be managed at all via means of modularity. One reason for this is probably the strict total weight limit which had lead to case-optimized solutions. The new technology proved to be one source of the problems related to operational reliability. The implemented modularity was not able to minimize this problem. It is obvious that no clear goals were set for modularity.

Analyzing the company strategic landscape framework model is not straightforward in this case. The figure shows that the most difficult requirements are related to product weight and operational reliability. The figure also shows that a number of factors related to modularity remain unknown.



Weight restricts the design! Here is considerable risk dimension, because the engine dimensions are not known.

Only preproduction series is under work, so all optimising with production is only speculation.

1. Time between failures and longevity in lifetime are important Considerable risk, taking account the strategy!
2. There are multiple engine variations and not all engine dimensions are known
3. The variations of possible product family are not known

Production in-house

Only preproduction series is sold

Unproven high technology in electrical transmission is selected to form the competitive edge of the product

There is uncertainties in engine deliveries

FIGURE 99. The CSL-framework model of the development of the product structure in the case of a diesel locomotive. The framework model shows that a number of factors related to modularity still remain unknown.

The analysis would have highlighted the following as important factors affecting modularity:

1. There exists a need to manage the risk related to the use of the new technology, as required by operational reliability
2. There exists a need to manage the total weight and configuration with different engine

In the implemented product, these issues were not in order. The question remains whether modularity would have been the correct solution to manage these issues. The analysis would not have supported applying an overall modularity in the product (which was performed). A conclusion of the analysis could even be that in a prototype series of a weight-critical product containing untested high technology, applying modularity to the entire product is not a solution required by the business environment. Perhaps modularity was a wrong choice considering the maturity level of the product.

For comparison, let us consider another view on the modularity of a locomotive dating from the same era. The figure below shows the modular casing system of the German DE 1000 locomotive. In its case, the goals probably lie in the savings in production (if large locomotive series are achieved) and the facilitation of service operations. As shown in the figure, the modular system does not contain the actual locomotive mechanisms.

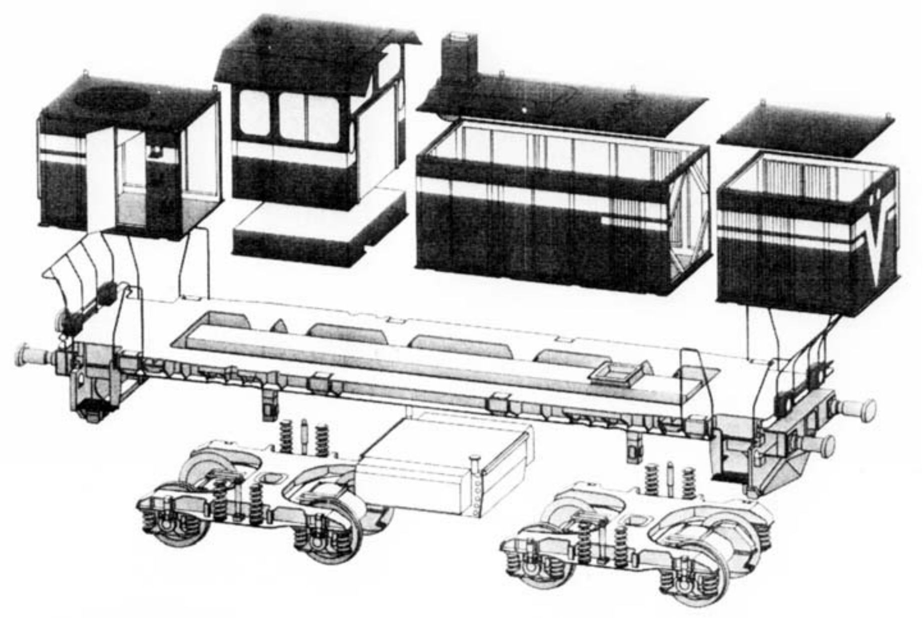


FIGURE 100. The modular system of the casing of the DE 1000 locomotive [Eisenbahn Technische Revue, Januar/Februar 1987]

10.4. A passenger ship

In 2004-2006, the author was the leading researcher in the ”Improving the efficiency of a ship delivery via means of modularity and flexible standardization” project funded by Finnish Funding Agency for Technology and Innovation. The purpose of the research was to discover on which bases the division into modules ought to be performed in a ship delivery in the Finnish marine industry cluster. At the same time, we aimed to clarify which business goals would require modularity and which could be reached via standardization. The term flexible standardization” was included in the title of the research to remind us of the fact that the suggested standardizations ought to be directed to economically important issues and any unnecessary limitations to the freedom of operations ought to be avoided. Warning examples exist of standardization that has become an obstacle.[*] Passenger cruise ships and passenger ferries were chosen as the scopes of the research project, as they are the most important market segments currently. This case is explained in more detail in [Lehtonen & al 2007].

In the project, we aimed to present such a product structure and a related method of operation that the first prototype ship in its series could be delivered for the price of a similar, so-called serial ship delivered earlier. To enable this, the level of design reuse in similar-design serial ships ought to be reached in the prototype ship. This is not as impossible a goal as it might seem at a rapid glance. In the passenger ship business, serial ships are not completely identical - there may, in fact, be considerable differences between two sister cruise ships .

Differences arise on the basis of the customers' requirements, but also of the managing of a big project delivery and the competition of the supplier network. In Finnish shipyards, outsourcing and networking have been a long-standing development trend, and most of the ship design and construction are carried out by a supplier network. One challenge of the product structure lies in its ability to meet the requirements of the management of the decentralized network of suppliers. Let

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[*] In the 1960s, the German association of public transport operators (Verband Öffentlicher Verkehrsbetriebe, VÖV) developed an idea of a manufacturer-independent, standardized city bus model. The idea as such had already been introduced in 1959, but the development work of such a norm bus was not started until 1966. The project was lead by the transport operator Hamburger Hochbahn AG, and the other participants were the leading manufacturers of the time: Büssing, Daimler-Benz, and Magirus-Deutz. The VÖV standard bus specification, the result of the work, defined ten issues, for example the main dimensions of the vehicle, the size and shape of the windshield and the windows, the driver place arrangements, the size and the operating method of the doors, the locations of the signs and the plates, and the organization of the electrical equipment. Issues related to the chassis manufacturer of the chassis, such as the type of the engine and the gear system, were not standardized. [Hamburger Hochbahn 1969]. In the early 1970s, a standard for the scheduled-service buses was created on the basis of the city bus standard (Standard-Überlandlinienbus StÜLB).

In Germany, standardization worked and seemed to bring savings. These ideas were also tried in Finland, where the first bus following the StÜLB standard was manufactured by Delta Plan Oy in 1973. The three biggest public transport services in Finland (in Helsinki, Tampere, and Turku) acquired the version called the "norm bus" which was adapted for use in Finland. This standard model was based in part on the R model city bus concept developed at the Helsinki City Transport Services which also paid attention to the technical solutions of the chassis. In Finland, the norm bus model was manufactured at three vehicle body factories (Ajokki Oy, Delta Plan Oy, and Wiima Oy) primarily for three customers on the chassises of three different manufacturers (Sisu, Scania, and Volvo). However, such completely identical series were very short-lived in Finland, and they brought only lesser advantages. Instead, the fact that three manufacturers took a model with external specifications into their manufacturing program along with their standard models caused that the norm bus could be up to 1.5 times more expensive than the standard buses of the body factories, purchased by individual public-transport entrepreneurs for the same purpose (in 1972, a bus purchased by the cooperative of public transporters in Turku cost maksoi FIM 104,500, while the price of the vehicles in the series bought by the Turku City Public Transport was FIM 155,500.). In Germany, the cost effect was the opposite – there a norm bus was the cheapest one could buy from any supplier. [Lehtonen 2005 (2)].

us mention, that the importance of managing the network of suppliers is no novelty here. The delivery of the very first ship that was being built at the shipyard that was the predecessor of Turku shipyard was delayed because of the subcontracted interior design and woodwork. This took place in 1873. [von Knorring 1995 pp. 35-36]. The size range of the challenges has, however, reached whole new dimensions since those days. The figure below shows the development of the cruise ship sizes built in Finland. Over the same period of time, the construction time of the ships in relation to the building and equipping has been considerably reduced.

FIGURE 101. The size of the cruise ship projects has multiplied while the respective time of construction has been reduced. This sets major challenges for the methods of operation in the marine industry cluster. Picture Aker Yards / C-G Rotkirch.

Functionality as the basis of product structure

At the beginning of this research project, the product structure of the ship was a combination of various issues. In shipbuilding, the construction of the hull has traditionally been the most important task of the shipyard. The product structure of a passenger ship is thus divided into two parts: the steel structure and the ”fittings”. Even though the hull of a ship is no longer separately launched and the interiors designed in an equipment quay, the design of steel structures has still largely remained a separate task. For example, even though attempts are made for the assembly of the pipelines and the finishing of the bushings to be shifted from the equipment phase to the steel block construction phase, no established method of operation has emerged. From the design viewpoint, the equipping of the ship and the interior design are thus performed by ”building in a finished cover”. For this reason, the justification for the division of the product structure is almost completely area-specific. However, this is not as straightforward as it seems. We are dealing with a big project delivery in which the view to the product structure also depends on the implementation phase of the design. At the time the delivery agreement is signed, there exists a two-dimensional floor plan of the ship which is called the General Arrangement (GA). In this design phase, for example, the pipelines are described as systems. In the basic design phase, the design work is carried out area-specifically, and the elements intended for a specific space are designed at this point. The measurements are specified in drawing the working designs. In these two latter phases, for example, a pipe that goes through a certain area is only an element in area without functionality, and the link to a bigger system is not interesting for the point of view of design, as long as the bushing occurs in the same location as in the area next door. An additional dimension is added by the fact that the ship is being built and designed simultaneously. The figure below shows an example of the lifting order of the blocks. Blocks that enter assembly and construction first also lead the way in design. In an extreme situation, the spaces on the lowest decks are finished by the time the design still goes on with the topmost decks.

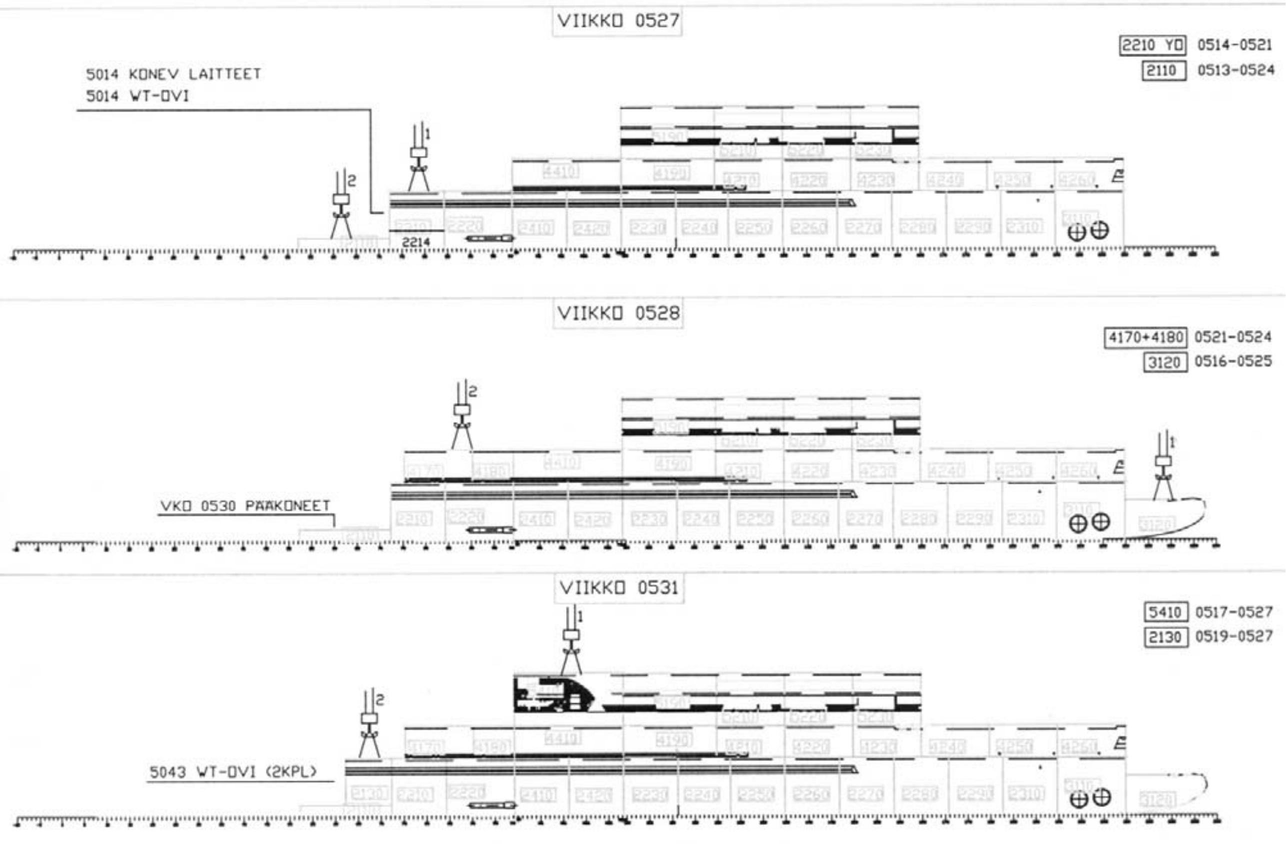

FIGURE 102. An example of a shipbuilding method that is dominant at the time of writing. The ship is constructed of prefabricated blocks the maximum size of which is determined by the lifting capacity of the cranes at the shipyard. The blocks contain a varying number of prefabricated bushings, pipelines, or even insulations and panellings. The raising of the prefabrication level of the blocks is most often limited by simultaneous interior design and block construction. The ship in the example is "Galaxy" by the shipping company Tallink, built under the manufacturing number 435 in Rauma, Finland, in 2005. The figure shows the project weeks 27–31. The manufacturing dates of the blocks are indicated in the top right corner. Picture: Aker Yards.

At the beginning of the research, two alternatives were selected as the starting points for the modularity of a ship delivery. One alternative was the process/life cycle model. The other approach was to create a function-based model. The ideas of the process/life cycle model were not developed in this project, but modelled on a solution for a process plant delivery project that was carried out previously. In this approach, called the "horseshoe model", the product structure is formed as a model phased according to the work sequence in the project. This is done by determining the documents belonging to each phase by describing their relations to the part structure of the product and by describing the spatial shifts between the phases. As a result, a cross breeding of the product structure and the design support system is created, which also contains a number of product data management elements. [A public report does not exist on the project]. Adapted to ship delivery, the approach is shown in the figure below.

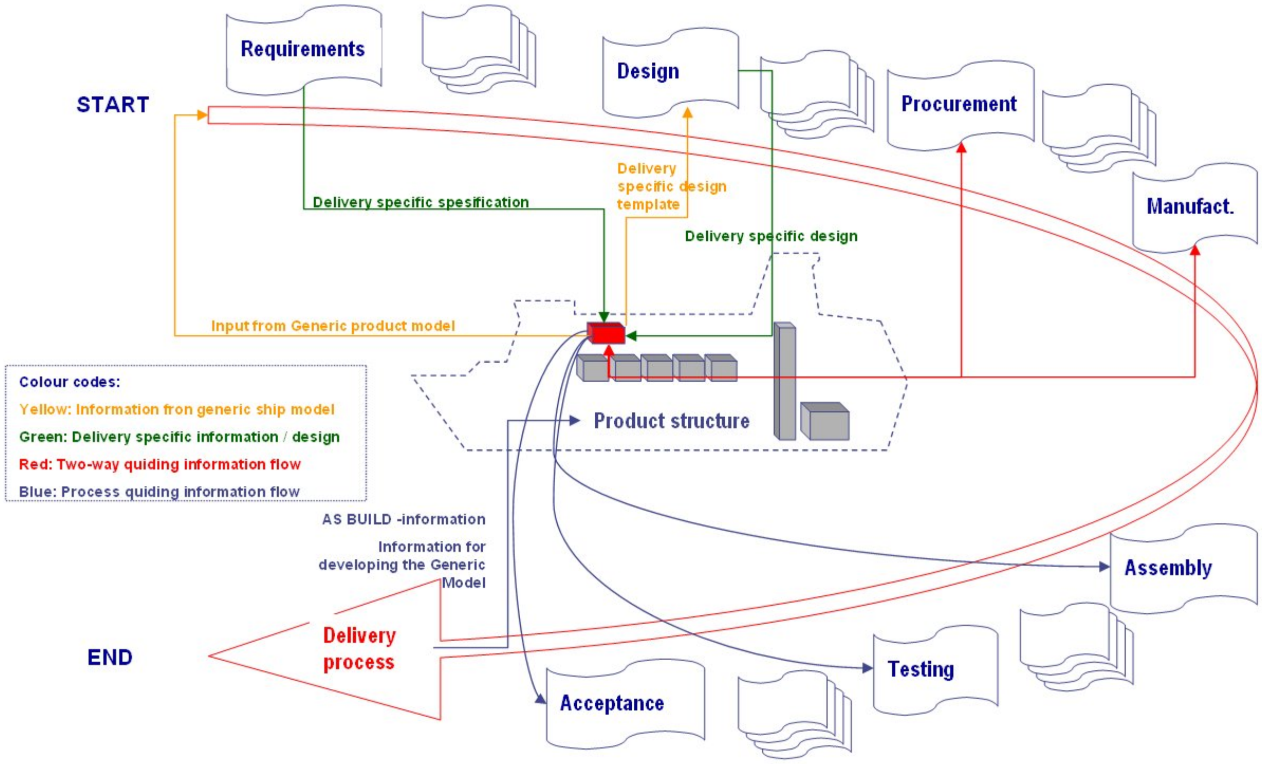

FIGURE 103. In the approach called the "horseshoe model", the product structure is formed as a model phased according to the work sequence *in the project. This is done by determining the documents belonging to each phase by describing their relations to the part structure of the product and by describing the spatial shifts between the phases. As a result, a cross breeding of the product structure and the design support system is created, which also contains a number of product data management elements. Picture: Lehtonen, presentation at the Mety meeting 16.08.2005*

This, however, was not a suitable solution for the ship delivery case. In this model, the product structure is formed on the basis of the phases of the delivery process, which requires that the delivery always take place according to a standard procedure. When examining the issue is greater detail, we discovered that this also leads to the requirement whereby the task descriptions and divisions, or roles, in the delivery must remain standard. For a number of reasons,– discussed in more detail in [Juuti & Lehtonen 2006] – this is not the aim of the marine industry, which meant that the model was discarded at the very beginning.

The remaining alternative was the function-based division of the product structure. This division was designed for three locations: on the level of the entire ship delivery, in the cabins, and in the machine rooms (separate M.Sc. thesises were written on the two latter). On the level of the ship delivery, the main elements in the functional division were easy to recognize. The principalities of the suggested division are shown in the figure below. The benefits of the functional division were apparent: elements of the similar (or even identical) type are arranged in the same delivery entity, the integration phase of systems such as pipelines is facilitated or eliminated, and reuse is facilitated as the *function carrier* (or organ) level becomes visible in the design documentation.

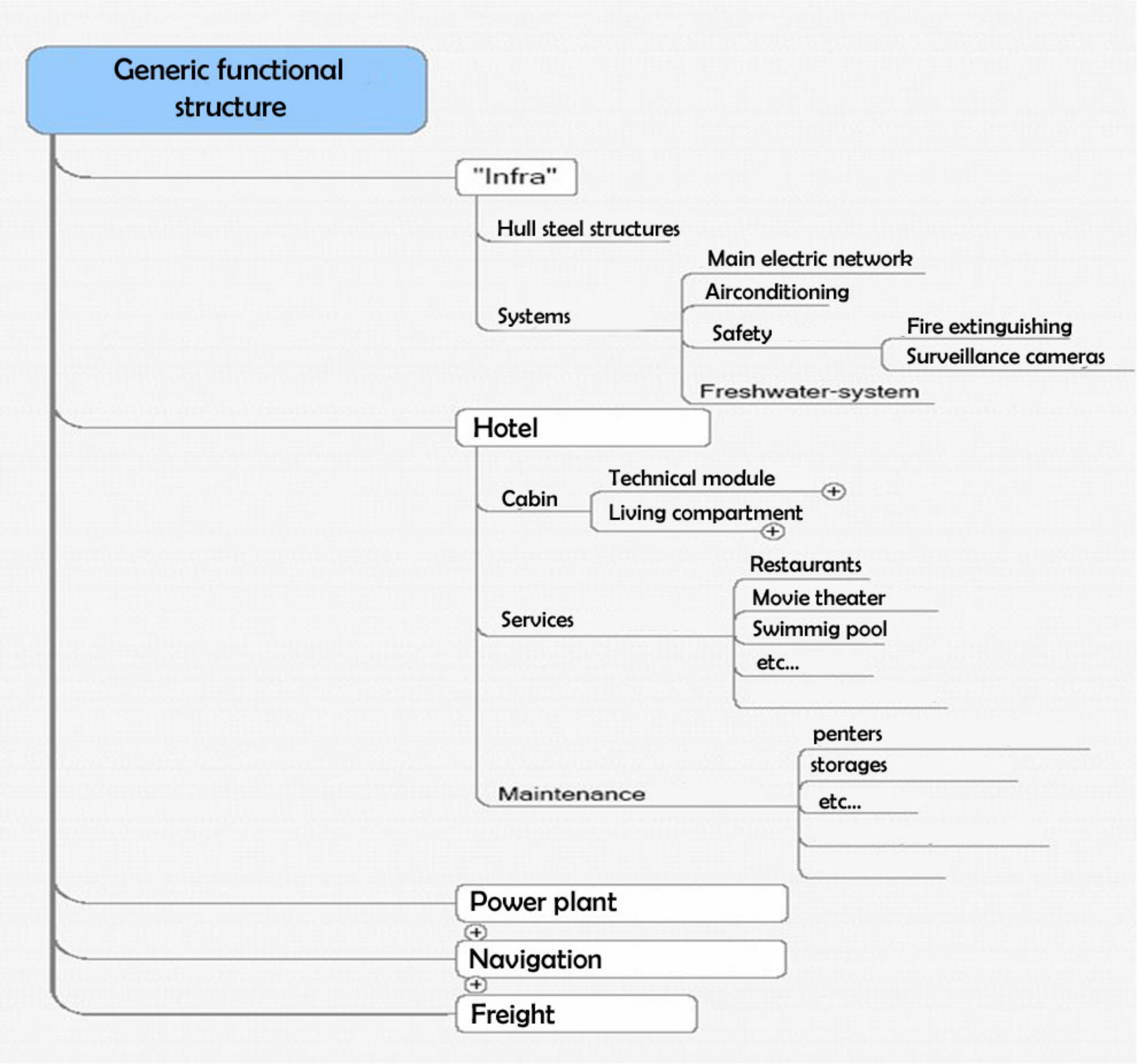

FIGURE 104. An example of the suggested functional modular division of a ship. Picture: Alanko/Lehtonen/steering group presentation 13.09.2006

The problems in this approach were not related to the theory or the product but practice. A big problem was the increased requirement level for design, brought about by the suggested approach. As a number of designers on various levels are designing function-based systems for the same area, it is necessary to use 3D design, for example, to enable the examination of collisions. Creating cubic 3D models is not a problem for design agencies operating in the first circle of the marine industry network (1. Tier). For example, DeltaMarin had developed its own 3D design product called DeltaGen for the area. Instead, in the cases of big ship deliveries (such as Genesis), the level of knowhow and skills of the necessary auxiliary designers already varies considerably. For this reason, it was difficult to accept a product structure model that requires the use of 3D design and skilled co-operation between the design offices, as the only method of operation. It is important to manage fluent co-operation, as the physical location of the interfaces is determined in the operational model only in the course of design.

For this reason, the organization found that the functional product structure was a difficult and perhaps also expensive solution. Another important factor was that *the research team was not able to convince the representatives of the marine industry network on the operational profits yielded by* *the functional product structure model*. The advantages were listed earlier. However, these were not considered to convert into operational profit *with the present method of operation.* The designs of a function-modular structure in the ship delivery were thus discarded.

Next, functional modularity was examined in individual areas. On the cabin deck, the Finnish marine industry has rather long traditions in using modularity. Cabins have been delivered more or less as modules since 1982. An important part of the M.Sc. thesis on this issue was to discover the potential advantages of a function-based perspective in the design of the cabin deck. When drawing the functional structure model, an important question was whether the cabin deck was to be examined as a static system or whether passenger functions (services, such as cleaning, etc.) were to be included in the functional model. The supervisor of the M.Sc. theses, Professor Asko Riitahuhta, and the author decided that the cabin deck is to be examined as a technical system excluding the passenger-related functions, but that in the M.Sc. thesis on the machine area, maintenance-related repair operations are included in the functional model.

In his M.Sc. –thesis Heikki Taneli created a functional model of the cabin-area systems. Taneli's conclusion on the usability of the functional structure repeats the observations made in part on the ship level: ”*The functional structure of the cabin area is easy to generate. No such functional variations between ship deliveries take place that would justify forming the production on the basis of the functional structures. Product-external spreading stems from the delivery. For this reason, the functional structure does not provide a guiding line on how to form the product structure. To be able to use functional structures even in theory, the functions ought to be bound to the organizational structure. It would be futile to create functional structures in this business environment.*”

The larger modelling method selected for the machine room set considerable challenges for creating the product structure model. From the point of view of academic research, the results are interesting, but it would seem that only a handful of small modules can be created on the basis of functionality for the machine room, either.

Creating product structure models according to the delivery processes

In the halfway of the research, then, we returned to the starting point and had to admit that the case cannot be solved with textbook methods or ideas borrowed from the process industry. The changes in the implementation methods and the ship delivery assembly were so great that they were eventually considered a critical variable. Next, we focused on the various methods of delivering the ship parts, arisen in interviews and the analyses of the documentation. In the research, we outlined the design processes in the various delivery methods. As a result, four different delivery processes were recognized in which design takes place according to a different process. The last delivery method was based on the method outlined in the network strategy of the marine industry.

1. Shipyard-lead free project delivery
2. A turnkey delivery
3. A modular ship
4. A network delivery

The design process of a shipyard-lead free project delivery

The first delivery method is the traditional shipyard-lead free project delivery. The word ”free” here refers to the fact that the work distribution is freely determined for each delivery. The contracts can be allotted based on the profits of the individual sales combinations. This method is very flexible and it enables the direct contract relationship between the shipyard and the subcontractors equipped with even the most modest resources.

However, there are also considerable weaknesses in the method. Partial cost optimization does not bring about overall economic efficiency, as controlling the decentralized tasks requires additional work and causes indirect costs. In addition, the most cost-effective provider is not necessarily the one with the most knowhow, which may cause warranty costs or uncompensated delay in the schedule. Learning in shipbuilding only takes place at the shipyard, as the other tasks circle from contractor to contractor. Earlier, this method was supported by the shipyard's ability to carry out almost any task as required by using its own resources supported this method. This is, however, a method that is more or less gradually being discontinued. The shipyards no longer have reserve resources, either.

In shipyard-lead free project delivery, the design starts with taking in the requirements. The process described in the instructions of the shipyard is almost identical to the process of systematical design. In the following, the process is drawn by using the terminology of the ship delivery. The corresponding terms used in the systematical design process are indicated in brackets.

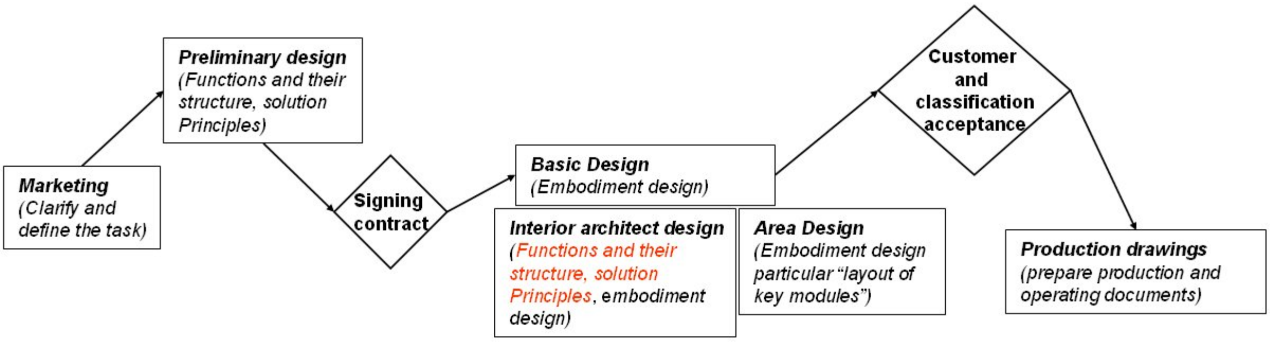

FIGURE 105. The design phases of a ship delivery according to free project delivery. The corresponding names for the phases in systematical design are given in brackets. The only exception is the interior design which takes place in too late a stage according to the textbook". [Lehtonen & al 2007] [Lehtonen & al 2007(2)]

This delivery method does not favour selling a product that is ready designed and specified to a great extent, as strict specifications limit the number of implementing candidates and thus minimizes competition in the purchases. The delivery method does not thus enable design reuse, and committing to a modular system is mostly an unnecessary obstacle for it. From the subcontractors' viewpoint, large-scale investments on product development are big risks particularly because the entities may be sold as pieces. Changing the implementor causes internal variation, which prevents learning and may have a negative effect on quality. In short, this method suits unique products involving manual work but does not in any way support the rationalization of the product or the reuse of design.

The design process of a turnkey delivery

In the turnkey delivery method, the ship is divided into areas (usually physical spaces) that are allotted to contractors after competition. This improves quality management, as there is one company responsible for the bigger entities. Despite this, the systems crossing the areas may still be problematic.

In the turnkey method, the internal interfaces of the ship are defined, and the perspective is that of outlining the product as a whole and then proceeding ”on board”. After the areas are implemented, their compatibility must be confirmed, and finally, the functionalities of the whole are tested. This approach can be found among the design methodologies in Systems Engineering [e.g. Stevens & al 1998]. The V model in the figure below shows the Systems Engineering design process.

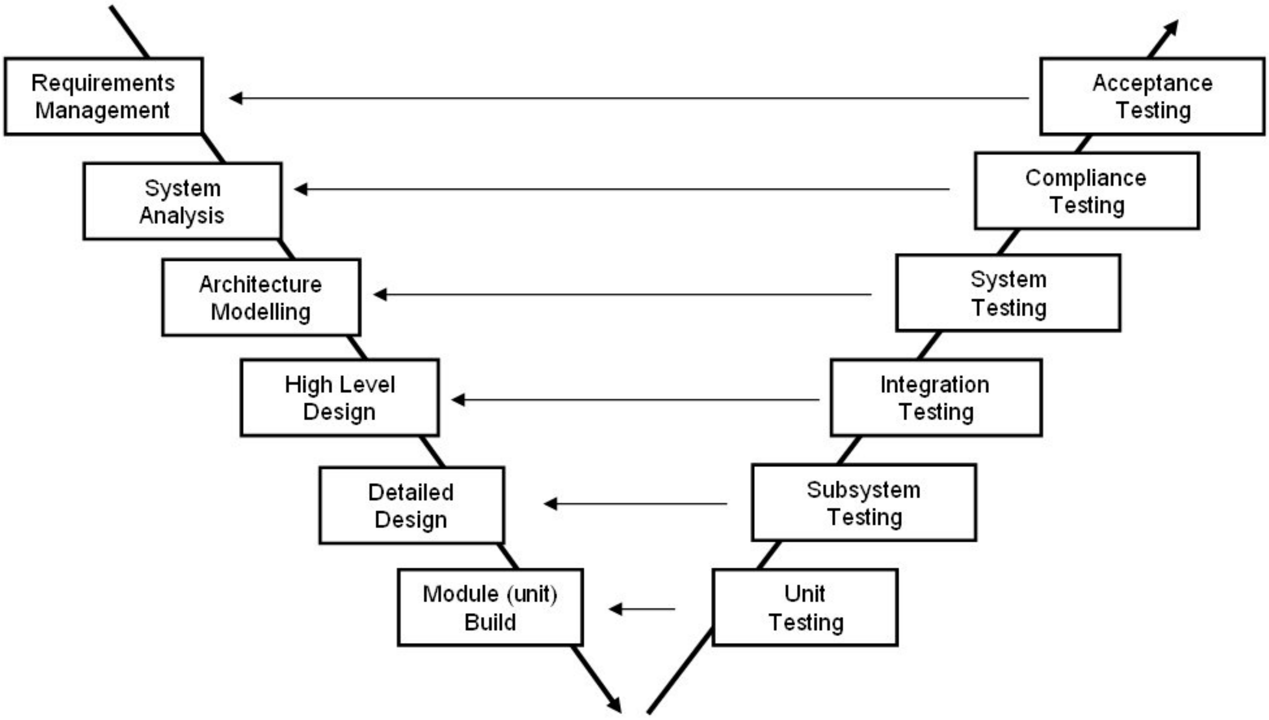

FIGURE 106. The starting point of Systems Engineering is the whole from which the design proceeds into details by dividing the whole into elements. The division into elements requires checking their compatibility as element entities before the assembly and as entities after that (the right-hand branch)

The starting point of Systems Engineering thus suits the project deliveries of large system products – including ships. In a certain sense, it also directs into the design of product families – the congruence of the products can be compared on the system and the architectural level. For this dissertation, the problem is that the method does not directly lead to reuse. Two products that have a similar architecture according to Systems Engineering can very well be implemented so that they have not a single element in common.

This delivery method provides, however, opportunities for the reuse of design. Still, the standardization of interfaces and the purchase of big entities do not as such create modular solutions: the shipyard needs to support these projects. It is possible to design assembly-modular elements on standardized interfaces. These do not, however, easily create reusable units, and the biggest profits are reached via means of standardization.

The design process of a modular ship

Modular construction is carried out to some extent in the marine industry already today. Most often, the problem is that the same module is only used in one delivery, in which case *these disposable modules are spatial element the construction of which has been removed from the ship. In actual fact, therefore, these are delivered by using delivery method 2*. In a real modular delivery method, the data of the modules is already available at the time the order is placed, and solutions developed in them are sold to the customer. Quality resulting from tested solutions, cost savings, and the potential shortened time-to-customer can be presented as the sales arguments. In this method, the modules can be physical ship parts or systems but also (delivery) process modules, that is, carrying out a task necessary for the delivery of the ship

When building of modules, we must therefore have some sort of a conception of the architecture and the modules. The first modular ship will have to be designed by using either one of the mentioned methods, or by using other architectural or modular design methods. In later deliveries, it is a case of systematical variation, that is, configuration. The ship design process, when drawn into a configuration, is as follows:

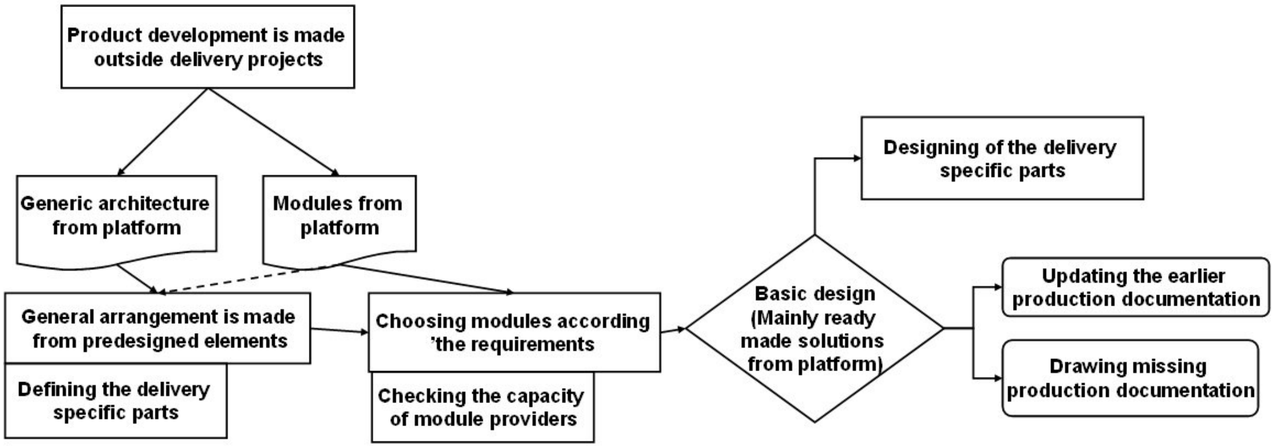

FIGURE 107. The building of a ship out of (reusable) modules. In this design process, the product is assembled by using previously designed elements, and routine design tasks (selection, integration) occur in the delivery [Lehtonen & al 2007] [Lehtonen & al 2007(2)]

In this delivery method, the idea of productification is introduced already in the sales stage, in which case it is profitable to develop modular structures. Modularity may also be more function-based, in which case it provides greater opportunities for variation with different module combinations and benefiting from the configuration enabled by modularity. This method directs us to a more industrial direction, and it may also open up new opportunities for developing networked operations.

Network delivery

In network delivery, the research speaks of the concept of Extended Enterprise (EE). In the ideal model, the EE consists of a network of rather equal corporate partners, each of which is a special expert in its field. This network forms a cluster for each delivery, in which the companies share the profits and the losses as a group. In practice, such clusters have one leading company around which the network is grouped. The transparency of the costs in corporate operations is often also much more difficult an issue as is generally believed in the research circles. No ready-made solution models have been discovered yet for the implementation of the transparency and the models for sharing the profits and losses.

The design process of a network delivery cannot be identified, but its features – the ability to adapt and the open decentralized architecture – might refer to a case of dynamic modularity (Dymo). The Dymo delivery process is the same as that of a configurable product. Figure 69 on page 94, in connection with dynamic modularity, shows in outline what the design process would look like in a ship delivery.

The essential idea in a network delivery model is that the shipyard has given part of the value chain to the network. In addition to having a responsibility for a certain delivery part, the companies in the network have a real responsibility for the development work, and the control measures of the shipyard are limited to replacing a potentially uncompetitive network member by a better one. The services provided by the suppliers are formed into products, which also enables the business operations of the network members also outside the network if desired. The network delivery is built on a shared product platform, or *(industry) branch platform,* and it very efficiently utilizes reuse at least on the design level.

Conclusions of a passenger ship

In the passenger ship delivery research, we concluded that in this business environment, the use of several parallel product structure must be allowed. In this dissertation, we will not discuss the results in any more detail – the dilemma of using multiple product structures is discussed extensively in [Juuti & Lehtonen 2006]. Instead, an important question is whether using the company strategic landscape framework model would have directed us to this solution. The figure below shows the framework model drawn on the case. Drawing a framework model would have lead to the charting of the value chains and the processes (which are reached anyway). Drawn in a framework model, however, they clearly show that there exist good product structure and delivery process pairs. The acknowledging of this information at the beginning of the research project would have directed the research in the direction of the results.

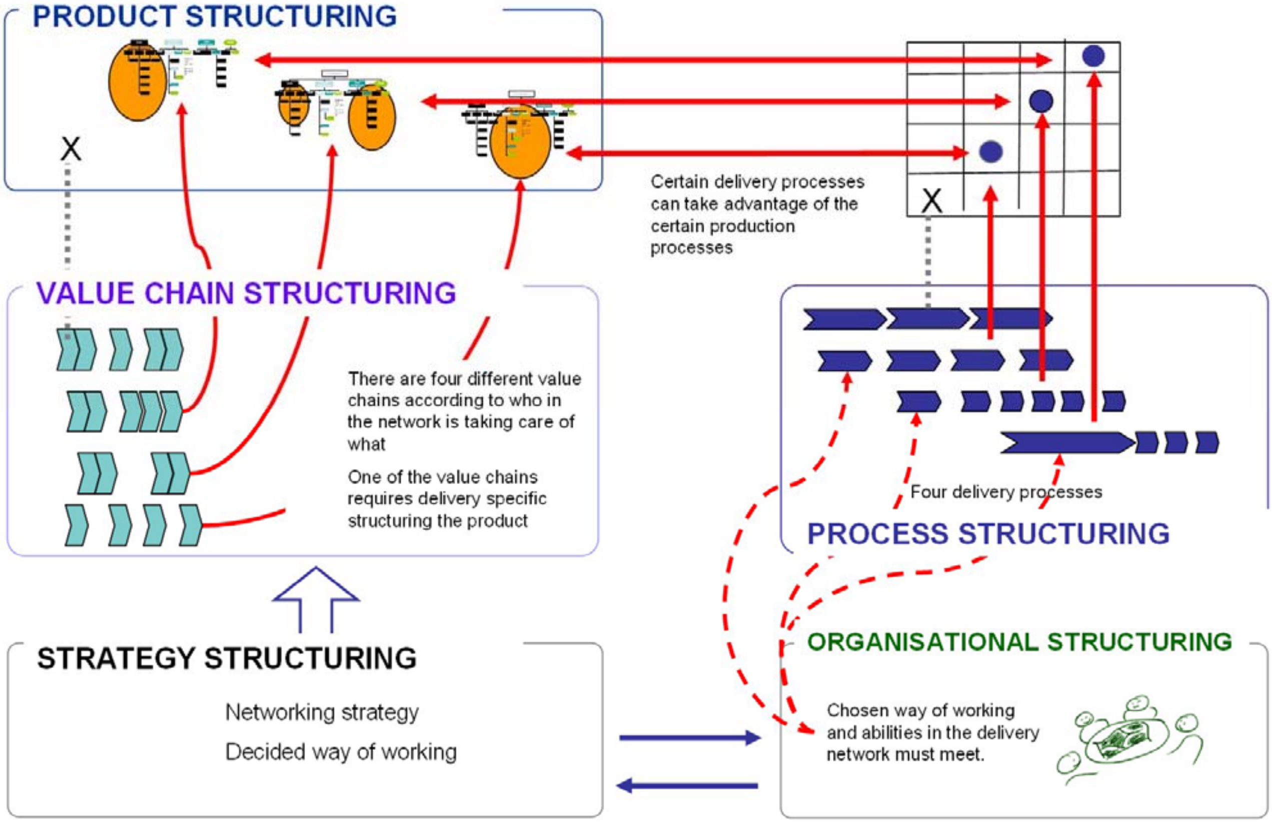

FIGURE 108. The CSL-framework model of developing the product structure in the case of a passenger ship. The framework model shows that the selected delivery process and network assembly are dominant in determining the structure of the product in all other cases except on a free project delivery.

10.5. A safe box

Research related to applying modularity in the structure of a safe box was conducted at the Helsinki-based Kaso Oy during the Konsta project in 1997-99. The participants in this project were the author, researchers Antti Pulkkinen, Juha Tiihonen, and Tero Juuti, and research assistants Jani Malvisalo and Lumi Koivunen.

During the project, we examined the product families of burglary-safe boxes and fire-safe boxes. The aim was to discover the opportunities for shifting from the production of standard models into the production of configurable products. Following this view, the examination was large in scope and research was conducted in four areas:

1. Managing the configuration data in sales
2. Discovering the preferences of the customer needs
3. The manufacturing materials
4. The creation of a modular structure for a burglary-safe box and a fire-safe box.

For managing the configuration data in sales, light solutions to be built on the office software were developed. This concept was called the *ULSC Ultra Light Sales Configurator*. In the case with Kaso, the configuration event involved free layout design, and a visualization tool was created on PowerPoint presentation software to support this. The ULSC concept was applied in two other corporate projects within the Konsta project. In the project with Tunturipyörä Oy, the implementation took place on an Excel sheet, and the application designed for Hydrovoima Oy operated on the ABC-Flowcharter program. The ULSC concept is introduced, for, example, in [Lehtonen & al 1998] and [Lehtonen & al 2000].

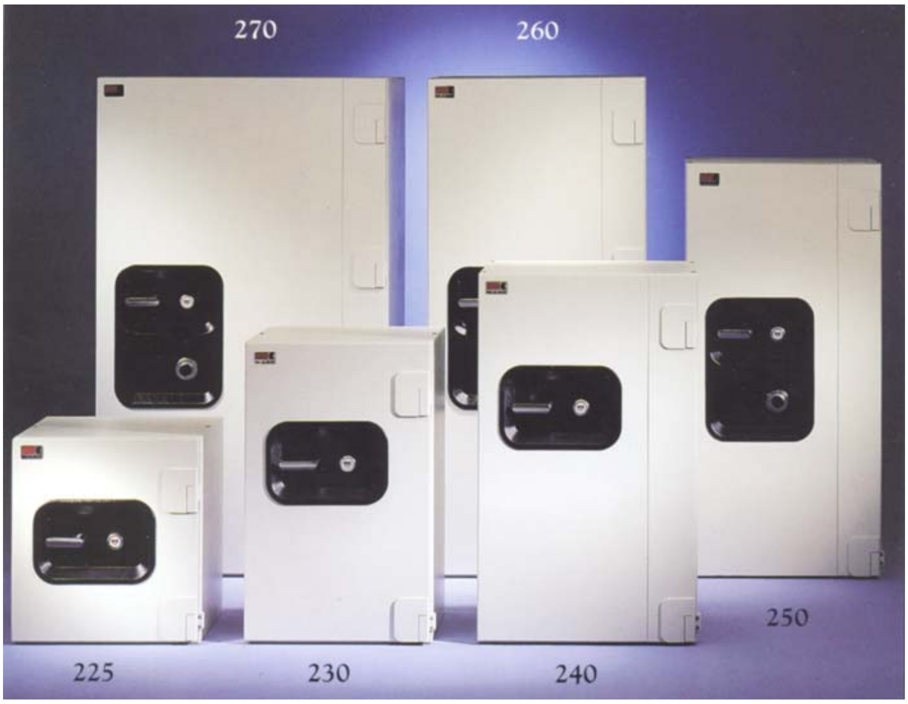

FIGURE 109. The size ranges of the E series safe boxes: the height of the smallest box is 750 mm and the biggest 2050 mm.

The priorities and the preference of order of the customer selections were examined with two customer surveys implemented by means of a Conjoint analysis. Of these, the first one focused on the major customers in Finland, while the second one interviewed major international customers [Report: Lumi Koivunen, Juha Tiihonen, ”The international distributors of the Kaso Oy safe boxes – a market survey” 15 September, 1998]. The study on the manufacturing materials focused on the concrete used as the filling material in the safe boxes [Report: Jani Malvisalo, ”Burglary-safe boxes and fire-safe boxes; the structure and the concrete types suitable for the manufacturing” 3 December, 1998].

For this dissertation, the most interesting area was the last one: the developing of a modular structure for a burglary-safe and a fire-safe box. Two things were hoped of the modular structure: the streamlining of production and the decreasing of the value of ongoing work, as well as the ability to manufacture made-to-order safe boxes according to the customer's measurements. The figure above shows the size ranges of the E series safe boxes in 1998.

The structure and the manufacturing method of a safe box

At the time of the research, the structure of a safe box consisted of the outside layer made of sheet metal and the sheet-metal inside. Between these layers, there was a filling that provided the actual burglary or fire protection. At the time, various types of concrete were used as the filling material. In fire-safe boxes intended for protecting delicate materials – data security boxes – , there was an insert made of heat-insulating cellular plastic inside the box. The figure below shows the general structure of a safe box. In this dissertation, we will not focus on the special problems related to the locking mechanisms or the door hinges of the safe box. For the viewpoint of modularity, these behave in production similarly to the actual box part.

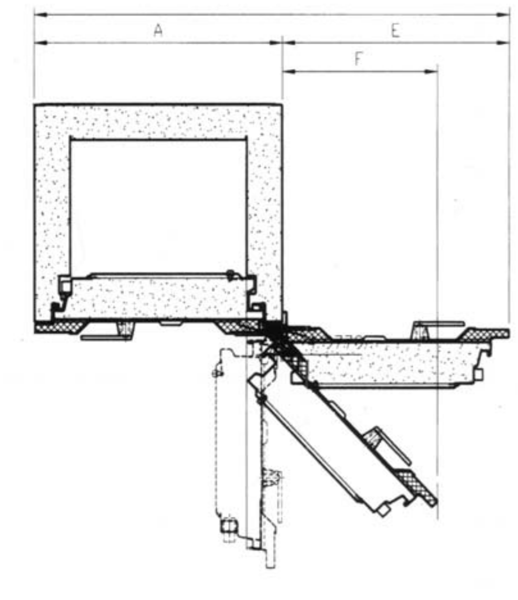

FIGURE 110. A sectional view of the structure of a safe box, as seen from above. The frame of the safe box consists of the outside and inside layers made of sheet metal, between which there is a concrete filling. [The Kaso brochure]

Burglary-safe boxes and fire-safe boxes are tested and certified products. Certification institutes, such as Det Norske Veritas, grant a certificate for the burglary and/or fire safety class of the box model on the basis of a test carried out by an accredited test center. At the time of the research, the burglary safety classes provided by Kaso were E1, E2, E3, E4, and E5, following the Euronorm EN-1143-1. The burglary protection is tested in a situation equivalent of a real burglary. The employees of the test center break in the box to be tested, and the protection class indicates how long the box is able to resists the burglary attempts and how challenging tools the burglars must use. In burglary protection, the filling material is crucial, and the safe boxes of different protection classes differ from each other in that respect. The higher the burglary-safe protection class, the more iron fittings and, in the higher classes, the aluminium silicate armour plates in the filling alongside concrete. Examining the weight of the various safe boxes provides us with an idea of this. A small safe box of 686 x 628 x 750 in the weight class E1 weighs 290 kilograms, but in the E5 class the weight of a similar box is 600 kilograms. The importance of the protection class for the customer is related to insurances. Insurance companies require using a safe box of a certain protection class as a condition for the insurance, or the issue may be connected to the insurance payments.

Fire-safe boxes had similar protection classes. An example of the challenges of such a test is the test performed for the Kaso data security boxes in 1986. In the second part of the test, the safe box was put in an oven heated to +1,090 degrees Celsius for 45 minutes. After this, the box was dropped from 9.15 metres on a concrete floor. After this, the box was held in a temperature of +900 degrees Celsius for 45 minutes. After this, the box was let to cool down for 20 hours. The box passed the test, as the indoor temperature never exceeded the maximum of +49 degrees Celsius [The Kaso Data safe 4000 S 120 DIS brochure material, 1997]. The concrete filling is crucial for the fire-safe box as well. Concrete contains crystallized water, and the evaporated water mainly prevents the temperature from rising in the burning test, which means that the thermal resistance of the boxes is only in part based on thermal insulation. Fire-safe boxes may also have a burglary-safe class certificate. At the time of the research, there existed separate product series for both of these purposes.

The practical arrangements in the manufacturing of the safe boxes were as follows. The manufacturing of a safe box starts with the cutting of the sheet metal parts for the inside and the outside layers and for the door. At the time of the research, these parts were manufactured in batches. As a number of boxes of various sizes were being manufactured at the same time, there were a number of prefabricated sheet metal parts temporarily stored in production. The layers were assembled by welding on jigs. The inside layer was placed inside the outside layer. In this phase, the possible iron fittings and armour plates required by the burglary-safe protection class were inserted in the box. After this, the concrete was cast between the layers while the box lay on its back. The drying time of the concrete limited the production speed. Humidity may be trapped inside a box that is closed too soon, which may in an extreme situation lead to corrosion and the wetting of the box contents. After the concrete has dried, the box is painted, the door part is assembled, and the box is equipped with accessories. The cellular-plastic inserts for the fire-safe boxes were manufactured in moulds. An extra layer was placed inside the insert to fit in the middle shelves.

A modular configurable safe box

There were several goals in the development of a modular, configurable safe box:

- The burglary-safe and the fire-safe classes as "modules" in the same product
- The customer-specific selection of the outer dimensions of the safe box, to be implemented freely or with a dense parametrical division
- The reduction of the number of metal parts stored in production
- Shortening the delivery cycle of the product.

The burglary-safe and the fire-safe classes mostly affect the filling and the locking mechanisms of the safe box. In burglary protection, the differences could be generally listed as follows:

- In class E1, light concrete is used as the filling material. The lock mechanism has drilling prevention plates.
- In class E2, special concrete with iron fittings is used as the filling material. The lock mechanism has drilling prevention plates similar to those in class E1.
- In class E3, the concrete filling has more iron fittings than in class E2.
- In class E4, steel fibre reinforced concrete with iron fittings is used. An aluminium silicate armour plate protects the lock mechanism. The lock mechanism has a tempered glass plate, and the door has explosion-proof latches.
- In class E5, special concrete strengthened with aluminium silicate armour plates is used as the filling material. The lock mechanism has prevention features similar to those in class E4.

Combining these with the fire-protection classes within the same product family seemed possible at the time – the challenge was mostly related to the various test requirements in the different market areas and the difficulty of controlling the costs cause by the various requirements in some of the feature combinations. From the viewpoint of modularity, protection can be seen as a function - the ability to resist mechanical or thermal penetration for a certain time. As can be seen in the above burglary protection classes, the modules in the product structure lead to nearly traditional element entities. In this case, the casting of the concrete is considered one element.

Here, we must return to the definitions of modularity and remind the reader of the idea of mixed modules (see section 5.6.). Does not a cast concrete filling with iron fittings and armour plates represent a modularity implemented by mixing, presented by Joseph Pine? If we regarded the situation as such, the form ought to be accepted as the starting point of the research, contrary to the author's argument. It must be admitted that such a cast module is a borderline case of assembly. According to the author's view, however, it is a case of assembly, not mixing, as the concrete, the armour plates, and the iron fittings do not *mix* and the ingredients to be mixed to make the concrete remain outside the solution level (Auflösungsgrad) of the modular system.

There were no physical, product-related obstacles for the free or parametric configuration of the outer dimensions of the burglary-safe boxes. In fire-safe boxes with an insert, the number of size ranges was limited by the manufacturing of the inserts in moulds, the number of which could not be large due to economic reasons. In production, the number of the different sheet metal parts in safe boxes of various sizes could have been controlled with a parametric size range division and by dividing the sheet metal parts into variable and stabile ones. An example of such an approach is the rationalization of the cabins in the Scania Series Three (See Chapter 4). However, the used production organization provided a poor support for such a solution. The introduction of a flexible production system in which the box parts were made-to-order in the machining centre, would have enabled the free variation of the size (excluding the inserts). This, however, would have required changes in the entire delivery chain. The product ought to have been designed as to be parameterized, the production would have required new machines, the production control ought to have been renewed and linked to sales, and the sales network (of which the international network was not controlled by the company) ought to have been equipped with the knowhow and the software enabled by configuration.

The mentioned issues would not as such have shortened the delivery cycle. Some drafts were presented on how the casting of the concrete could be replaced by assembly in the process. The following presents an idea of using superimposed bars. [The author's memo, 8 April, 1998] As was seen in the explained fire-protection test, the requirements set for the structure were so high that the concept was not considered to be able to meet them.

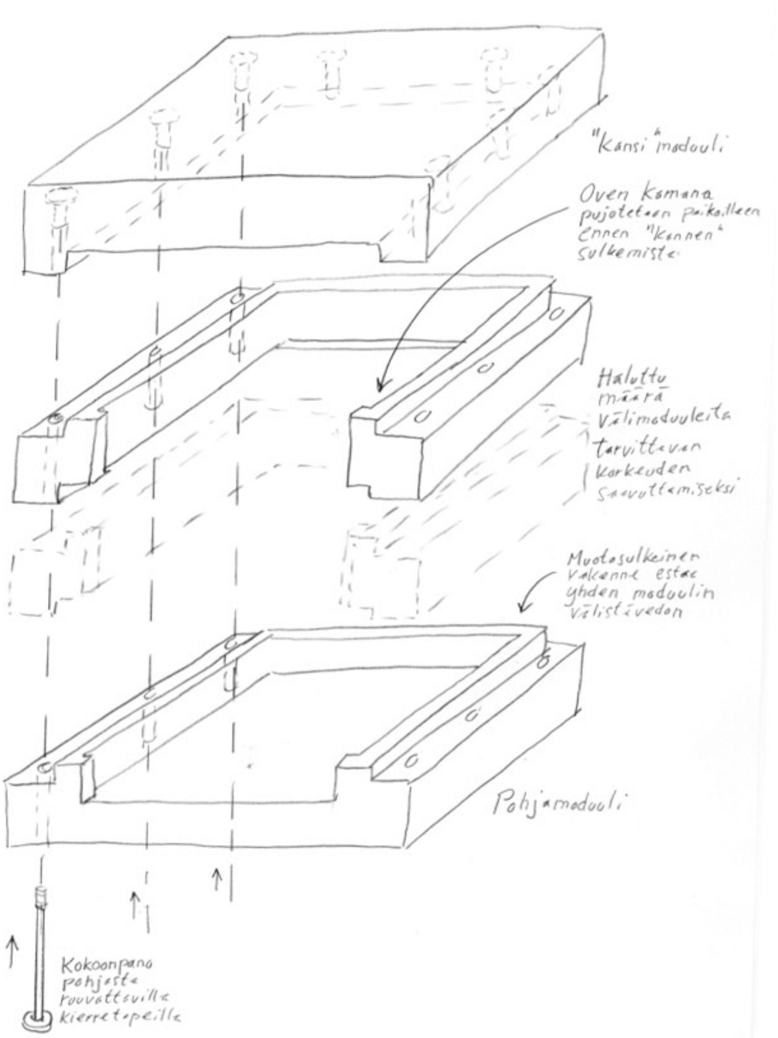

FIGURE 111. An improvement suggestion for changing the casting into an assembly [The author's drawing]

Conclusions of the safe box

In principle, it would have been possible to create a modular and configurable safe box. We can even claim that the modular structure is function-based if the functions of the safe box are the ability to take in items and the ability to provide a safe place for them. In this case, the size range is related to the first function and the security classification to the second. However, here we must pose the reservation that the design-related challenges were not solved during the research.

Even though it seemed possible to achieve modularity when examining the product, the case was no longer so when examining the production arrangements: big changes and investments would have been necessary. In addition, from the viewpoint of business operations and value chains, the benefits to be gained with modularity remained alarmingly thin (this was detected in customer surveys carried out via means of a conjoint analysis). For this reason, the concept of a modular safe box was shelved for the time being.

Drawing company strategic landscape framework would have highlighted the importance of the synchronization of production and the product structure from the very beginning. However, this was already apparent anyway. The framework model cannot pinpoint technological solutions for dividing the product so that it would have fit the existing production structure. The framework model would thus not have brought any new aspects to the issue.

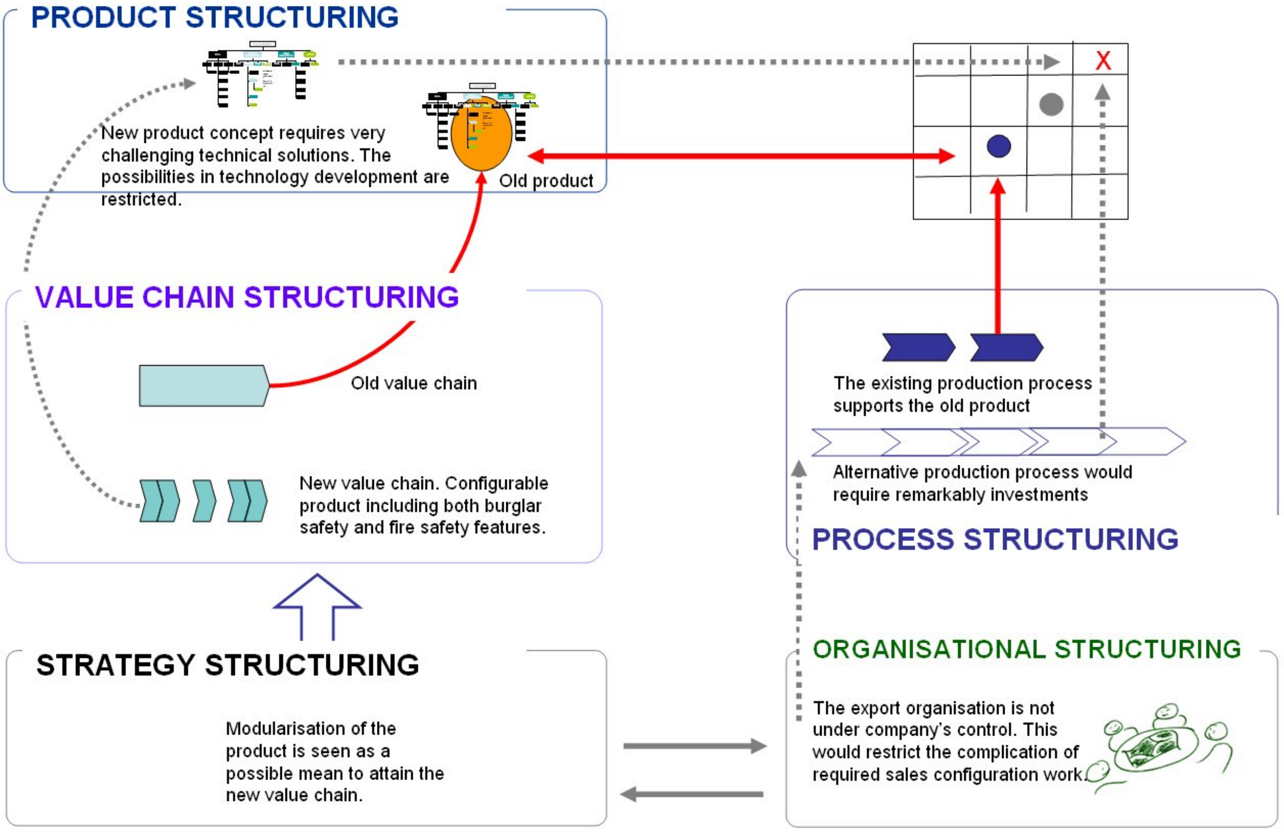

FIGURE 112. The CSL-framework model of the development of the product structure in the case of a safe box. The existing production resources did not enable shifting into the new value chain using the technological solution shown in the figure.

To conclude, we could present an observation of the concept "integral" often mentioned in the research on modular products. One would think that a safe box inside which concrete is cast would belong to the class of ”integral” products. However, we have shown in the previous section that the most important modifiable features of the product, the security classification and the size, can be separated into individual modules, and the modular system can even be called function-based. The ”integral” nature that prevents modularity does not, therefore, arise from the structure of the product but from the processes of production and sales and their operational capacity. (The quotes are necessary, as the reader will notice that it is very difficult to define the meaning of the word ”integral” in this context.)

Even though the tools presented above could not bring added value to this sample case, the observations are valuable for this dissertation. The critical factors for the use of the modular structure were not located in the product or its functional structure, but in the production process. This observation supports Hypothesis 2.

10.6. A machine tool

The sample case to be presented here is a product development project carried out Fastems Oy in 2001. At the time, three M.Sc. theses were being written for the company, related to the development of product development, sales, and the product range. For the viewpoint of modularity, the most important task was to develop the product structure for the machining centre. The author of the M.Sc. thesis was Jani Malvisalo, and the work was supervised by the author, researcher Antti Pulkkinen, and Professor Asko Riitahuhta. The product development project and the related technical details are explained in more detail in [Malvisalo 2001]. In addition to this, the case has also been discussed as an example of partial configuration [Pulkkinen, Lehtonen & Riitahuhta 2003]. The following analysis of the case is not, however, included in either of the mentioned references.

The Twin-Mill concept

The Twin-Mill machine tool concept consists of two horizontal machine tools that are placed contrarily. The figure below shows one side of the machine and its main parts.

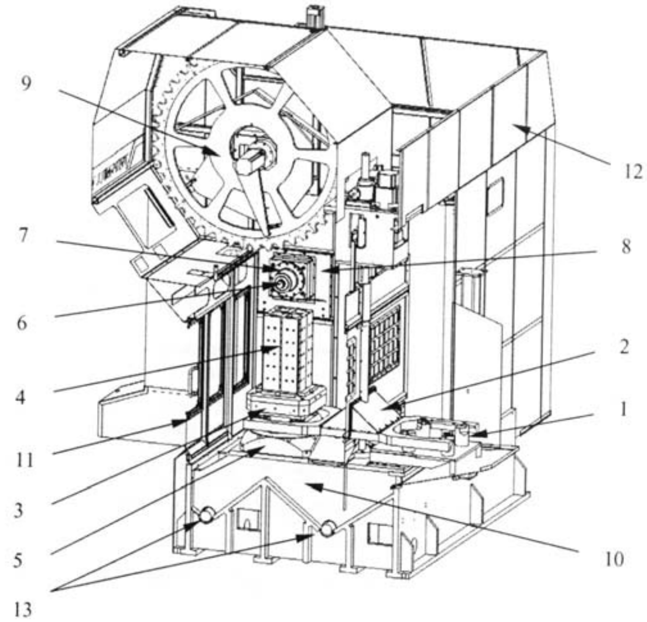

FIGURE 113. The main parts of the Twin-Mill machine tool [Malvisalo 2001 p. 24]

The items to be machined are attached to the clamps (4) that in turn are attached to the pallets (3). The item is brought from the loading station (1) to be machined on the pallet changer (2). The pallet is attached to the rotating table (5) which enables the turning of the item to be machined into various positions. The cutting tool (6) is rotated with spindle (7) that is moved with the sliding units in relation to machined item (8). The cutting tools are stored in the tool magazine (9) from which the desired tool is picked with the tool changer or the spindle. The machining units have a shared frame (10). The machining area is surrounded by the casing (11) that separates the machining area from the other parts. The entire machine is surrounded by another casing (12). [Malvisalo 2001] In the Twin-Mill machining centre, the two machines are assembled contrarily in one frame. The parts shared by the machining units are the control system, the pallet change system, all auxiliary systems, and all connections to the energy systems of the plant. The figure below shows a conceptual drawing of the layout of the machining centre. Most of the casings are removed from the picture.

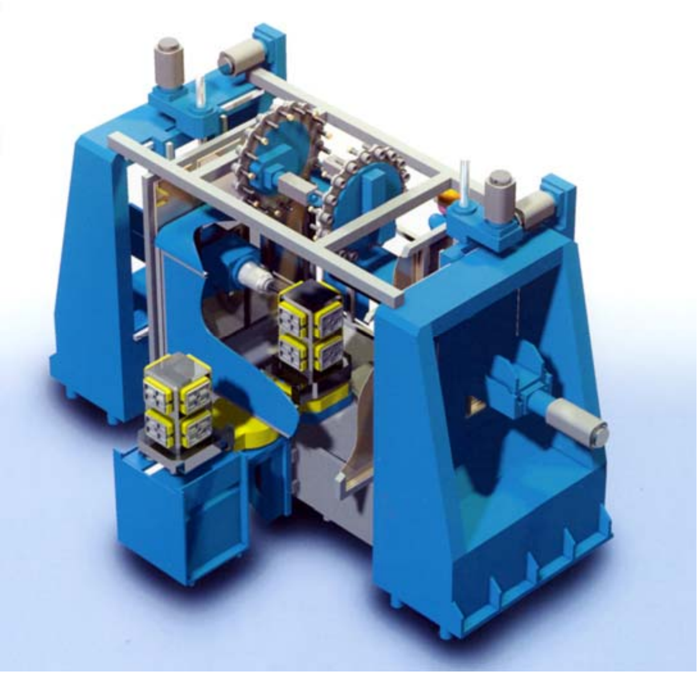

FIGURE 114. The main structure of the Twin-Mill machine tool. The picture shows the machine without the casings. Picture: the Fastems brochure.

The product development project

The starting point of the product development project was a situation in which several machining centres of the Twin-Mill concept had been delivered to the customer as project deliveries. In these deliveries, the design process had started with the items to be machined, around which the machine tool was then designed. Previously designed components were utilized in the design as much as possible, but the selection between design reuse and new product design was made in full in the delivery projects. A considerable number of products were designed case-specifically in these projects, that is, the products created in this delivery process were one-of-a-kind deliveries.

The product development project started with the estimate that the number of deliveries was sufficient to enable the definition of the market needs as the basis for the development of a systematically configurable product. On this basis, we set out to develop configurable machining centre products, of which the development project of machines in the D5 product family are discussed here.

Thus, the product development project was based on machines created as project deliveries that were considered to cover the configurations required by the market. The first problem was to acknowledge which part of the configuration between the machine deliveries was real, required customer configuration, which was related to the possible technical improvements, and which was unnecessary internal configuration caused by the delivery method. It would have been futile to carry out research on, for example, the drawing number level, as the assembly elements of the machine change slightly from one delivery and the other due to the project delivery method used. On the basis of the drawing numbers, no common use structural elements could be formed for the machines (for more information on the method, see Malvisalo pp 32-33).

As seen in the figure showing the main parts of the Twin-Mill machine tool, the element entities are functional. In this case, it was possible to implement a function-based module division so that the modules were also rational assemblies from the perspective of design and manufacturing. A functional modular structure was thus selected as the basis for forming the product architecture of a configurable product range. The next problem was to recognize which of the modules delivered in the projects could have been the same. The variation of the modules was evaluated so that the modules were identified as identical if they met the same customer need.

This examination alone did not lead to a usable product structure. A considerable part of the machine consisted of variable modules, and we could see that the number of module variants in relation to the delivered numbers of machines would be very large. Presented from the production viewpoint, a large number of different modules must be kept in production, and an individual module model is delivered in small numbers. The situation is shown in the figure below.

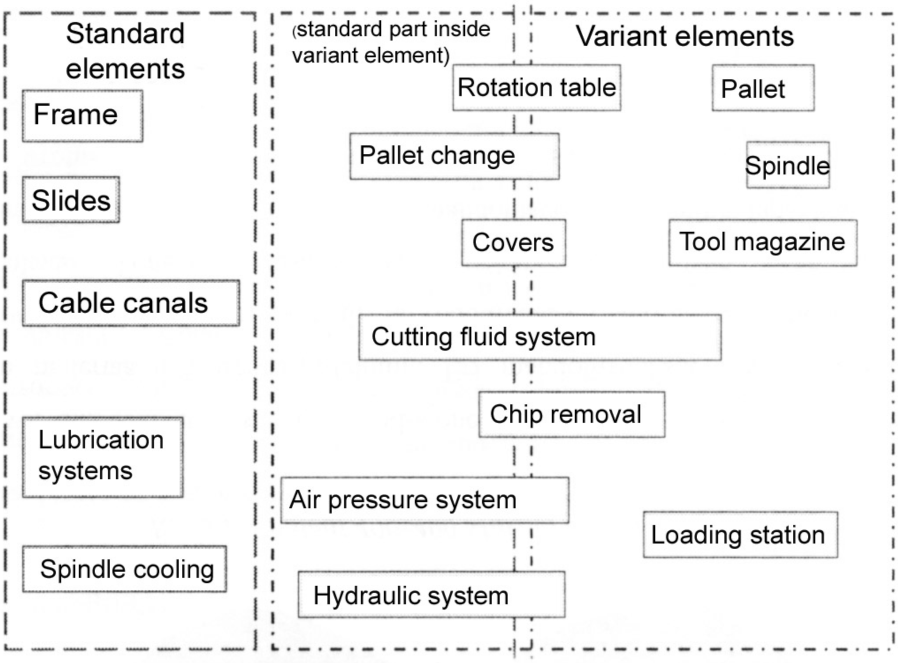

FIGURE 115. Forming the product structure purely on the basis of the functional structure leads to a large number of modules that contain variation and very few standard modules. The standard elements which are frame, slides, cable canals, lubrication systems and spindle cooling are on the left. On the right are variant elements; rotation table, pallet, pallet change system, spindle, covers, tool magazine, cutting fluid system, chip removal system, air pressure system, loading station and hydraulic system.[Malvisalo p. 46]

For this reason, we sought to divide the functional modules that contain configuration into a standard and a variable part in the product structure. In most cases, it was technically possible to implement this and retain the modules as assemblies. Implementing the pneumatic system and the hydraulic system described as systems as fully systematically configurable was considered unprofitable in regard to the challenging nature of the task. We decided to allow for slight machine-specific design and configuration in these cases (for example, in the pipe lengths and locations). The desired product structure is shown in the figure below. The relational arrow between the ”Chip removal from the work area” and the ”Frame” parts indicates that there exists a large number of elements functionally related to chip removal physically located in the frame.

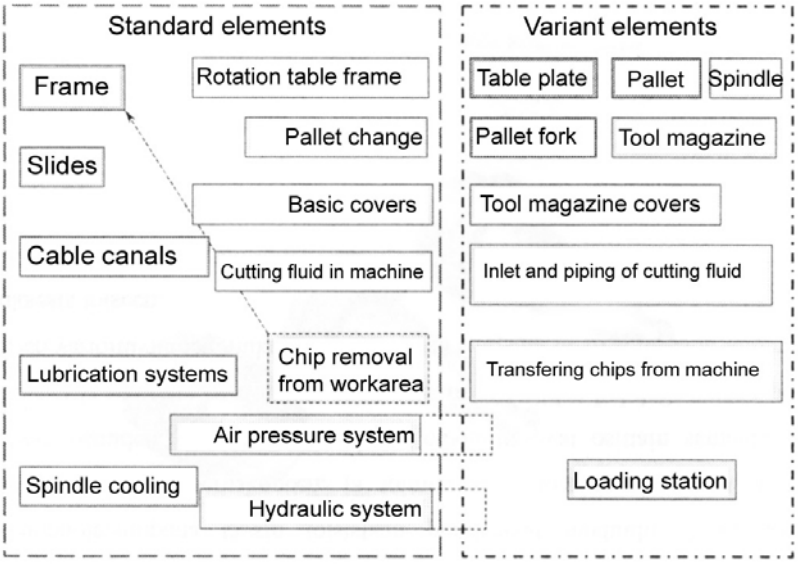

FIGURE 116. In the division that was selected, customer configuration is limited in the respective modules with interchangeable versions. Rotating table and its frame were separated to standard and variable elements. Similarly pallet exchange system was standardized except so called "fork". Covers, cutting fluid system and chip removal were divided in variating and standard elements. Converting the pneumatic system or the hydraulic system into systematically configurable products was not considered worth doing. [Malvisalo p. 47]

This product structure brought us to a situation in which the delivery time could be shortened, as long order and manufacturing times were included in the formed basic machine. When desired, the ordering and the manufacturing of the basic machine could be started even before the order is placed, as shown in the figure below. This was the same goal as expressed in the earlier case of the tunnel drilling rig, carried out by the same research team (see section 10.1.).

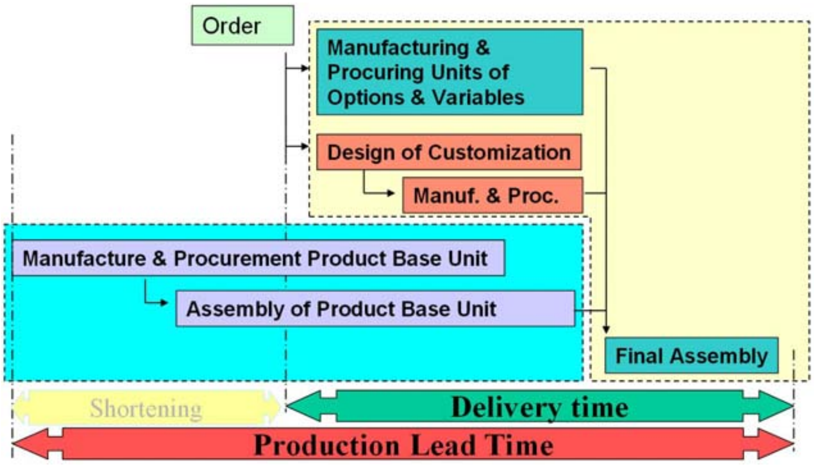

FIGURE 117. Forming a large standard entity enabled the shortened time-to-customer. [Malvisalo p. 71]

As the product structure consisted of functional modules that were also assemblies, a one-level configuration model could be used. In this case, the delivery was modelled on the Ponsse Oy "clothes-line model", explained in section 10.8. In this case, the product structure was presented as a variation tree in which one configuration selection is made on each level. This is shown in the figure below.

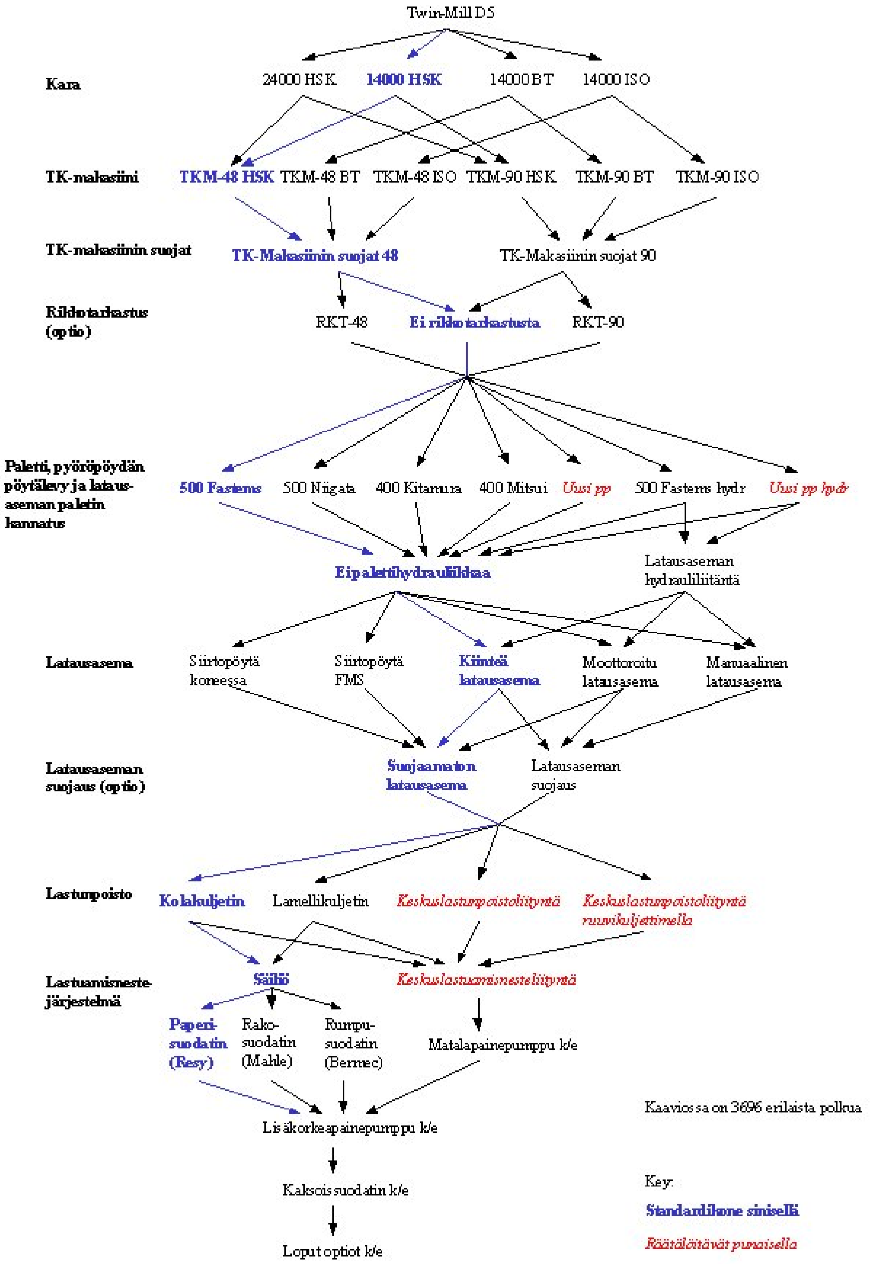

FIGURE 118. The product structure as a variation tree diagram. The configurations are selected by following the arrows, but the starting point of configuration can be freely selected. Each route through the diagram represents one configuration. The total number of different configurations is 3,696. Black items are optional modules, blue items are modules of the basic machine and red ones are project delivery parts. From the top: first the spindle is selected, then tool magazine, tool magazine covers etc.. *[Malvisalo p. 68]*

In this case, the unnecessary internal dependencies in the product structure were so well eliminated that we can freely proceed up or down in the selection tree and configuration can be started at random on any level. Certain parts of the machine delivery were excluded from systematical configuration. The most important reason for the fact that there is no way of foreseeing future customer requirements, for example, when adapting to the customers' existing machines (for example, a pallet system). Here, the delivery project is divided into two subprojects: the systematically configurable machine delivery that contains the main part of the delivery value, and the part to be tailored as a project delivery. From the viewpoint of the modular systems, the parts to be tailored are indicated as black boxes. For the scope of this dissertation, partial configurability is not relevant. For more information in the viewpoint of partly configurable products, see the article [Pulkkinen, Lehtonen & Riitahuhta 2003], and for the utilization of the various product-internal delivery methods [Juuti & Lehtonen 2006].

Conclusions of the machine tool

A machine tool is a product in which the customer's requirements are product functions and the function-carrying elements are mainly assemblies. A function-based division into modules fits such a product perfectly. In this case, then, new methods were not necessary. However, the company strategic landscape framework in the figure below shows interesting issues. The focus of the development project has been very narrow. The customer's processes and the associated requirements have not been considered, which in this case has not been a problem, either. *Development work was mainly carried out in the domain of product structuring, where the regularities of the product design process are valid in the form of the principle of emphasizing functionality*. As long as the focus of the development work is this, the framework model will not yield an added value. Drawing a CSL-framework model will, however, illustrate how bold a decision in the product strategy lies at the core of the development project. Despite the risks, the product development project succeeded in its entirety and all aims were reached.

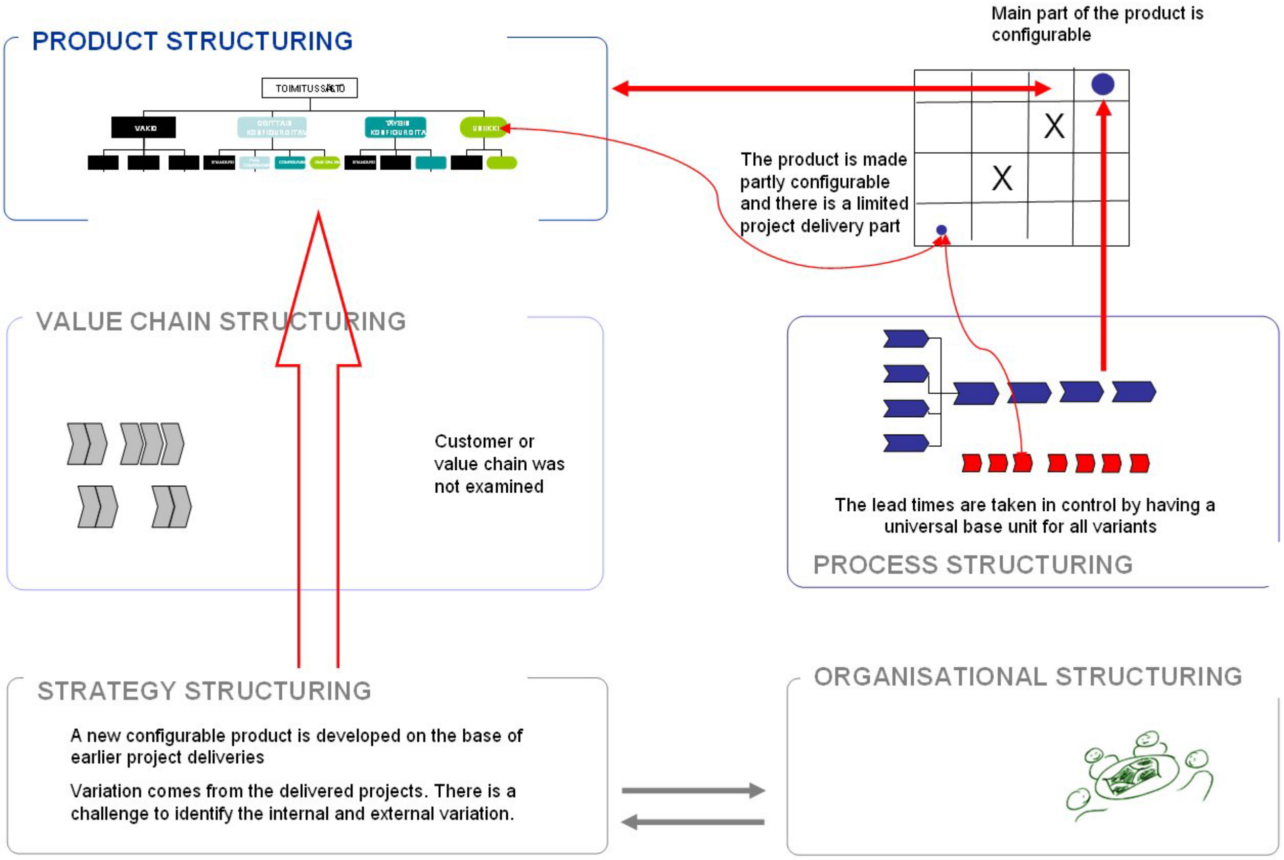

FIGURE 119. The CSL-framework model of the development of the product structure in the case of a machine tool. The framework model shows that product development takes brave advances mainly in the structuring of the product. In such a case, the function-based approach is relevant and fully sufficient. The goal to divide the functional modules into changing and standardized ones derives from the production.

10.7. An ambulance

The development projects described here were conducted for Profile Vehicles Oy in 2005-2006. At the time, Professor Asko Riitahuhta, researcher Antti Pulkkinen, and the author taught the application of product development methods at the company. The project was related to the launching of the Profile product development centre. The project was carried out as part of the ”Improving the co-operation and competitive edge of the metal companies in Northern Savo” project. The project was funded by the companies and the European Social Fund. In the development projects, the author served as a trainer, which means that the solutions to be presented were developed by the R&D team at Profile.

The ambulance product

Ambulance building belongs to the branch of industry that involves the body works and the equipment of commercial vehicles, which has long traditions in Finland. In an industrial scope, the manufacturing of body works for buses and cabins and superstructures for trucks began in the 1920s, and even earlier operations exist in the manufacturing of horse-drawn vehicles. Already in the 1970s and 1980s, the production volumes of the leading Finnish manufacturers exceeded the domestic market. This is also the case in the field of ambulance production. For Profile, the leading manufacturer in Finland, export is a vital condition, and thus the company is in a direct competitive situation with the other European manufacturers also on markets where there are no home-ground benefits.

Currently, no European manufacturer composes the vehicle of components from start to finish, but ambulances are built on known van models. There are three main methods of manufacturing. The number of the vehicle manufacturer's body parts is the largest when the ambulance interior is fitted on an empty van frame. The body structure of a van is also much utilized when the roof is cut open and replaced by a raised element manufactured by the ambulance factory. The ambulance part can also be made by making the body as a completely separate structure on the vehicle chassis, in which case the ambulance cabin is the only remainder of the body structure of the vehicle factory. Such a construction method is used, for example, in England. Of the Finnish customers, for example, the Armed Forces order such an ambulance type. The latter method of construction is sometimes also called a ”modular ambulance”.

When using the first structural method – in which the chassis, the cabin, and the outer structure of the body come from the chassis manufacturer –, the task of the ambulance factory is to fit in the indoor wall solutions, the cabinets, the equipment shelves, the working area of the nurse, the stretcher systems, the lighting fixtures in the treatment area, and the ventilation (in some cases, also heating), the partition wall, the alarm devices, the communication devices, the outlook and the painting of the vehicle, and the customer-specific equipments. When looking into the treatment area of an ambulance, everything there belongs to the delivery entity of the ambulance factory.

FIGURE 120. The basis of an ambulance is an unfurnished van whose roof is cut open and a new roof element is installed. When looking into the treatment area of an ambulance, everything there belongs to the delivery entity of the ambulance factory. The figure illustrates the Profile Genios ambulance.

A great deal of obligatory variation is related to an ambulance product. As the manufacturing method is the so-called building in a box, the big main parts (the floor, the left wall, the right wall, the partition wall, and the ceiling) are different for each ambulance to be built on a vehicle chassis of a different shape. This has naturally lead to the fact that standardization has taken place in the vehicle models to be built as ambulances. Currently, the leading chassis makes in Finland are Mercedes-Benz (Vito and Sprinter) and Volkswagen (Transporter). A large number of van-based ambulances are made for export with a General Motors chassis (for example to Norway). However, variation arising from the body structure does not end here. Body structures with a low and a high (in some cases, also middle) roof structure are available from the manufacturers. As the garage space of the customers sometimes sets limits for the height of the vehicle, there exists a demand for vehicles of different heights. The door structures of the vehicles also vary. Depending on the practices, the customer may wish to have a sliding door on the left-hand side as well. In this way, the ambulances can be manufactured as four-door or five-door models. Depending on the manufacturer, a low and a high version of the doors can also be available, which naturally affects the roof in the least. The importance of the chassis also sets pace to the cycle of product development. As the chassis manufacturer renews its van model line, the ambulance factory must also renew its product.

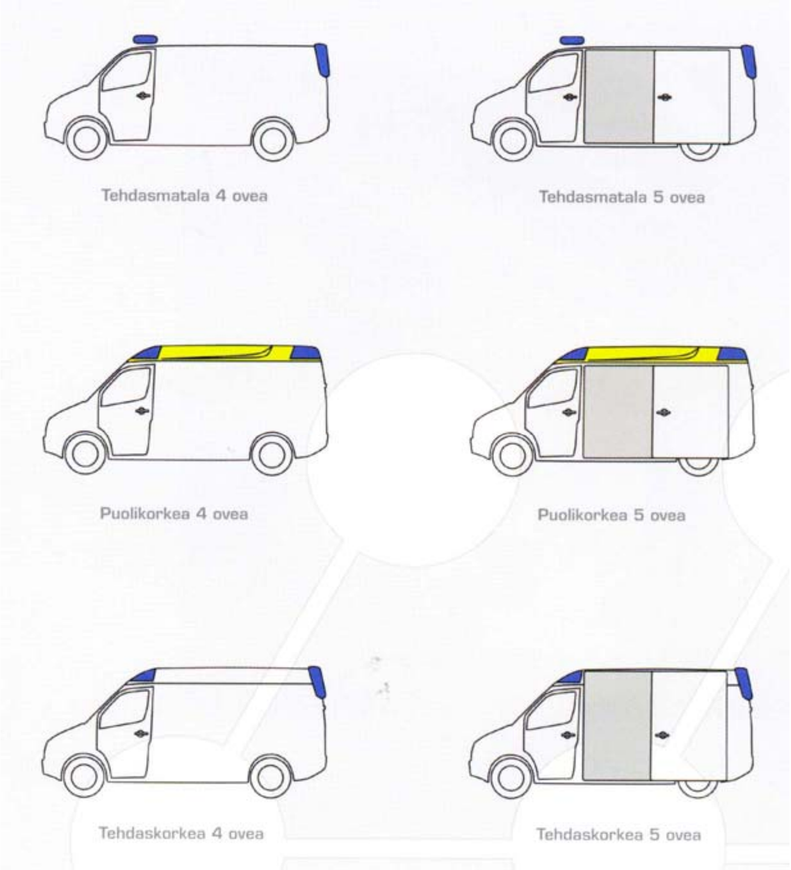

FIGURE 121. As intermediate versions were radically cut from the body alternatives for the ambulance with a Sprinter chassis, we were left with the six variations absolutely required by the market: the four- and five-door vehicles with three roof heights. A semi-high vehicle has a roof structure manufactured by Profile. Picture: Profile.

In addition to the variation arising from the chassis, there are types of customer-specific variation and market area specific variation. The orders of the authorities are becoming uniform across Europe, but the market area specific variation will not disappear due to the different treatment practices. The rescue personnel are, of course, the best experts to estimate optimal practices in rescue operations and ambulance operations. This naturally causes a large number of various preferences on the equipment and their location. The ambulances to be delivered in the same delivery batch are similar, but as the size of the delivery batch varies from one to a couple of dozen, there may not be many similar vehicles on the production line.

In light of what was previously discussed, it is clear that managing variation in the product range is of utmost importance in the field. There seems to be great potential in an ambulance for the use of modular product structures.

Looking for the modular structure of an ambulance

As was mentioned earlier, our research team taught product development methods at Profile. In this way, the functional structure of the product was evaluated already as part of the methodology training. Two drafts were drawn of the main functions of an ambulance: a list of main functions based on the transformation model, and a Function-Means –tree. In meetings lead by the author, the opportunities for creating the modular structure of an ambulance on the basis of the functional structure were examined. The working method was a work book. The work book was an A3 sheet given to each participating designer which was divided into fields presenting the key issues in the development of the product structure systematics. The work book, shown in the figure below, consists of six fields. The field of the product function lies on the top left, in which are the functions that implement the transformation of the technical system. The title of the field – ”The reason for the existence of the product” – emphasizes the fundamental nature of the transformation. The organs that carry out the function are collected in the next field to the left. The title of the field is ”The design solution environment”. Below this, there is the field for the part structure. Next to that, there is the field for the image s of the product. This was the only pre-filled field, as the main lines of the shapes and the layout of the new product had already been outlined, and the designer team held a shared vision of the design. In the bottom left corner of the work book, there was the ”Business environment” field, in which the changing features required by the market could be collected. In the bottom right corner, there was space for outlining the modular structure. The underlying idea in the layout was to emphasize the simultaneous connection of the modular structure to the part structure and the requirements of the business environment.

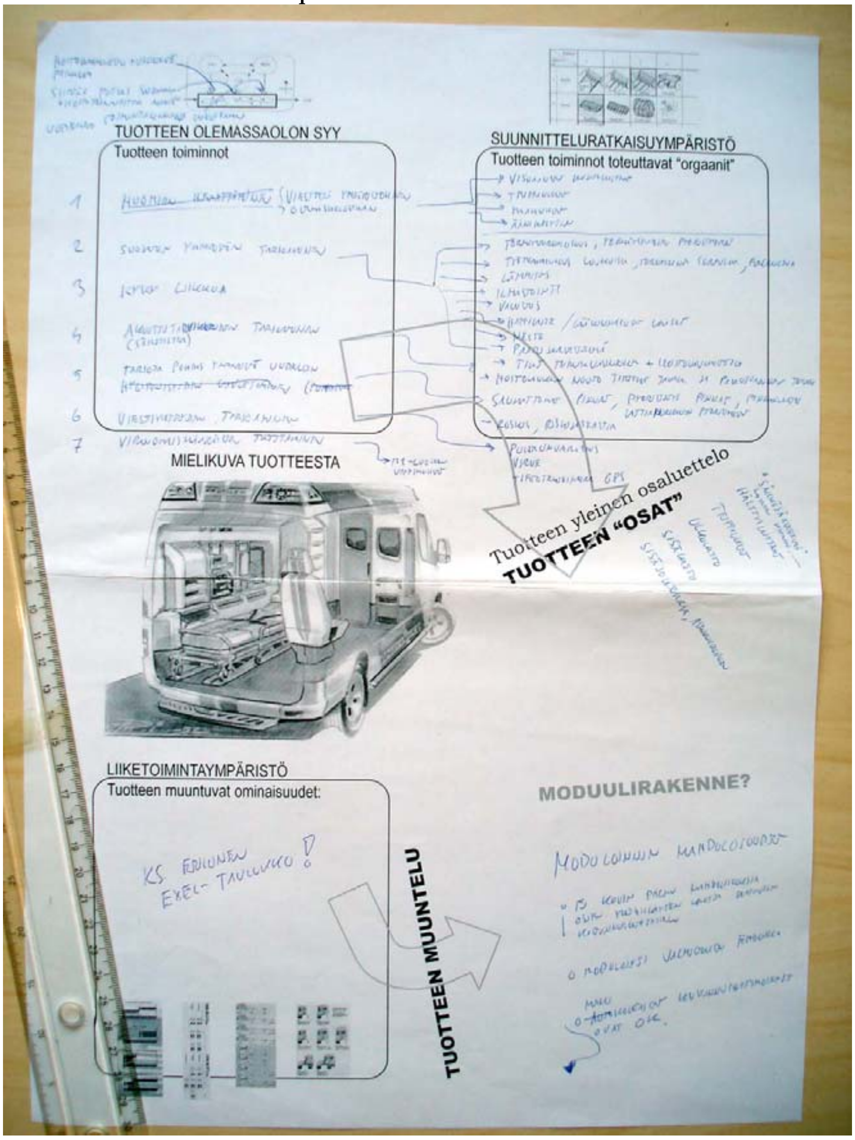

FIGURE 122. A work book with which a function-based modular structure was sought for the ambulance

Seven issues were defined as the main functions of the product:

1. The ability to move
2. Providing a protective indoor space and transportation, inclusive of an outdoor passage that can be closed
3. Providing acute treatment supplies (mostly realized as storage space)
4. The ability to recurrently provide a clean indoor space (realized as hygiene and cleanability)
5. Providing communication connections
6. The ability to stand out in traffic (on emergency drives and standing in the treatment location)
7. Meeting the requirements of the authorities.

The technical system that is capable of implementing these functions in a satisfactory manner can be used as an ambulance. Therefore, this is *the generic functional structure of an ambulance*.

The *organs* implementing the above functions were also easy to discover. In some cases, one solution corresponded to one function. For example, the vehicle chassis provides the ability to move, which is also one component on the part structure. Some issues showed as qualifiers of the design solution. For example, ”meeting the requirements of the authorities” here referred to meeting the requirements in the vehicle class M1 that for example stipulates the maximal width of the vehicle. (If this had been a dominant issue for design, the stipulations ought to have been written in full as functions. For example: ”maximal width” is the ability to traverse a lane of a certain size.) Two of the functions (2 and 3) contained the majority of the delivery of the ambulance factory. Item 4 ” the ability to recurrently provide a clean indoor space” mostly affects the selection of the surface materials and the method of making the seams.

When examining the connections of the organs to the part structure, no comprehensive view could be formed. As was mentioned earlier, some functions can be grouped in a certain part structure. On the other hand, some organs were located around the part structure – surface hygiene is the worst example of this. Therefore, a connection to show the structure could not be created between the product and the generic functional structure. *From this, we can deduct that the functions of most parts are related to the selected method of implementation instead of being directly related to the generic function of the ambulance.* Now the functional structure could have been redefined by listing the functions that the part structure in the existing concept have. Where this might lead is not of interest for the scope of this dissertation, as it means analyzing an existing product, not the design of a new product.

The other approach to modularity in the work book stemmed from the viewpoint of configuration. This is in principle the design method of a modular structure presented by Juhola and Välimaa (see section 5.7.3. ”Plus modularity”). The design object was a Volkswagen Transporter T5. All main parts of the ambulance were examined and an answer was sought to the question of how the need for configuration arising from customer variation could be directed to one part only. The strategy used for applying modularity was the encapsulation of variety. In this task, we were soon faced with strategic decisions concerning the product range. Which customer requirements will be included in product type A, to be implemented as a serial product? How large customer-specific special tasks are to be accepted in product type B that contains a separately-designed part, before they are classified as project deliveries to be manufactured outside the assembly line (product type C)?

In defining the product structure of the T5, we managed to take a quantum leap in two areas. The first of these was related to product policy, where compromises were discovered that enabled remarkable standardization. Another advance was taken in the development of the product structure, where the number of module variations plummeted as the interface of the modules and the structure of the product were changed. For example, a module that previously required dozens of variations, could now be implemented with one module manufactured as parametric in the production. This was not a case of transferring complexity from the product structure to product management, but a simple and easy-to-manage parametric operation of cutting one standard-size hole in the prefabricated vehicle element.

In the final T5 design, the interior to be produced at the ambulance factory consisted of six modules and the equipment to be added on them using the plus principle. Most often, only one or two versions of the modules were necessary. The left wall is the most complex module in terms of product structure technology, as it contains a separate modular system (bus modularity) for the cabinets, based on fixing rails. The main ideas in this system were developed in the previous Genios project. Similarly, in a number of other issues, the good solutions were achieved because of the development work on the materials and the structural method in the previous Genios project.

Conclusions of the ambulance

From the viewpoint of modularity and standardization, a very satisfactory product structure concept was created for the T5. The concept was entirely based on standardization, the principle of limiting variation, and utilizing the opportunity for variation in production. Functionality proved to be unimportant for the modular structure of the product. The figure below shows the company strategic landscape framework model for this sample case.

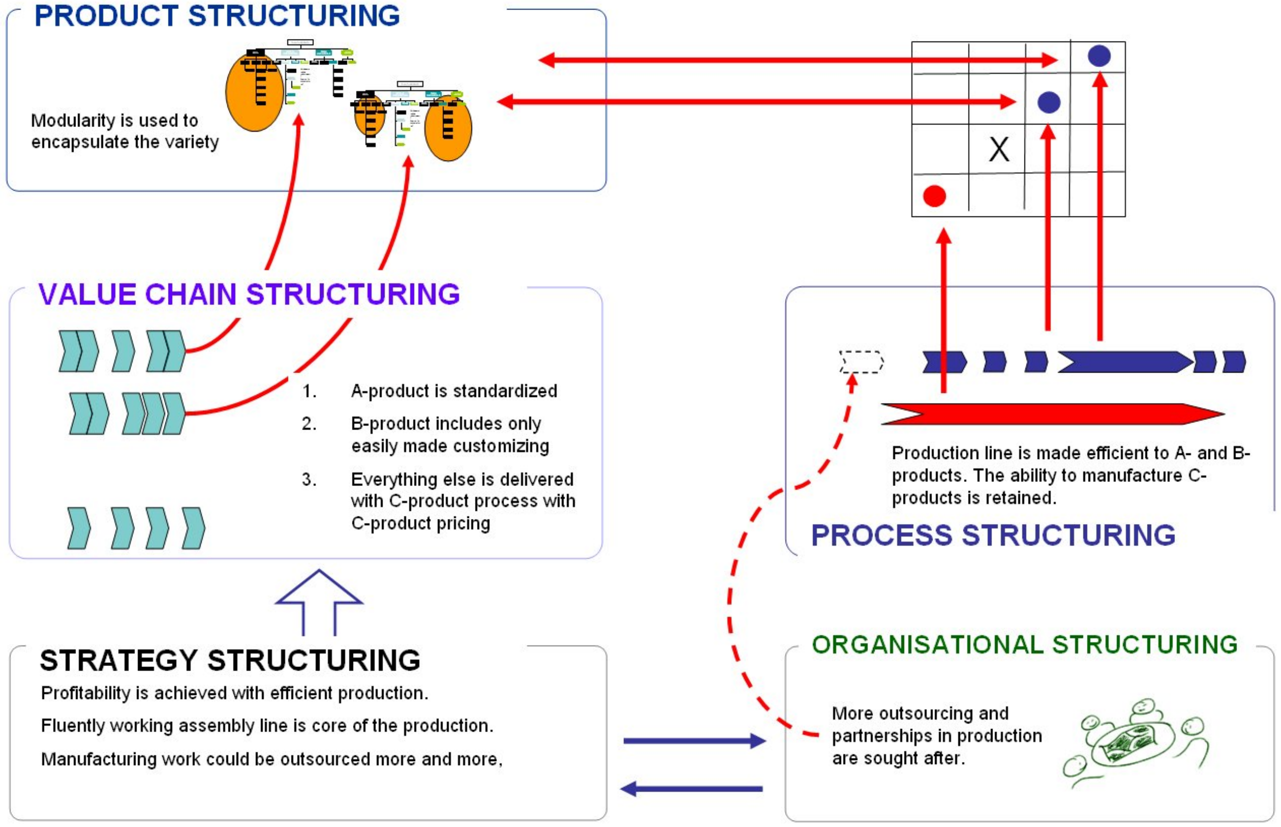

Figure 123. The CSL-framework model of developing a product structure in the case of an ambulance. Shifting from one-off production to serial production on an assembly line is a crucial factor for the development of the modular structure.

The CSL-framework model leads the product structure design into the implemented direction. However, it can be seen in the framework model that even though the developed solution can be considered good, it is not necessarily optimal. The framework model shows the key strategic goals in organizing production into serial assembly work on an assembly line and the separation of the manufacturing and, when possible, moving the manufacturing to subcontractors. Managing variations strongly supports these goals, but the development work only occasionally considered the delivery method of the components and the resulting estimate times and changes in the process. This viewpoint was further examined mostly as an exercise carried out by the researchers. At this stage, the issue was not implemented on the product structure, as it was estimated to be a matter of little importance with the present production volumes.

The design exercise is based on the theorem presented by Juuti on the internal division of the product according to the delivery process type of the part and its effect on the efficiency of the product development and production processes [e.g. Juuti & Lehtonen 2006]. All the main parts of the product were divided into four categories according to the process applied in their delivery. The classes were:

1. COTS (commercial of the shelf): the so-called hardware items that can be bought as such from several suppliers
2. A standard part manufactured according to the company's own specification. Can be stored on the shelf if necessary.
3. A configurable, delivery-specific part to be assembled of the two mentioned above
4. The delivery-specific part that only contains purchases or design related to this specific delivery.

The classes above differ from each other in terms of their cost structure, estimated delivery time, and the process time. A conceptual drawing made on the process effect. The lengths of the arrows in the figure below are estimates, but they are not based on any implemented deliveries, and a scale cannot be directly attached to the drawing.

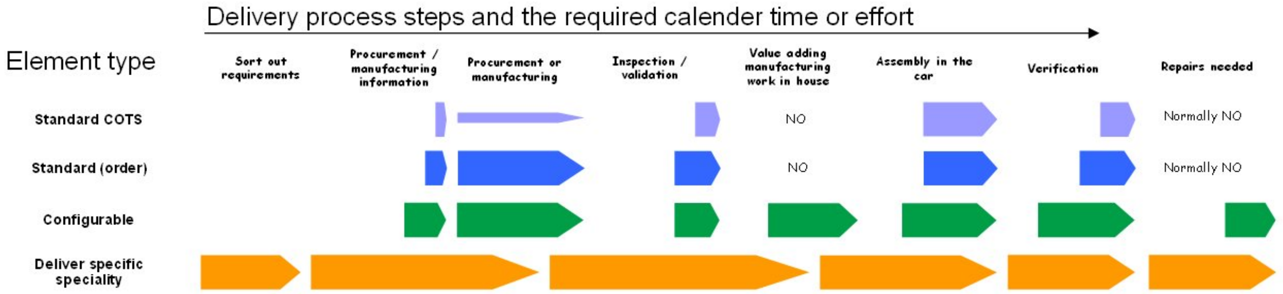

FIGURE 124. The various delivery processes of the product-internal elements in the case of an ambulance, according to the theorem presented by Juuti

The figure above clearly shows that the different elements are in a completely different position in terms of the production flow. In some cases, this might have a considerable effect on the delivery cycle of the product, as is outlined in the figure below, showing the example deliveries type A and C.

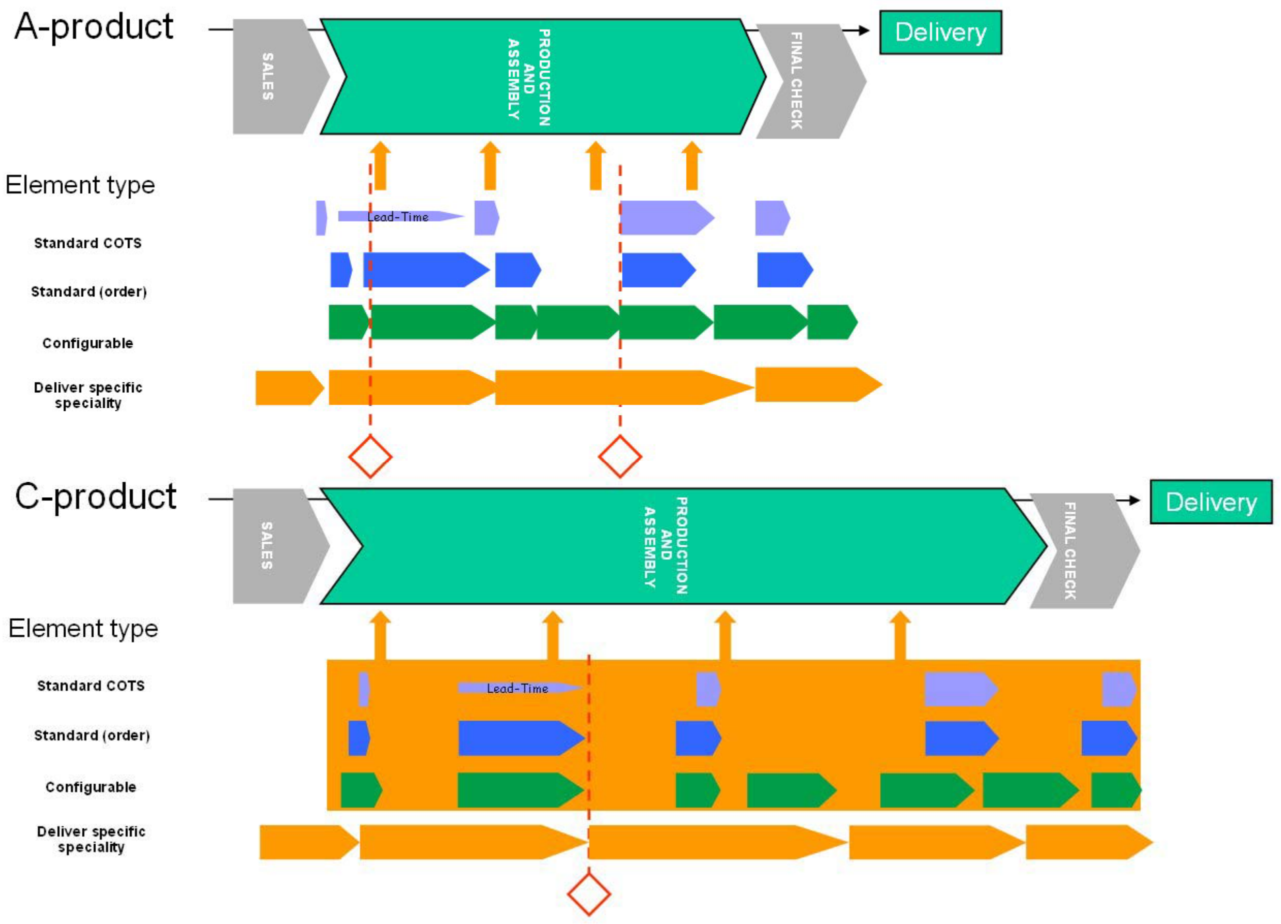

FIGURE 125. For the delivery cycle of products type A and C, elements of various types were crucial. In product A of this example, the production speed is determined by the elements configured. In product C, the time-to-customer is determined by delivery-specific parts. In product C, the stage-gate model checkpoints "delivery content defined" and "ready for the assembly line" cannot be kept (the red lozenges in the figure).

Should we, then, also consider in the design of the module structure the fact that there are no elements to be produced in the delivery process in the module that have a negative effect on the process time of the module? This must be done in cases in which the production cycles and the value of ongoing work are to be optimized. In this case, it was not considered necessary. Instead, the same result was thought to be reached via recognizing and fixing the most imminent problems.

10.8. A forestry machine

The case of the product structure of forestry machines introduces the product structure systematics applied at Ponsse Oy in 1999. In January 1999, our research team made an excursion and examined the product structures and interviewed representatives of the company in connection with the Konsta research project [Konsta 1999]. Some of material herein is from events organized by the TEKES research projects in the technology program, in which Ponsse presented its product structure systematics. In this dissertation, the ideas in the Ponsse product structure systematics are presented in the form they were implemented at the time the factory extension was introduced in 1998. The later advances in structure management (see e.g. [Nummela 2006]) are not discussed.

Corporate history

Ponsse is an engineering company launched around knowhow in a specific area of application. Einari Vidgrén, the founder of the company, used to work at felling sites. In 1968, he and his partner Erkki Tarvainen started to design a forestry tractor that would resist the conditions of logging and felling sites better than the existing models. The prototype machine was called ”Ponsse” and its durability was praised at the Tehdaspuu Oy felling site in 1970. This provided the partners with faith in starting forestry machine production in Vieremä [Kellberg 2000 p 19]. The figure below shows an early product.

FIGURE 126. The figure shows the first-generation ”Ponsse” at a forestry machine fair in the early 1970s. This product was not systematically configurable. The machine structure was improved and developed from one delivery to another. Desired changes or new properties could also be added for each customer. [Kellberg 2000 p 55]

Production was thus based on individual products made to customer needs. The company has acquired knowhow on the production or product structure technology as the operations have expanded. In 1986, for example, the situation with the machining tools at the factory was such that the new employee Pertti Korhonen reports to have wondered at how forestry machines could be produced with the available tools in the factory. Next, the company shifted without intermediary phases from one slide lathe into computer-controlled CNC machines [Kellberg 2000 p. 50].

As the operations expanded, the company faced a situation in which the old method was no longer sufficient. Each customer delivery could not be designed or configured following the projecting engineering workshop tradition. It was stated that genuine serial production must be launched and customer requirements must be systematically managed. The goal was thus to rationalize production and eventually reach systematical customer configuration.

The company underwent a radical change from 1995 onwards. The entire model line was redesigned, while a product data management (PDM) project was carried out in the company. In 1996, the chopping machines Ergo HS16 and Cobra HS10 were launched. The following year, the forwarders Buffalo S16 and Caribou S10 were launched. In 1998, the model line was complemented with the Bison S15 forwarder [Kellberg 2000 p. 33]. The machines in the model line were designed to form a product family that utilizes shared components and design solutions and whose versions could be produced and sold as a systematically configurable product. The product range is shown in the figure on next page.

The product structure systematics

The implemented product structure systematics had a simple principle and it strongly relied on standardization. The product structure division has been performed based on customer configuration. The first principle to determine the structure was the simplicity of management. This stemmed from the fact that at the time of the interview, the company did not want to make heavy software/hardware investments in, for example, the configurator. Configuration in sales had to be simple, and there had to be an opportunity to create the bill-of-materials (BOM) list of the product item directly from the configuration implemented, without computer-based tools. This was solved as follows:

- the product structure only included two levels
- as much of the attribute data and the parametric values as possible were processed as module alternatives.

In the presentations, this product structure method was called a ”clothes line”. The writer is familiar with the approach precisely as "the Ponsse clothes-line", even though the company itself did not use this name. The idea is that each product model has its own ”clothes line” where the modules possible for the products hang. It must be possible to perform configuration so that the module variations that correspond to the customer requirements are picked from the ”clothes line”. Each module variation has an unchanging item structure; these together form the BOM for the product instance. From the product management viewpoint, the clothes lines of the various products cross with the modules shared by the products.

The structure was implemented to a large extent following the outlines of plus-modularity ([Juhola & Välimaa 1997] see section 5.7.3. ”Plus modularity”). The Ponsse modules, however, were not assembly modules. A number of the modules were collections of parts located around the machine that could not be assembled separately. This approach lead to a division that resembles a functional module division at first glance. However, there are differences between the approaches. In a functional division, for example, the tyres of the wheels would not form a separate module, as they are available from two manufacturers. This, however, was done in the case of Ponsse, and the tyres did no longer have attribute data.

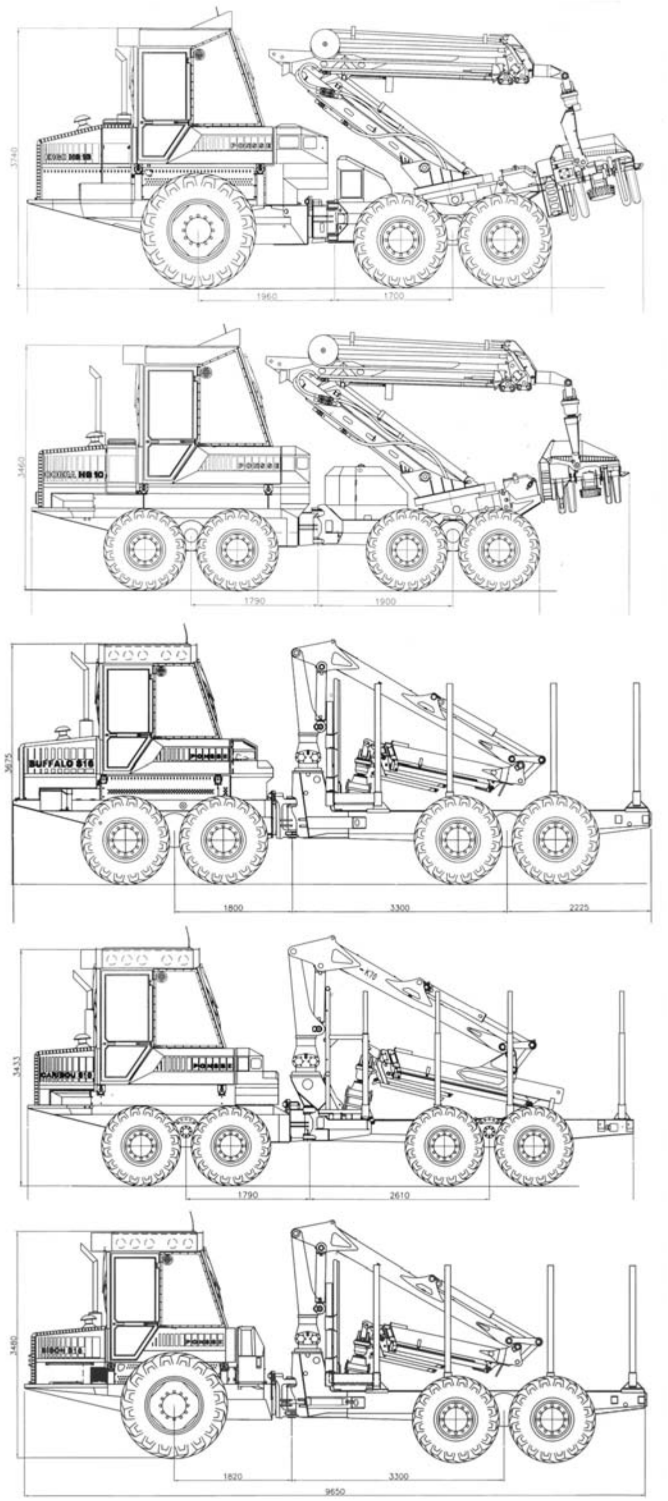

FIGURE 127. The forestry machine series introduced by Ponsse in 1996-1998 is implemented as a series of products that can be systematically varied. Machines from top to bottom: Ergo HS16, Cobra HS10, Buffalo S16, Caribou S10, and Bison S15. The pictures are from the 1998 Ponsse catalogues.

An apparent challenge with this method was that it had to be possible to manufacture the product item on the basis of the BOM. Certainly, there existed generic assembly drawings, but complete drawing lists of the structural design (Bauprogram) were not available. The company did not intend to create such lists, but the practice relied on the expertise of the employees at the assembly line. The corporate culture also supported the easy assembly of the product: design included the ”overall day tradition”. On the “overall day”, the designers worked at the assembly line for a full day to retain contact with the actual production. At the time of the interview, production was just being started at the new factory; the method has later been further developed. For example, Heikki Ojala, factory manager at the time, reports in [Kellberg 2000 p 39] that ”the work cycle data is linked to the modules”.

Notes on the case

The Ponsse case can be considered a case in which the method development succeeded in an exemplary way. Even though the investment in a new factory took place at a non-favourable time on the market, the company was able to utilize its development investments after the minor initial problems, and it has succeeded extremely well financially. We can make some notes on the process of change that apparently contributed to the success:

- A very small, uniform team designed the entire new product range, and the systematics of the product range did not have to be documented.
- In connection with the change, the alternatives provided at sales were also radically standardized. For example, it was decided that a standard-model crane was to be launched without an opportunity for variations.
- In a small and low organization, a comprehensive view and a shared opinion was formed of the views of the sales, design, and production design.
- The change was comprehensive. No "traditional" models remained in the model line.

Compared to the case of the tunnel drilling rig, we note that there exists much less configuration in the Ponsse product and it does not affect the technical function of the machine as deeply. As a technical solution of a product structure, this might not be possible for a tunnel drilling rig. Compared to the truck case, then, the number of variations is much smaller, but the cases are very similar in other respects. If we regard the selection of a machine model at Ponsse as corresponding to the combined selection of a chassis series and a chassis layout Scania, we can see similarities in the two solutions.

Conclusions of the forestry machine

The Ponsse product structure in 1999 resembled a function-modular product to the extent that even the author has previously suggested it as function-modular. However, here we have mistakenly examined the finished product and used it as the basis for the evaluation of the systematics of the product structure division. *The division into modules is not, however, based on the technical structure of the product, but the necessary customer variations and the selected two-level product structure systematics.* A modular division that stems from the functional structure thus comes close to the implemented structure, but it does not prove the critical solutions for this case.

The framework model of the forestry machine cases in illustrated in the following. Similarly to Scania, Ponsse also held to the most important elements for the product and the production. In this way, the structuring of the network was rather irrelevant for the case. The strategic projects related to the engine purchases at the time are left outside the scope of this description, and the entire brochure material features machines that still had engines manufactured by Caterpillar and Perkins. The decision on not binding organizational resources to the purchases and maintenance of product configurators systems belonged, however, to the area of organizational structuring. This set a direct challenge for the product structure (note the relation that does not exist in the generic presentation of the CSL-framework).

The most important part of the analysis was to note that a systematically configurable product was a strong corporate-strategic choice which, together with the factory investments, was expected to provide the required prerequisites for growth. The strategy was implemented with minor delay. As the corporate management had committed themselves to the project, product decisions related to the standardization of the product supply could be implemented. It is reported that customers were eventually taken to the management to hear why the production of some special version does not serve the interests of the company – or the customer.

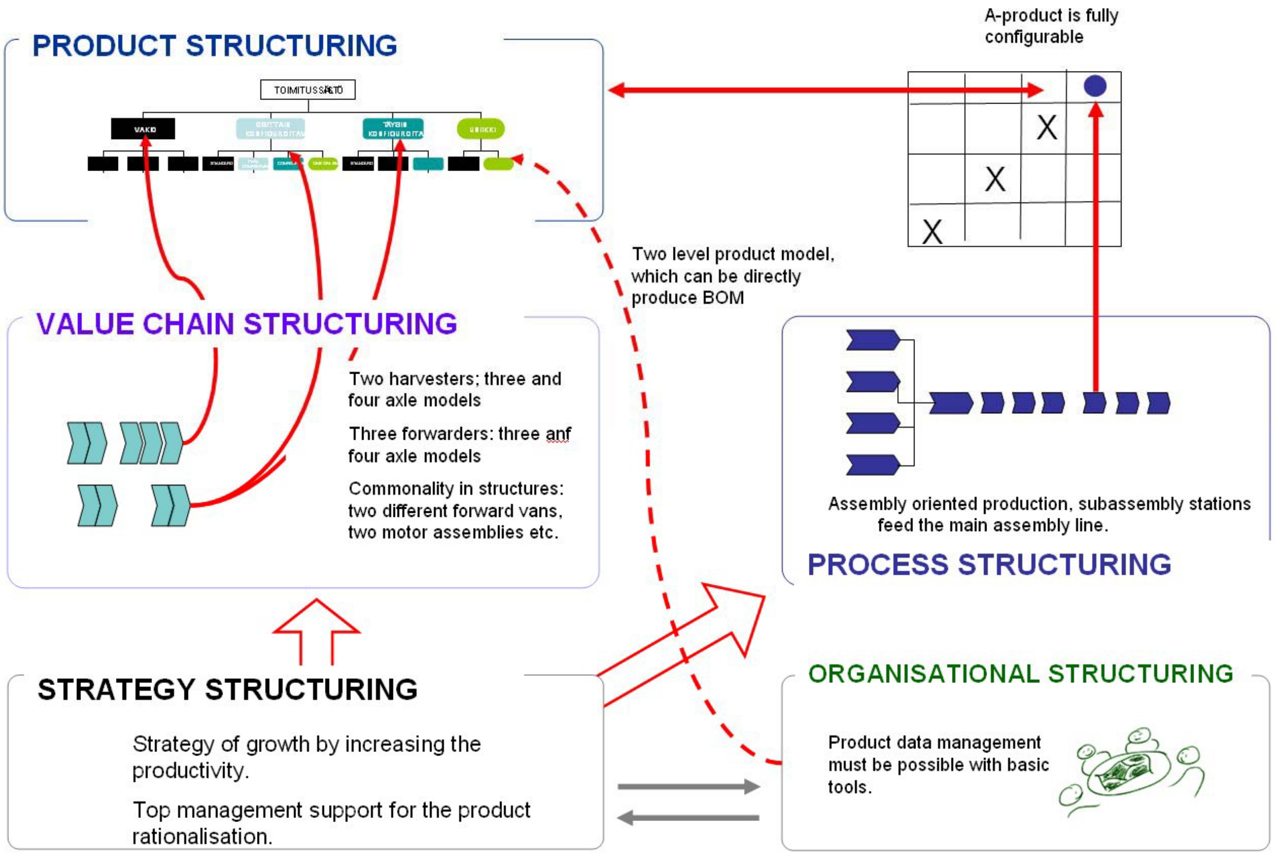

FIGURE 128. The CSL-framework model of a forestry machine. Note the atypical relation from the structuring of the organization directly to the structuring of the product.

The company strategic landscape framework model shows the key elements. The required simplicity of the product data management and the possibility to rely on expert production are visible. The framework model does not show the product series division. This may be due to the writer's (author's) minor knowledge of the application area. Thus, the possible missing elements are not the method's flaw. The sought product structure was to make the sales structure of the product resemble the one used production control. This can be seen in the framework model.

10.9 The proof of Hypothesis 2

The results of the industrial examples are collected in the table below. The table evaluates the opportunities developing the functional module structure and its rate of success in business operations. Respectively, it is evaluated whether the key criteria are shown in the company strategic framework models created. Finally, the superiority of the framework model approach is evaluated.

TABLE 3: Applying function-based modularity and the company strategic framework in defining the modular structure in the sample cases

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

In principle, it is possible to form a function-based modular structure for the products in all the sample cases. Of the eight cases, however, it clearly lead to a profitable result for the business environment in only one (with a reservation, two). In six cases, the result was not the desired one. Examining the examples in the framework model would have indicated the guidelines for the development of the modular structure in five cases. In three cases, the framework model would have shown the challenges of the operational situation, but not been able to directly show the technical solutions necessary.

On the basis of this observation material, we can conclude that the functional structure is not an essential starting point for forming a modular architecture. **This is because the functional**

structure is related to the transformation implemented by the technical solution. Therefore, it is a dominant element *in the area of product structuring*. In an M modular product, the modularity of the product is no longer only related to the transformation implemented by the technical system. In strong terms, modularity does not exist in the mere area of product structuring. A value chain in which a technical system is included as a part, as well as the production process that provides the instantiation of the technical system must also be considered.

Hypothesis 2 argues that the functional structure cannot merely form the basis for a modular architecture. The theory on the evolution of modular systems and the framework model presented earlier in this work prove that the hypothesis is valid. In addition, Hypothesis 2 argues that the functional structure is not the most important starting point. The material presented strongly supports this argument. Our conclusion is that **on the basis of the material presented in this dissertation, Hypothesis 2 is valid.**

As we operate in the field of Design Science, we do not remain content with the way things stand. For valid and effective research, we must be able to show how the results can be utilized to improve the situation (see Chapter 3). This will be presented in part in the following chapter, even though it is a development that remains outside the actual scope of this dissertation. At the same time, we will prove that it is in principle possible to develop an outline for a modular system, that is, the *goal architecture of a modular system* in new product design. The phenomenon discussed in this dissertation thus exists! The practical methods of determining the goal architecture and its form will be presented in future publications.

11 The design process of a new modular product

In this dissertation, we will show that when using a systematic design process in new product design, relevant design decisions for defining the modular structure can only be made in connection with the evaluation of the concepts. This is not necessarily a problem, for example, in software design where the modular structure of the product is *free assembly enabled by standard interfaces* (mixed modularity). With the products examined in this dissertation, that is, machine construction, process plants, and multiple-technology products, a problem arises that I have called in my teaching (lecture series TTE-3140 Modularity at TUT) the difference of the *bottom up* and the *top down* approaches. There are no established terms to describe these approaches, and this difference in the approaches has not been considered at all in a number of studies. (In addition, the same English terms are used to refer to other phenomena as well).

11.1 The bottom up approach

In this approach of designing the product structure, we start from individual modules and the examination level is thus the part structure level of the product. For example, the mentioned module drivers can be used as the grounds for the module division. The product can be divided into elements so that it suits for, for example, road transportation, to be tested as modules, to allow for easy repair by changing the modules, and so on. This approach often leads to a large number of modules that are delivered in small numbers. The modules in each product version are unique for this variation, and there are not common modules. For this reason, when starting with individual modules, the main goal is to discover and utilize the commonalities between the elements that form the modules. When starting with individual modules, the risk pertains that the product remains as partly modular and no comprehensive modular architecture is created for it. [Lehtonen 2006]

This approach is thus possible by using existing methods. *This, however, is not new product design but dividing a product existing as selected concepts into modules.* In Addition to the mentioned risk of the approach that it will not lead to a modular architecture (but to the standardization of interfaces), there is another risk: the creation of non-designed dependencies over interface boundaries. On this issue, see for example the licentiate thesis of Ulf Lindholm [Lindholm 1999, ”Paper A: Unpurposeful Interactions”]. In the author's lecture course, this is simulated with a 7-hour simulation exercise in which a group of a minimum of 50 students receives the task of designing and implementing a configurable space station. During the exercise, a miniature model of a space station is built using a construction element set. Ten teams build the modules and finish the designed interface definition which enables building a modular space station that contains interchangeable parts. The lack of a comprehensive view, however, leads to the situation that the assembly of the first version never succeeds without changes in the individual module implementations. The architecture of the space station needs to be redesigned in every exercise, until a functional modular structure that fits the configurations is achieved.

The arguments presented on the properties of this approach are based on industrial experiences and they can also be proved in a simulated test environment. In this dissertation, however, we will not need to prove the weaknesses of the ”bottom up” approach, because, as mentioned earlier, there is no justification for accepting the method to be used in the new product design.

11.2 The top down approach

To avoid the mentioned problems, the author has taught an approach **that will in this dissertation be suggested as the design process of the modular structure in new product design.** In the course, it is taught that in this case, the main goal is to manage the product range. For this reason, the natural direction of proceeding in top down, from the system level to the substructures. According to the course material:

”...in this case, it is important to first recognize the necessary variations. After this, a product architecture is designed that is able to produce these variations. The product architecture defines all the necessary modules that are designed to meet the boundary conditions of the architecture. One description of such a design process is the V model of Systems Engineering.” [Lehtonen 2006]

In the course material, we also present a view on why this method is rarely used despite its superiority:

”This is a more demanding method of forming a modular product. It is more difficult to utilize existing design, as the modules are now produced according to the requirements of the system instead of approving existing entities as modules.” [Lehtonen 2006]

11.3 The design process of a new modular product

The phases of the design process of a new modular product follow the phases of the V model of Systems Engineering. The V model is shown in the figure below.

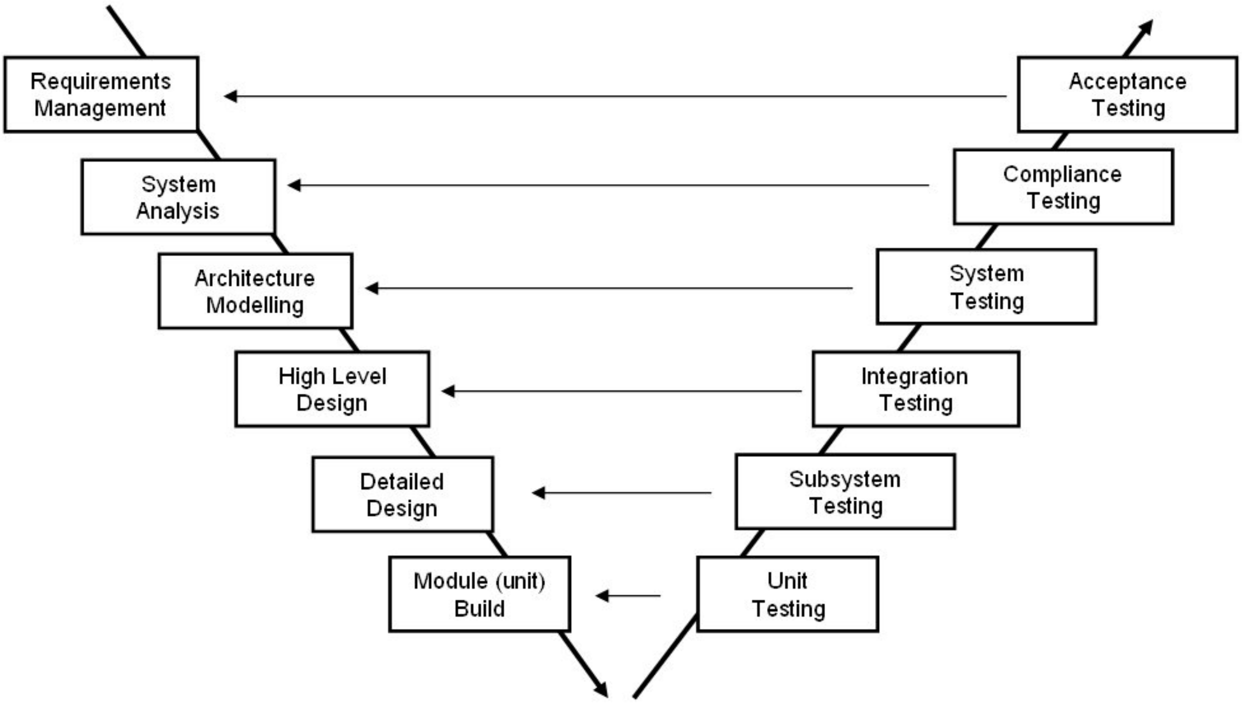

FIGURE 129. The V model of Systems Engineering, featuring the original steps.

We suggest the following as the phases of the *design process of a new modular product*:

1. **The value chain and production process analysis which produces the data of the *requirements for the modular structure***
2. **The system-level description of the modular system, to be created on the basis of the requirements. This corresponds to the ”system analysis” and ”architectural design” phases in the V model of Systems Engineering. The description based on this is called the *target architecture of the modular system*.**
3. **Individual modules are developed according to the process of systematic design. The concepts are created in the ”top-level design” phase of the V model.**
4. **The ”Detailed design” phase of the V model in this case contains the selection of the preliminary layout for the systematical design. As seen in section 5.9., this is a critical phase in the implementation of the modular structure where we will see whether the goals of the analysis can be achieved with the technology available. In this phase, then, we may need to return to the previous design phases or even discover that the selected technical structure does not enable the implementation of the product strategy.**
5. **The development of the modules in the V model here contains the ”Structural design of the product entity” (Establish Dimensional Layout) phase of detailed design. In this phase, the modularity of the product may be reduced but not increased (as seen in section 5.9).**
6. **The unit testing phase of the V model ensures that the module functionalities meet requirements.**
7. **The subsystem testing phase ensures the integrating of individual modules and ensures their functionality against requirements.**
8. **The integration testing phase ensures the integration of a product belonging to a product family.**
9. **The system testing phase ensures the ability of the modular system to produce the other required variations.**
10. **Congruence testing ensures that the variations meet the requirements of the business environment.**
11. **The approval phase actually contains only the decision of proceeding with the implementation of the product range (possibly as a platform). This does not take place in product development but in the corporate management. The contents of this phase vary considerably in the different business environments. In projecting, this phase may consist of customer approval and authority approval.**

The figure below shows the phases in the form of a graph. The relations between the phases are indicated with arrow. The design process strongly supports the design of M-modularity, but the process also enables the design of life-cycle-based modularity.

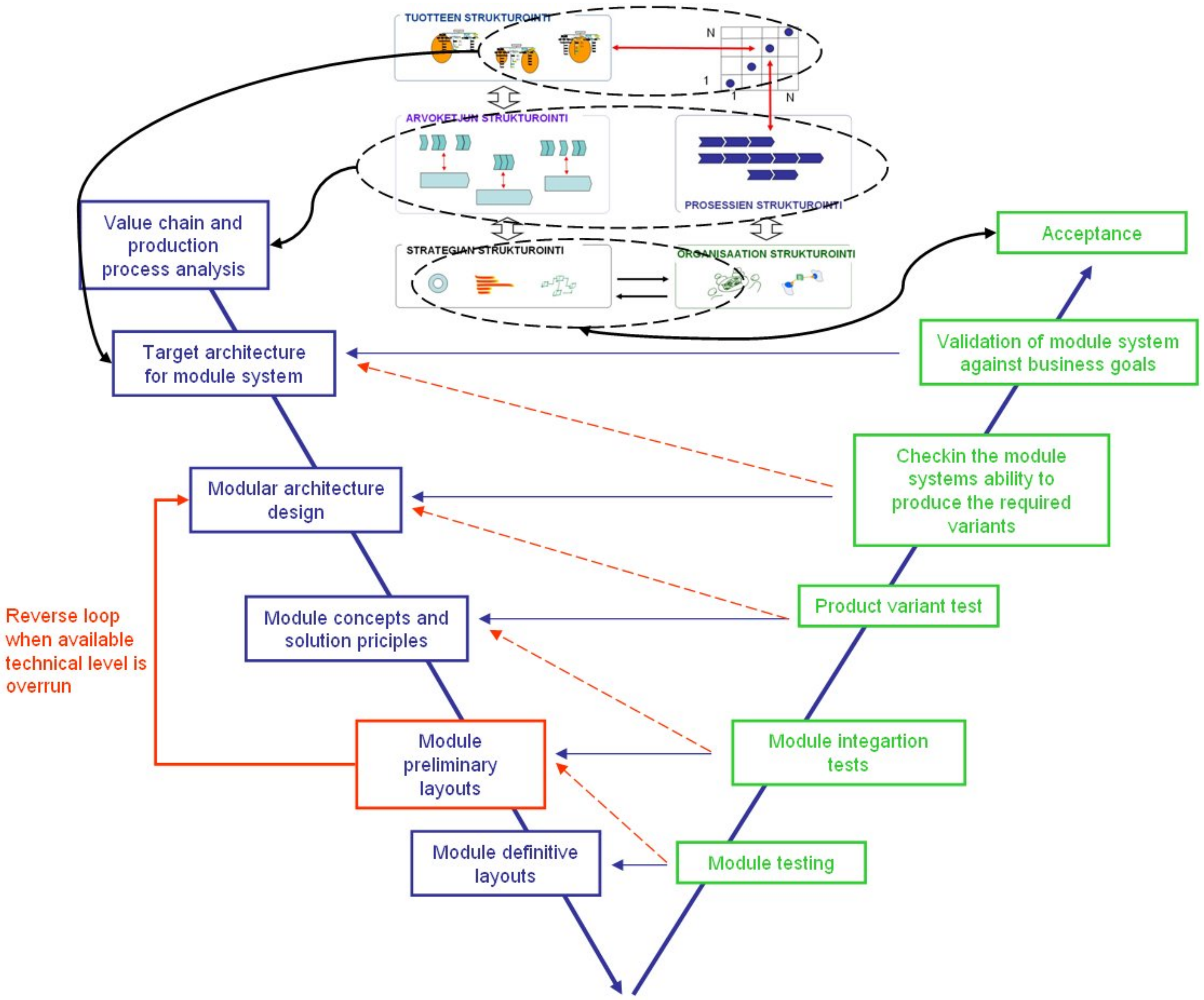

FIGURE 130.The design process of a new modular product, presented by the author. The process starts and ends within the company strategic landscape framework (presented in Chapter 9).

11.4 Other research and tools supporting the model

The value chain and production process analyses are performed according to the CSL-framework model presented earlier in this dissertation, in which case we can consider the causal relations between value chain and product structure as solved. However, at this point, there exist no tools for performing the analysis, and we can argue that for example the value chain analysis is still under construction. For example, a non-initiated reader is probably not able to outline the important configuration factors in the value chains mentioned in the case of the passenger ship [Lehtonen & al 2007]. This is an area in which further development is necessary in the future.

Applying the systematic design method as an inner loop of the V model does not pose problems. The same idea occurs in the VDI standard 2206 ”Entwicklungsmethodik für mechatronische Systeme” from 2004. In this work, the V model is called the main cycle ”*Makrozyklus*” and the processes of systematical design (*problemlösungszyklus*) within it are called microcycles ”*Mikrozyklus*”. [VDI 2004] The model presented here is, therefore, not completely new in Design

Science. Earlier, it has been suggested as a special case of mechatronic products, and the universality and the importance of the observations has not been proved. In this dissertation, the conclusions and the justifications for the solutions are taken on a whole different theoretical level; it is also proved that this is not a special design process applied only to mechatronic products.

Unfortunately, the V model proposed in Systems Engineering does not have as mature and ready tools and methodology as systematical design. (See e.g. [Stevens & al 1998]) One of the challenges for the tools is to bring its verification methods on the same level of maturity as those used in systematical design.

12. Comparing the results to other contemporary approaches

As a result of this research, we can state that the functionality cannot be taken for granted as the starting point for developing a modular division in the new product development, but for example systematic design process requires iteration via the ”detailed design” phase. In addition, we can state that in the development of a modular structure, examining the internal systematics of modularity, for example, in relation to functionality, is a viable solution only in some real business environments.

The results achieved must be compared to the other approaches in the research field of a modular product.

The other research approaches are divided as follows:

In section 12.1, we will introduce research that has more or less similar premises or results. Here, we will evaluate to what extent the results from other approaches support the issues presented in this dissertation. In addition, we will evaluate in what way the results of this research are (possibly) more practical than the compared methods/ideas.

In section 12.2, we will discuss previous research on defining the modular structure on the basis of the functional structure. There is a host of previous research on the issue, which means that we can only introduce a small fraction of it here. The evaluation will focus on whether these provide *new* justifications for using functionality as the basis.

In section 12.3, we will examine a study of modularity stemming from other premises than the mentioned cases. Recognizing research belonging to this category is based on personal judgment: what can be considered ”modularity research” and what is research on general product development methodology? This category, however, obviously includes the theory of modularity presented by Nam P. Suh, but for example the ideas presented by Genrich Altshuller are excluded for the scope of this dissertation.

Finally, in section 12.4, we will state the relationship of this dissertation to the research not used as a reference when examining the hypotheses.

12.1 Research including the same elements in the field of product structure development

12.1.1 Umeda, Nonomura, and Tomiyama

The ideas and results of this Japanese research on the effect of the product life cycle on the modular division of the product has served as an inspiration for the present dissertation. The writers of the ”Study on life-cycle design for post mass production paradigm” (AIEDAM 2000) article are Yasushi Umeda, Akira Nonomura, and Tetsuo Tomiyama. Umeda worked at the Tokyo Metropolitan University, Nonomura in the DENSO Corporation, and Tomiyama at the RACE (Research into Artefacts Center for Engineering) research institute at Tokyo University.

The main focus of the research was not on the methods of developing the product structure, but on the life-cycle effects of the product. The sample cases in the research were refrigerators. The life cycle of refrigerators was simulated as five different life cycles. In the simulation, the energy consumption, the building up of waste, and the turnover from manufacture and services during the life cycle of the product were examined. As a combination of the different life cycles, a preferred method from the ecological viewpoint was presented. Researchers called this the Post Mass Production Paradigm (PMPP). The other life cycles were the traditional "life-cycle pipe" from manufacture to waste, the recycle model, the reuse model, and the model based on maintenance. The figure below shows the PMPP model which also incorporates the phases of other life cycles. [Umeda, Nonomura & Tomiyama 2000]

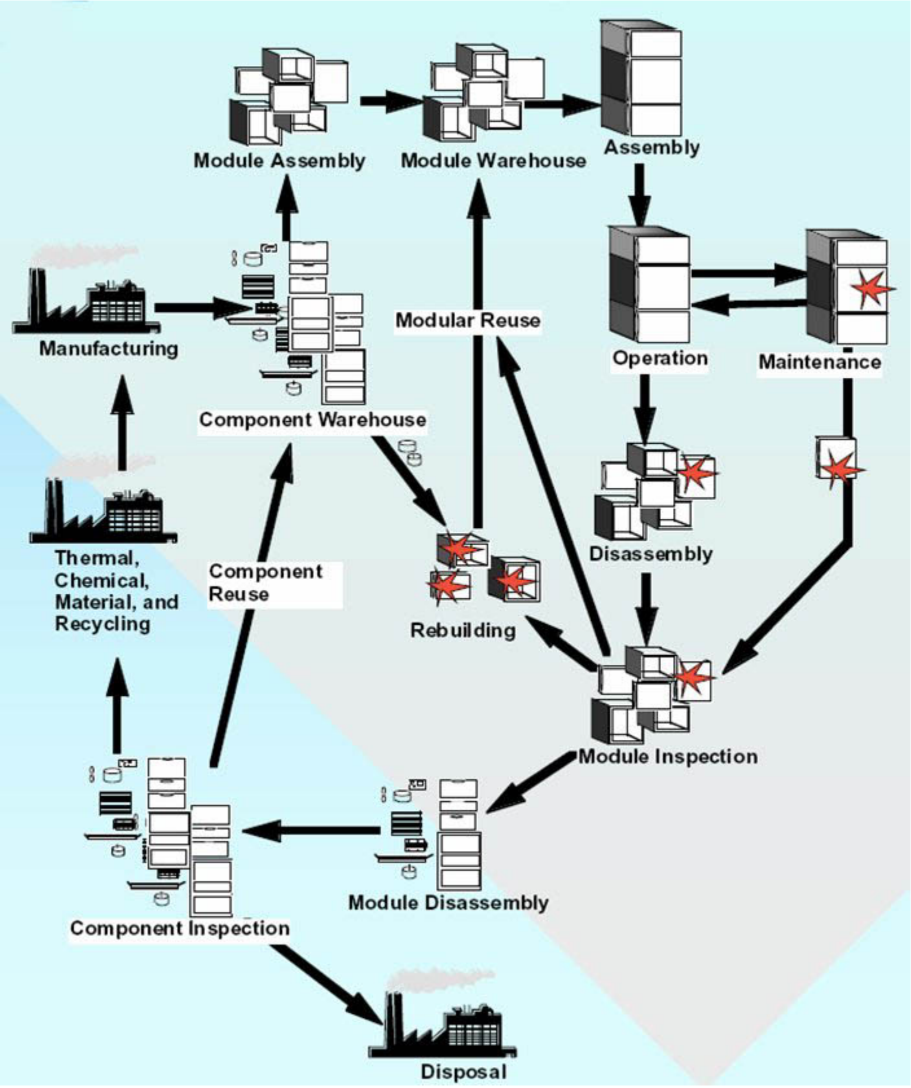

FIGURE 131. The life-cycle simulations were based on the various life cycles of refrigerators. The Post Mass Production Paradigm (PMPP) aims to utilize all forms of reuse and recycling. [Umeda, Nonomura & Tomiyama 2000]

The results that emerged as the life-cycle effects of the simulations were very interesting. Life cycles that contained reuse to varying extents naturally reduced the amount of waste. Instead, energy consumption even increased in the life cycle based on thermic reuse compared to the traditional "life-cycle pipe". This is shown in the figure below.

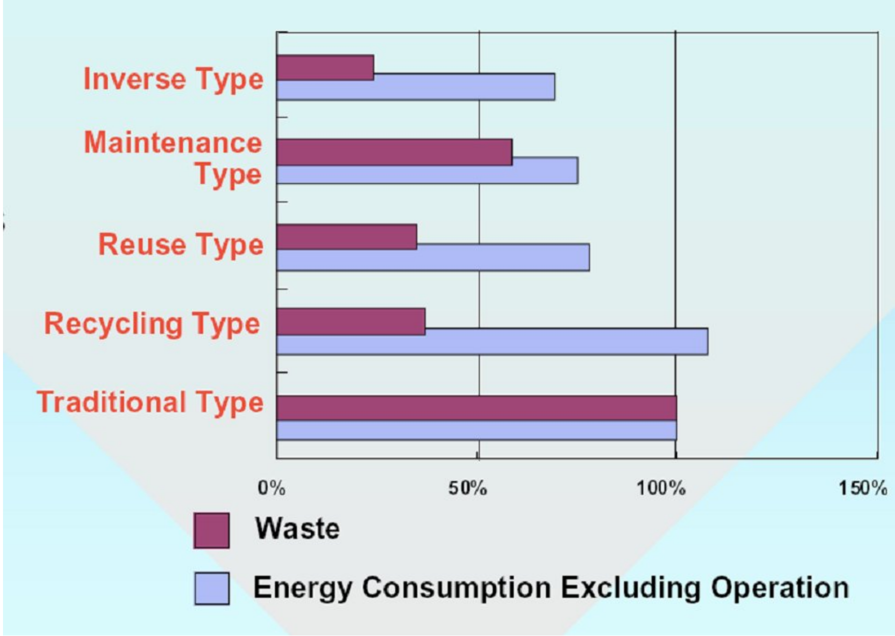

FIGURE 132. The creation of waste and the consumption of energy in the various life-cycle types [Umeda, Nonomura & Tomiyama 2000]

The financial results were also rather surprising. On the component or module structure, the business potential of life-cycle types that contained recycling or maintenance service even doubled that of the traditional model. Only the recycling cycle diminished the business opportunities. The results are shown in the figure below.

FIGURE 133. The creation of sales and profit in the various life-cycle types. [Umeda, Nonomura & Tomiyama 2000]

In the financial examination, the calculations were based on the assumption that all life-cycle phases take place in a same cost-level environment – which is not necessarily the situation today. The effects on the price to the customer were not defined in the research. However, the various processes also yield added value in other forms than increased invoicing, which means that the prices to the customer do not change in the same pace with the total profit curve of the product. The results also show the slightly alarming issue that if a refrigerator is a typical product, the strategy of thermal recycling established in the European Union seems to slightly reduce the profitability of the company and increase energy consumption, thus promoting the greenhouse effect.

From the viewpoint of modularity, the most important thing in the entire research was that in order to achieve results, the product structure of refrigerators ought to be optimized to fit the selected life-cycle type. In the research project, modular divisions for various life-cycle types were defined. Three of these are shown as graphs in the figure below. According to the research, recycling materials did not require a complex structure, as the product could be disassembled via crushing (the figure on the top left). On the other hand, a structure based on a long life cycle and maintenance consisted of very small replaceable modules. In the structure supporting the PMPP life cycle, the elements placed in the same module share a similar life cycle.

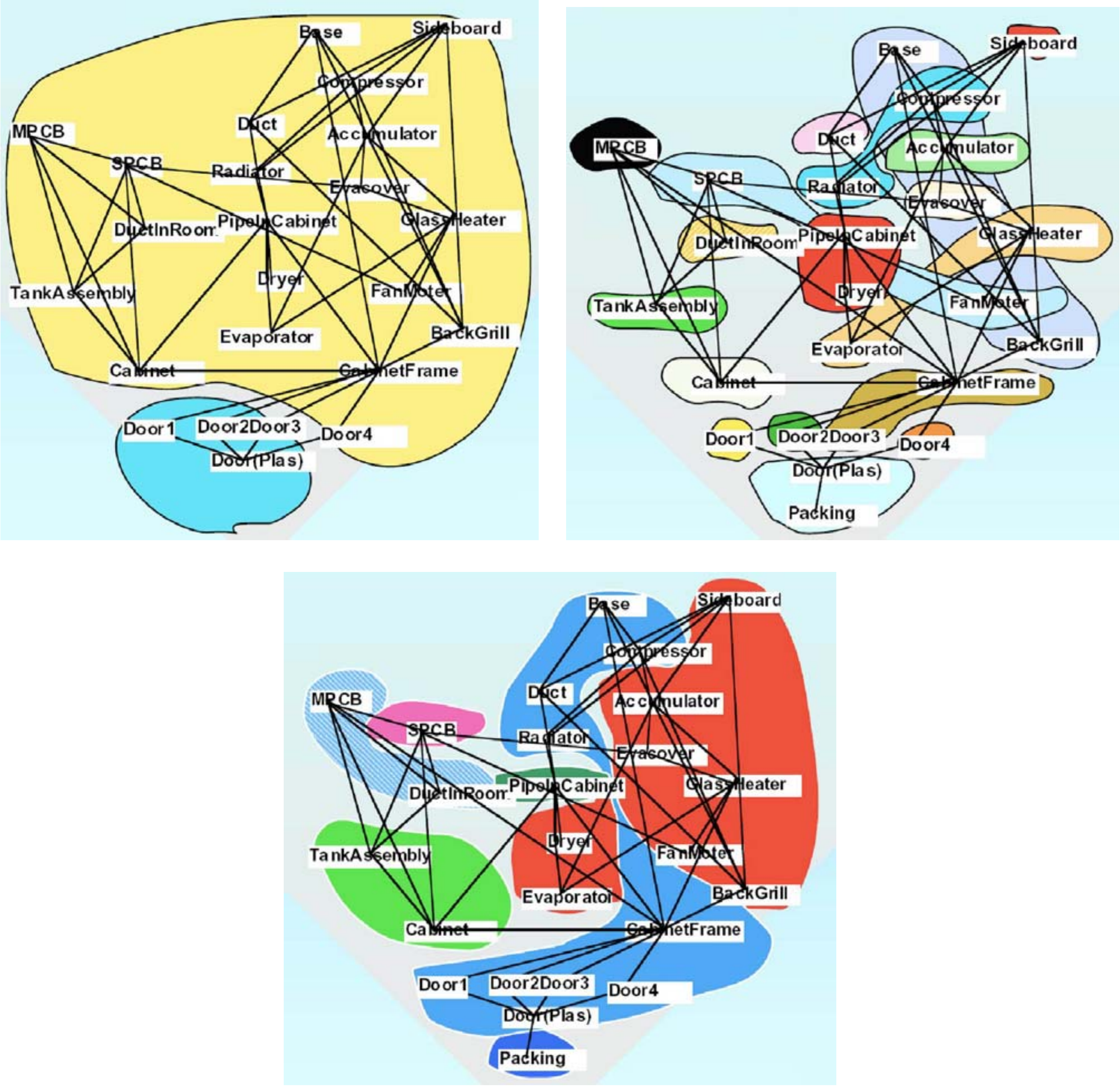

FIGURE 134. Target architectures of the modular division, created via means of simulation and optimization. The division into modules is indicated by the colored fields, and the dependencies between the components by the relation arrows. A structure supporting the recycling-based cycle appears in the top left corner, while a model supporting the maintenance-based cycle is on the top right. The bottom of the figure presents the modular division supporting the combined PMPP ”post-mass production paradigm” [Umeda, Nonomura & Tomiyama 2000].

These module vision graphs remain neutral on the issue of the functional structure of the product (the elements are refrigerator parts – not functions). Also, they do not indicate whether the presented division is functionally rational in terms of technology and implementation. They could be called ***the target architectures of the modular system***, presented in Chapter 11**.** As the elements in them are parts of an existing refrigerator structure, they however cannot be accepted as new product design. In addition, they have been created as a result of an optimization via means of simulation, whereas Chapter 11 of this dissertation aims at outlining theory-based tools to produce modular architecture. However, the research conducted by Umeda, Nonomura, and Tomiyama indicates that the same results can be achieved via means of developing the design support system and via developing a theory of product structure. After all, it is a question of discovering the easiest way to proceed. This issue was discussed earlier in the introduction of this dissertation.

12.1.2 Baldwin and Clark

Carliss Baldwin and Kim Clark have conducted much-quoted research in the field of modularity. The research material comes from the US computer and computer accessory manufacturing industry. The examination period in their research stretched from the post-WWII era to today. To support their views, they are able to present well-known business cases from the recent history of information technology in the United States. Their ideas on modularity are presented in the 400-page book ”Design Rules – The Power of Modularity” [Baldwin & Clark 2000].

The Baldwin and Clark idea of the development trends in industrial production and the importance of modularity corresponds to the ideas presented in this dissertation [Baldwin & Clark 1997] (See section 8.1. ”Conclusion on the importance of modularity to Design Science”). Even though Baldwin and Clark examine the development in the field of information technology during the past 50 years, while the present dissertation discusses a period in the manufacturing industry that stretches back at least 500 years, both studies reveal the same development trends. The conclusion on the future developments is also similar. Baldwin and Clark suggest that modularity will become the dominant norm in industrial operations. They introduce a view that corresponds to Dynamic Modularity and suggest that this has in part been implemented in information technology. According to Baldwin and Clark, when operating in a Modular Environment, the key issue is to form the product development organization according to the modular structure. We have also observed the importance of this in our own research (e.g. [Lehtonen & al 2003 (2)]) .

However, the Baldwin and Clark approach to modularity applies the perspective of business management, whereas this dissertation focuses of product design. The differences in the research material also lead to, for example, a very different terminology. B&C use the term ”architecture” mostly in the historical sample cases, such as in the case of the development of the world's first bus-modular computer [Baldwin & Clark 2000: IBM *Standard Modular System* development work 1957-1958, pages 163-165]. They talk of *Design Rules* that in their method that corresponds to Dynamic Modularity contain the compatibility data generally considered as the architecture. This, however, is not merely a case of using different terms, but of an underlying more fundamental difference. According to B&C, architecture is fixed (=a closed system), whereas the rule-based method using ”*Design Rules*” is open and dynamic.

The latter is related to another issue, on the basis of which this dissertation can be considered a contribution to an earlier work by Baldwin and Clark that includes similar ideas. B&C remain neutral on the relation of standardization and optimization, which provides an opportunity for speaking of general rulesets instead of the actual product architecture. In the business environment, however, standardization and optimization operate in part via fully different mechanisms, which mean that lumping these two issues together is not useful or justified.

The figure below shows the Baldwin and Clark presentation on the dependencies in the product structure of a modular laptop computer. The dependencies between the main components, that are modules from the system viewpoint, take place via the domain of the design rules (The reality of Design Rules). The modules are not directly dependent on each other, which means they are replaceable and the system can be implemented as an open system and the dynamicity of the product structure achieved [Baldwin & Clark 2000, p. 74]. As a comment to this, we could state that this approach is well suitable for the design of a bus modular product (for example, computer hardware) or a sectional modular product (for example, software). The method poorly suits the multiple-technology devices in the heavy engineering industry presented as examples in this dissertation and often leads to the development of the design support system instead of a modular system. (Cf. the implementation of a systematically configurable product via means of a design support system [Tanskanen 1997]).

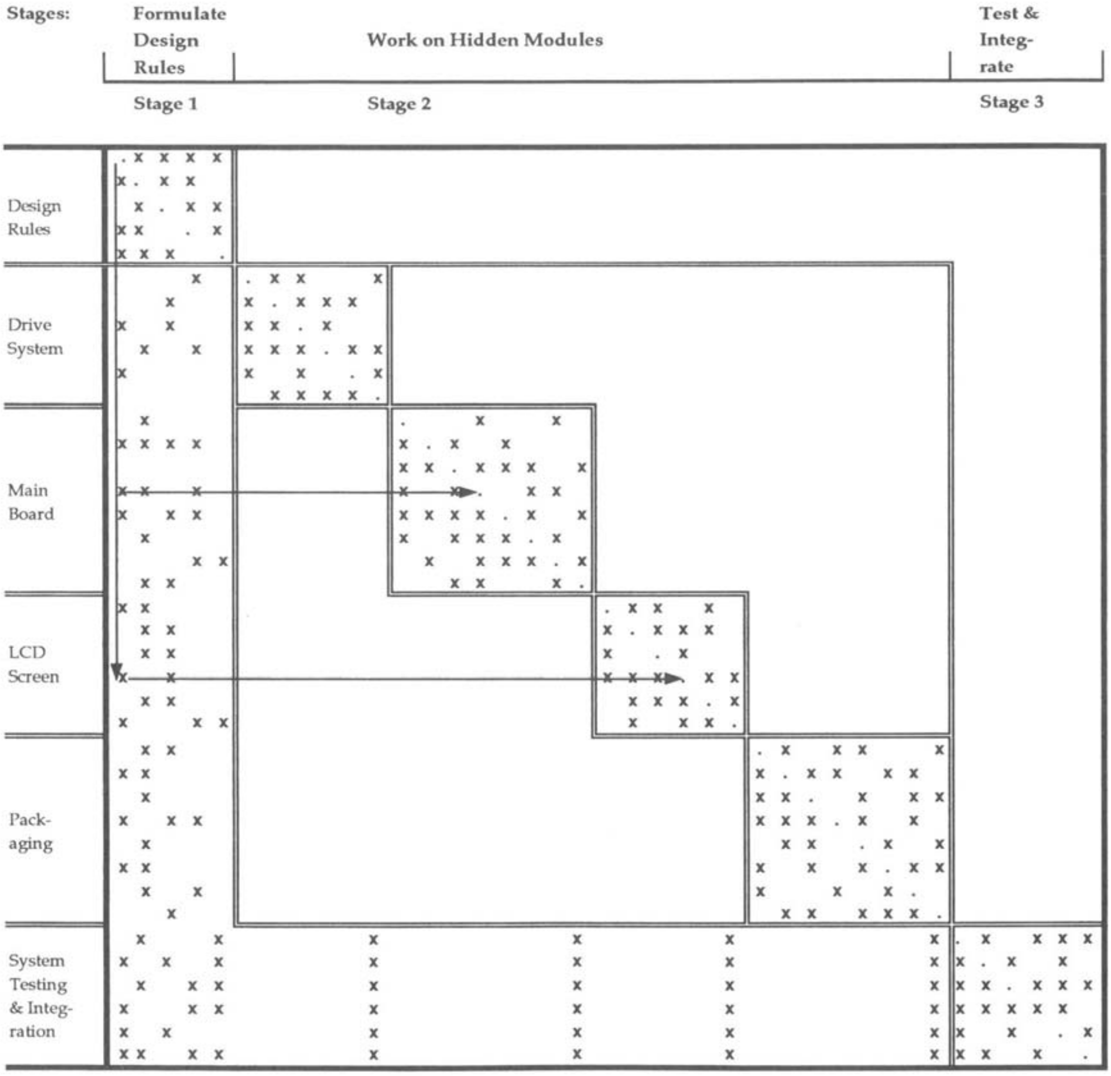

FIGURE 135. The hypothetical modularity of a laptop computer, according to Baldwin and Clark. Notice that the bonds between the modules cross via the design rules. [Baldwin & Clark 2000, p 74]

Baldwin and Clark examine modularity in a networked business environment, in which case the forming of the module structure as the dominant design emerges as one of the key issues. On the basis of this, B&C consider that a modular structure can only be created on the application area via evolution. This is probably true in a networked business environment, but it is too pessimistic an idea to be applied to product design in general.

12.1.3 Marco Cantamessa and Carlo Rafele

In their research, Cantamessa and Rafele highlight the conflict between the general definitions of modularity (e.g. Ulrich) and the industrial practices [Cantamessa & Rafele 2002]. Their application area is the car industry in which the situation is clearly visible. They refer to earlier research [Camuffo 2001] and argue that alternative approaches exist for applying modularity. They proceed to question the status of functionality in the development of modularity:

”The relevance of these alternative viewpoints suggests that, in product development, functionality is not the only aspect that should be taken into account when defining product architecture”

They present a model of the product development process in which the modular architecture is not formed by using the functional division as the main criterion. The structure of the presented method is shown in the figure below. The starting point is the bill-of-materials of the product, which are then grouped into modules. One criterion that deserves a separate mention is the charting of a technological roadmap that indicates the need for change in the modular structure (cf. the motivations for modularity as Erixon's ”technology push”). In addition to the development of technology, a case-specific reason hierarchy is formed as the basis for developing the modular architecture.

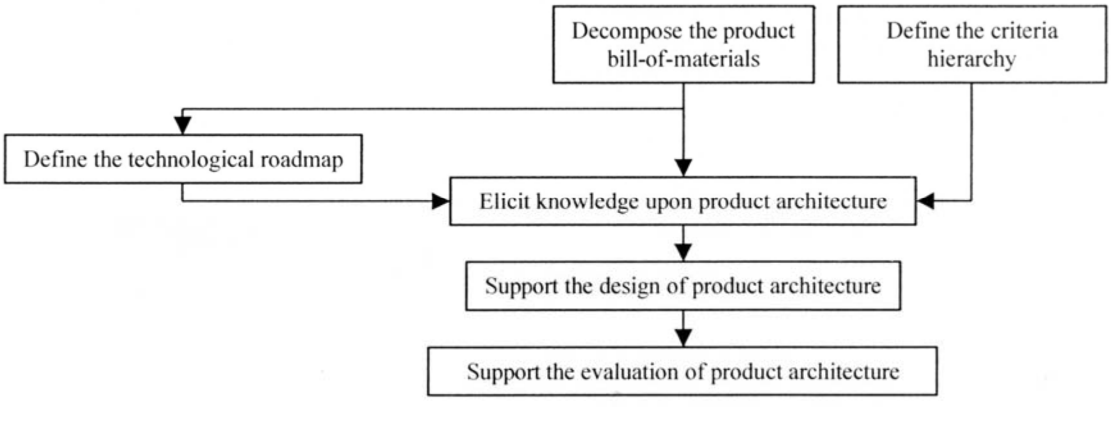

FIGURE 136. Cantamessa and Rafele suggest this process for developing a modular product structure. The requirements for the structure are determined from two directions, the life cycle of the product range and the life cycle of the product. The charting of the technology development direction related to the development of the product range is shown on the right, and the case-specific reason hierarchy is shown on the left. [Cantamessa & Rafele 2002]

As the basis of the reason hierarchy, the example uses the life cycle of the product, that is, evaluates the requirements for the modular structure in product development, manufacturing, purchases, and marketing. The figure below shows the example of the key criteria for the car industry: in some other areas of application, the criteria and perhaps even the phases of the life cycle could be different. If we compare this hierarchy tree to the company strategic landscape framework (Chapter

9), we find that the presented elements are the same, but that Cantemessa and Rafele do not evaluate the mutual relations between the criteria. We should also note that Cantemessa and Rafele consider functionality as belonging to product development. The conclusion here is the same as presented in section 10.9 *(...the functional structure is related to the transformation implemented by the technical solution. Therefore, it is a dominant element in the area of product structuring.)*

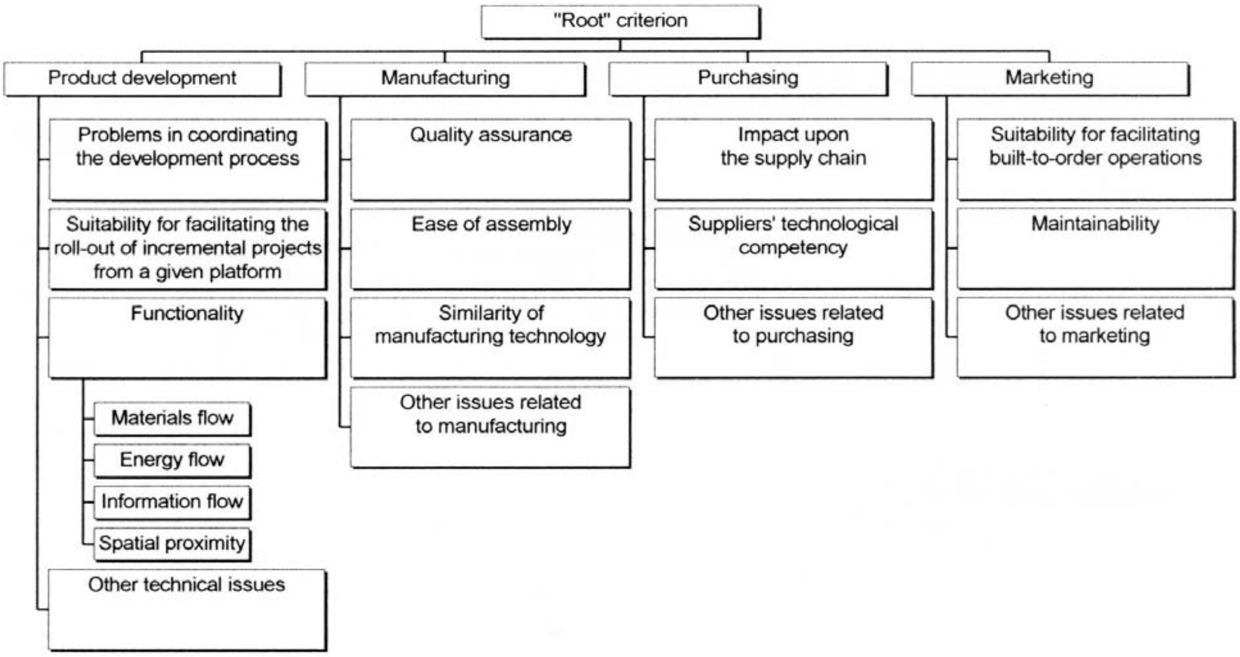

FIGURE 137. An example of the reason hierarchy structure of the requirements for a modular structure. In this presentation, reflecting the experiences from the vehicle industry, functionality is merely one criterion among many. [Cantamessa & Rafele 2002]

Cantamessa and Rafele also introduce a tool utilizing the method described above. The tool enables the definition of a module structure for a product range whose elements are known, when the requirements are considered heterogeneous. In this case, heterogeneity probably means that the criteria can be converted into vectors whose elements are numerically comparable. This tool, interesting as such, is not included in the scope of this dissertation, as starting from the part structure excludes it from the new product design. Also, it could be very challenging to form the heterogeneous criteria in connection with the new product design.

12.1.4 Design research in Denmark

The contribution of Professor Mogens Myryp Andreasen to design theory has been discussed earlier in this dissertation. It is only natural that an important research team in this field is located in Denmark. The research team started from Design Science and Hubka. The Danish have, however, created a very wide comprehensive view of the design process, and it is impossible to review their work without understanding this view.

In this dissertation, the research of modularity conducted in the field has been reproached for being blinkered and relying on one basic rule. However, this does not apply to the Danish approach whose view on product design is even wider than the one used in this dissertation. In a study carried out following the Danish research tradition, design is never examined as a separate event, but it is an operation carried out by certain organizations. The view on the product is not static but the life cycle of the product is always visible in the background. The effects of the design decisions on the various phases of the life cycle are considered. These are called *dispositions.* When we add that the methods and tools suggested by the Danish researchers often truly aim to apply the theory of domains, we see a distinct research tradition, even though we do not speak of a separate school.

A good idea of the Danish comprehensive view on product design can be acquired in, for example, the dissertation ”Design Modelling in a Designer’s Workbench – Contribution to a Design Language” by Niels Henrik Mortensen [Mortensen 1999]. The dissertation discusses the possibility to develop the ”design language” and examines the ideas and models related to design. The following presents an example figure on the models and elements associated with the design task of the product. The horizontal axis indicates the life cycle of the product. A description of the product, following the TTS and the domain theory, is shown in the middle. It is presented according to the chromosome model. On the product part level, the products have a part of model and a kind of model. The latter two-model system sets the basis for the *Product Family Master Plan* method (see e.g. [Harlou 2006]).

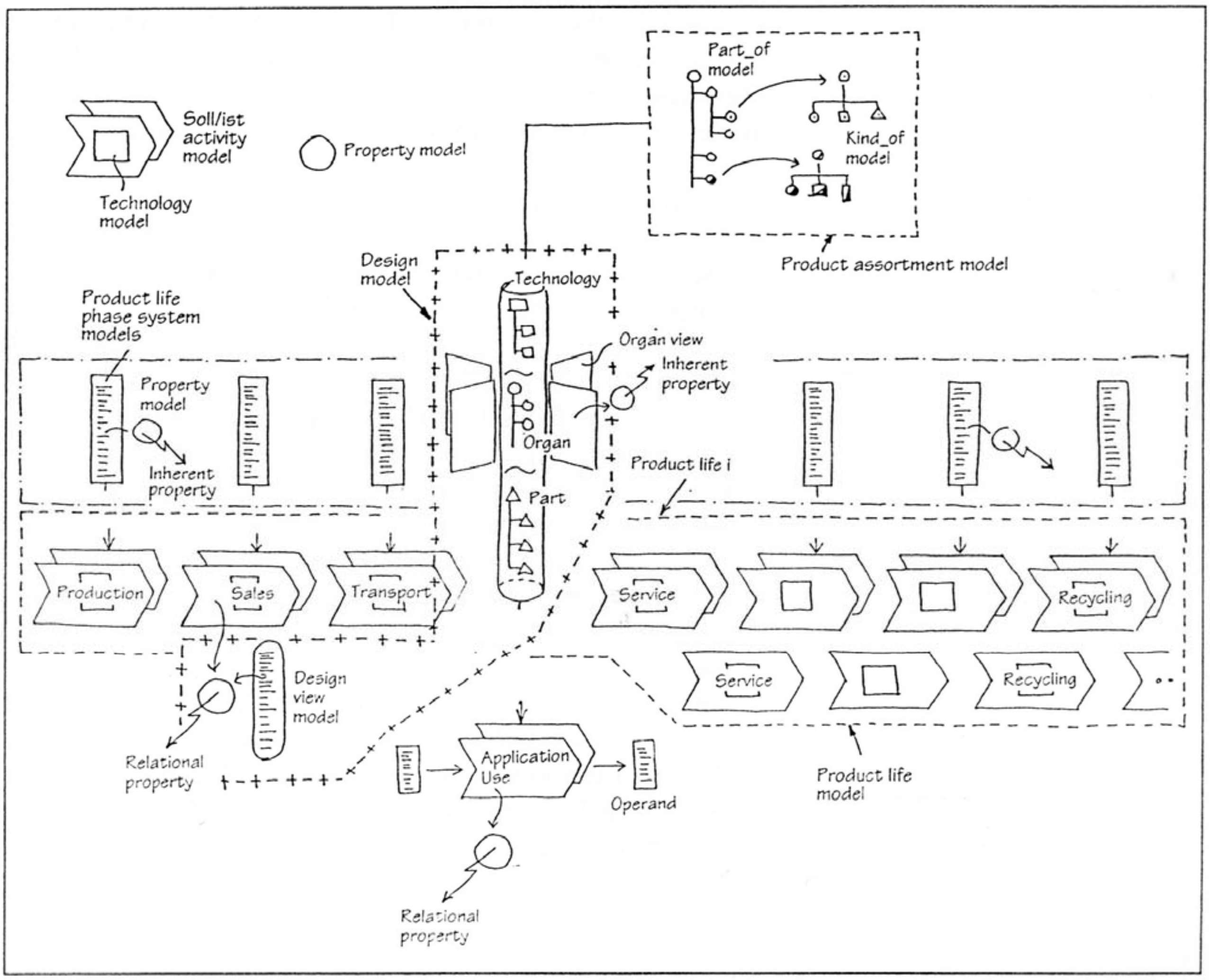

FIGURE 138. The Danish view on the elements related to the design of a product is wide. This figure serves as an example of this [Mortensen 1999 p. 80].

Danish research also includes the definition of the phenomena related to the design and the product with precise semantics. Therefore, for example, the *characteristics* and *properties* of design refer to different things in Danish research. The first one is related to the structure of the technical system and the latter to its behaviour (operations). The semantical structure hides another discipline related to design theory, as shown in the figure below. If the reader does not realize that the words are not used in their common-language meaning, it may be difficult to understand the Danish research. The approach is nearly the opposite of the US research. A senior researcher once joked that all terms ought to be translated into Latin to make research intelligible in the United States. This is part of a more general problem in the field of research.

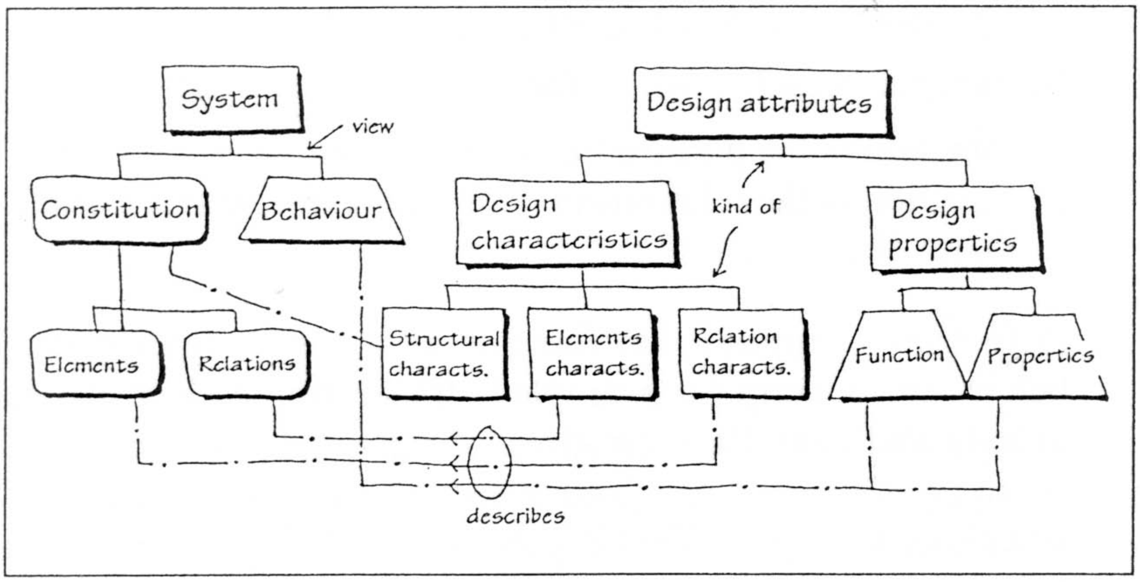

FIGURE 139. The Danish research tradition involves defining things via means of semantics. Therefore, a number of English words have a specific meaning, that is, an invisible ”design” prefix attached to them. [Mortensen 1999 p. 52]

Another viewpoint to design highlighted in the Danish research is the distinction between goals and results. This tradition derives from the German machine design where the issue has been presented by, for example, Hansen (1974) and Roth (1986). According to this, there exists a clear difference between the ”Sollen” (what ought to be) and ”Sein” (what is) items. Here we see that the division derives from much earlier traditions of German philosophy, as we may consider Max Weber (1864-1920) as being the first to crystallize this. This philosophy appears in the Danish research as shown in the figure below.

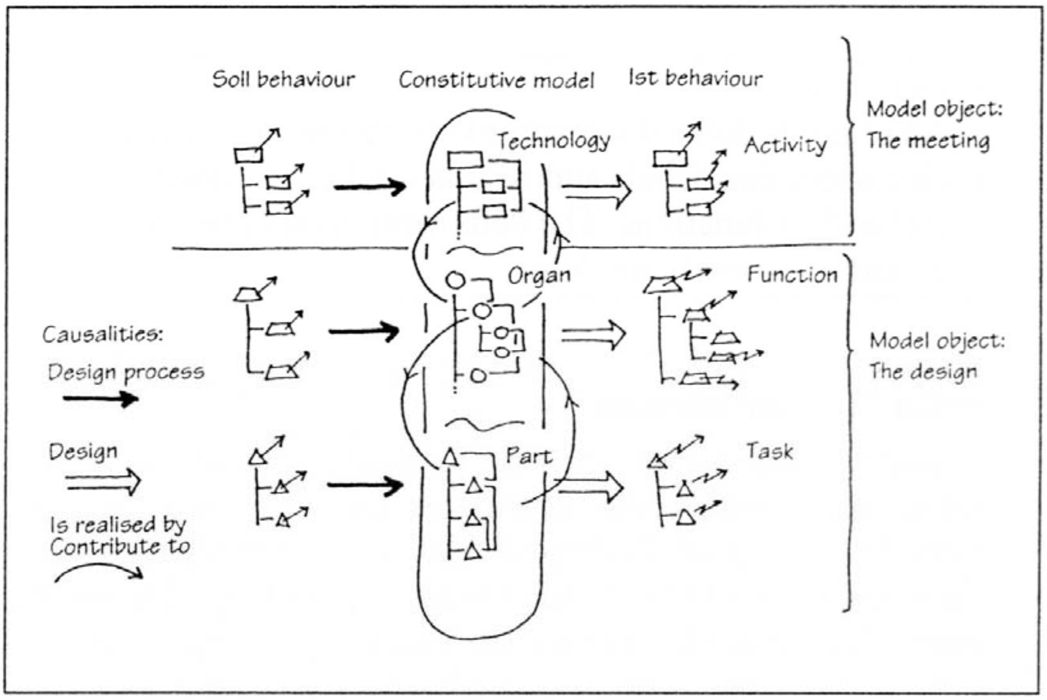

FIGURE 140. In the design process, the desired ”behaviour” (~functionality) (the Soll behaviour) changes into Ist behaviour, as shown in the figure by using the chromosome model. [Mortensen 1999 p. 71; also Andreasen 1999].

The described philosophy is important for this dissertation because the design process of a new modular product presented in Chapter 12 is based on the idea that a model can be created to describe the behaviour of the modular division in the Sollen context. The fact that the ”Sollen” elements are not necessarily implemented as ”Sein” elements is considered in the suggested design process as iteration between the phases, as the technical solutions do not enable the desired Soll behaviour.

In the research of designing modular structures, the Danish researchers Andreasen, Hansen, Jensen, and Mortensen have developed a framework model to guide the research. As shown in the figure below, the model differs from the pure function-based approach. The elements following Hypothesis 2 of this dissertation show in the framework model, but the Danish framework model remains neutral on the priority argument included in the hypothesis.

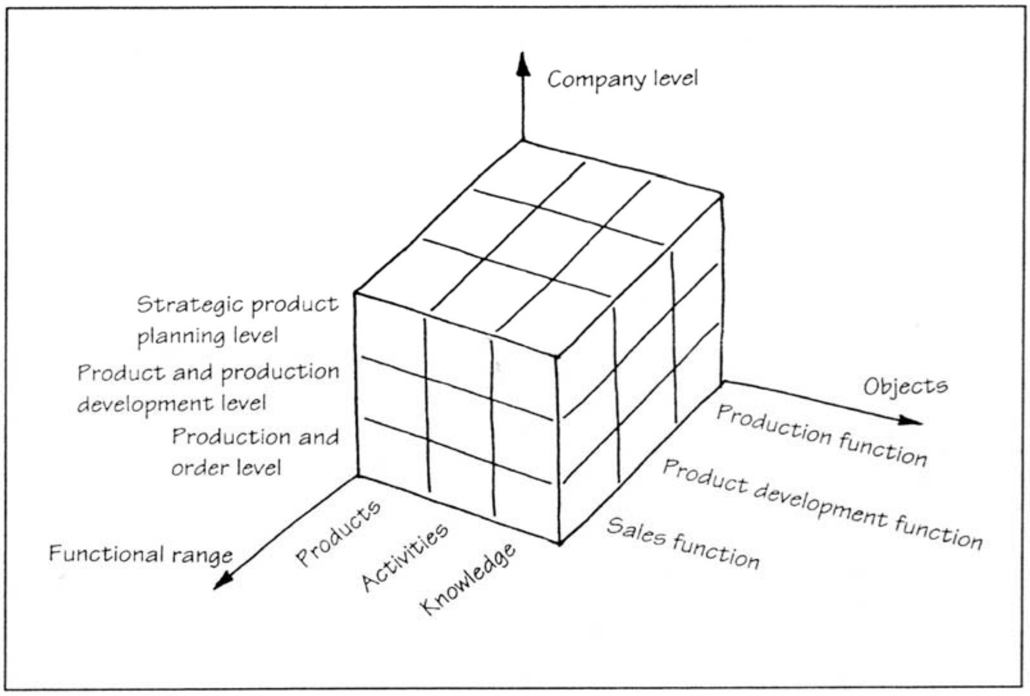

FIGURE 141. The framework model guiding the modularity research of the Danish researchers. The model in the figure is the version drawn by Andreasen [Andreasen & al 2001]. In the framework model drawn by Hansen, the vertical axis features the Strategic perspective, the Planning perspective, and the Realisation perspective [Hansen & al 2002].

The most recent crystallization of the views on designing modularity in the Danish research can be found in Ulf Harlou's dissertation ”Developing product families based on architectures” [Harlou 2006]. When comparing the present dissertation to Harlou's dissertation, the first important issue is that Harlou speaks of ”product families based on architectures”. This is a wider scope than a mere examination of modular systems, and a much wider view than ”*defining a modular product structure in the new product design*”. Harlou introduces a framework model on the development of product families, shown in the figure below. The scope of the present dissertation would be located on the top left corner in the figure. If we consider that modularity and platforms are practices developed by the industry, the figure title ought to be ”Research *and industrial practice* phenomenon”.

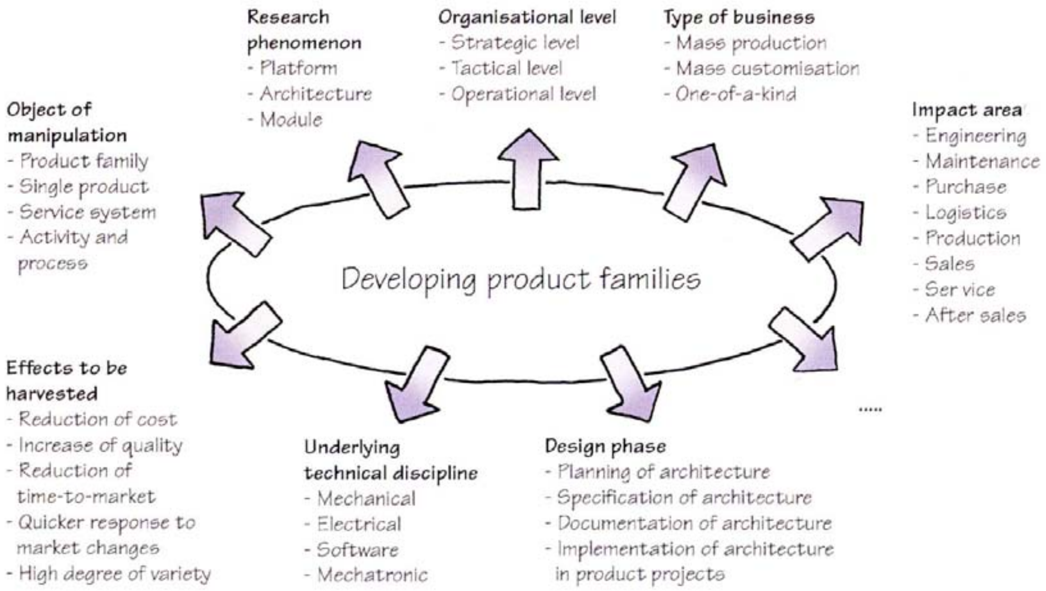

FIGURE 142. The framework model for developing product families, according to Harlou [Harlou 2006 p. 42].

In his work, Harlou suggests two tools for designing product families. The tools are the *Generic organ diagram (GOD)* and the *Product family master plan PFMP*. Both tools are based on the main theories of Design Science and the Danish research. The generic organ diagram is based on utilizing the Domain theory, and thus its roots lie in Hubka's Theory of technical systems. The Product family master plan, in turn, is based on the Danish idea of a class hierarchy to be created for the elements in the design (see earlier Figure 138). Both tools thus have distinct theoretical premises.

The elements for drawing a generic organ diagram are shown in the figure below. The dependencies between the organs are called *interfaces* and they may be related to the functions of the technical systems or to the other relationships – including the non-desired –between the structure and the elements.

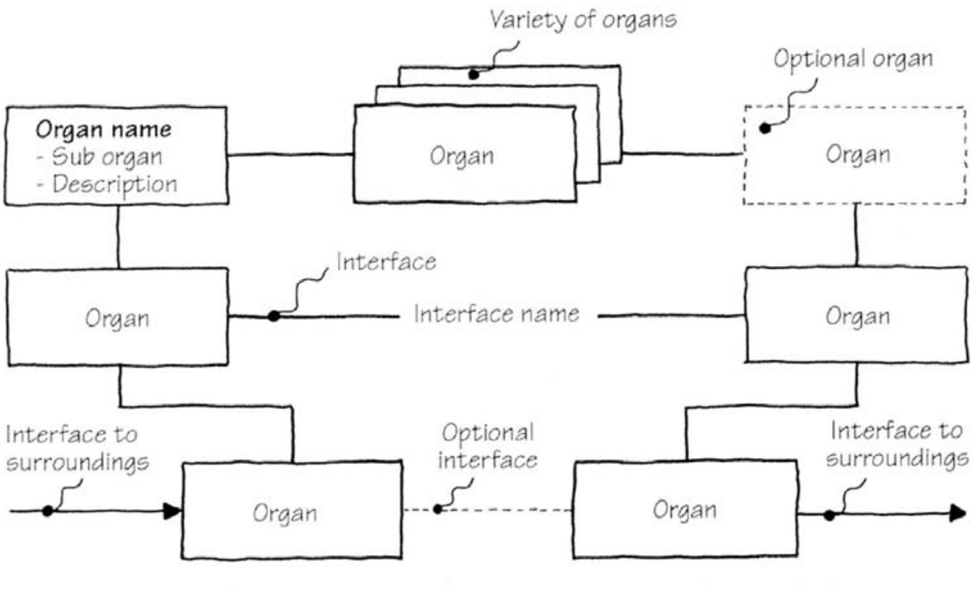

FIGURE 143. The elements for drawing a generic organ diagram [Harlou 2006 p. 101]

The generic organ diagram is drawn at the beginning of the product family design. It serves as the starting point for the design of each individual product in each product family. It directs towards implementing all products in the product families in the same way, and it also encourages the common use of solutions and components. The approach works best if the entire product range is designed simultaneously (cf. the observations in the industrial examples of Scania and Ponsse). The following shows the generic organ diagram of the Bang & Olufsen BeoLab 2000, 2500, 3500, 4000, 6000, and 8000 loudspeaker series.

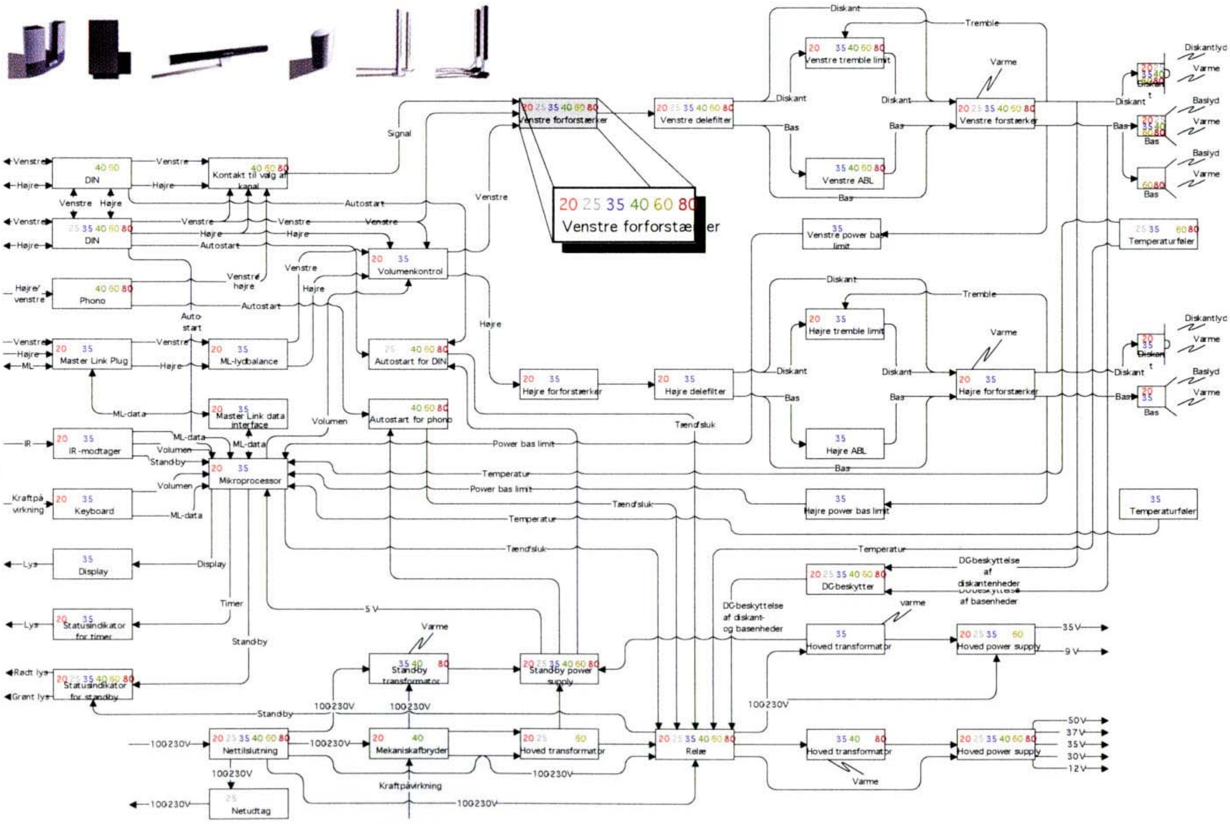

FIGURE 144. A generic organ diagram for a BeoLab loudspeaker product family. Most relations are related to functionality. [Harlou 2006 p. 103]

As we see, the generic organ diagram is an efficient design tool *that guides towards standardization.* The GOD remains neutral on the issue of whether some elements or their parts ought to be formed into modules; and it cannot do that, as it is not relevant for the business goals to form the modular structure solely on the basis of the organ structure, as has been proved in this dissertation. Therefore, the GOD is a *method for designing a product family* and it does not focus on *creating a modular system.* Of course, a product family can be designed without a modular system. That is to say, the fact that the method does not suit the scope of the present dissertation does not diminish its value.

The Product family master plan is based on a theoretical idea that in turn is based on the Object Oriented Modelling (OOM) method used in software (which is part of the Object Oriented Approach). OOM is based on the modelling of elements as entities that contain all their possible functions (in software engineering, this also includes the definition of via which variables the communication takes place over the interface of the entity). Physical structures can also be modelled according to the OOM [for example, see e.g. Korpela & Karjalainen 2007]. Operating in this way, the class hierarchy typical to object oriented approach becomes usable in part structure domain. The Danish presentation of the *kind-of* type hierarchy to be formed in addition to the assembly hierarchy is based on this. The PFMP method utilizes the class hierarchy and is thus able to show the *commonalities* between the various products in the product range. This is a method analyzing the structure of an existing product range, operating on the part structure level. As such, the method remains outside the scope of this dissertation*. The method and the good results achieved with it are explained in [Harlou 2006].

When comparing the author's dissertation to the Danish research as a whole, numerous similar elements and ideas can be found. This is not a coincidence, as there is strong co-operation between the research teams lead by Asko Riitahuhta and Mogens Myrup Andreasen. The Danish research would undoubtedly have plenty of things to give for future research in the issue as well. For example, the method of generic organ diagram (GOD) could form a basis for drawing a target architecture, but such a tool that would draw the desired module boundaries has not been developed yet. However, this research differs from the Danish one in applying the explicit data flow view. In this dissertation, we have not merely contented on stating which issues are related to which in design, but on the basis of the new product design processes it is evaluated where each design decision is created, what prerequisites it set to following phases. Thus the possible see sequence between design steps. This has enabled the re-evaluation of the importance of the functional structure in the definition of the architecture of a modular product.

12.1.5 The product structure development processes in the German-speaking world

In Germany and the German-speaking world, there exists research examining either the design of the structure of the product range as separate from the technical design of the product, or binding the business goals to the product structure development work. No established methods have been created on the basis of these studies – an exception might be the VDI 2206 standard mentioned earlier. The following briefly introduces the two other processes. They are good representatives of the approaches mentioned above.

Nils Kohlhase and Herbert Birkhofer suggested already in 1996 that the modular structure could be created on the basis of computer-based optimization [Kohlhase & Birkhofer 1996]. According to the development model of general modular systems presented by them, the design of modular systems is process-oriented until the concept phase. After this, the design of the modules proceeds as product-based, that is, according to the process of systematical design.

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* If we wish to shortly discuss the importance of the OO-methods for modular structures, we can take a look at the developments in software engineering. Along with the launch of the Object Oriented Approach methods and the C++ programming language based on them in the mid-1990s, ideas were presented on having finally found the ”silver bullet” to manage the profitability and the quality of software design. This, however, has not taken place: issues related to profitability and quality still remain the main problems in software engineering. At the time, the author was a software engineering student, and has over the years since often pondered why the OOA did not provide a solution to the problem of complexity in software production. The author's view is that the OOA creates the interfaces for the software, but not a system! Let us draw a direct analogy to the world of physical products: can a modular system be solely based on mere interface definitions? Or rather: does such a modular system provide advantages that cannot be achieved via means of standardization?

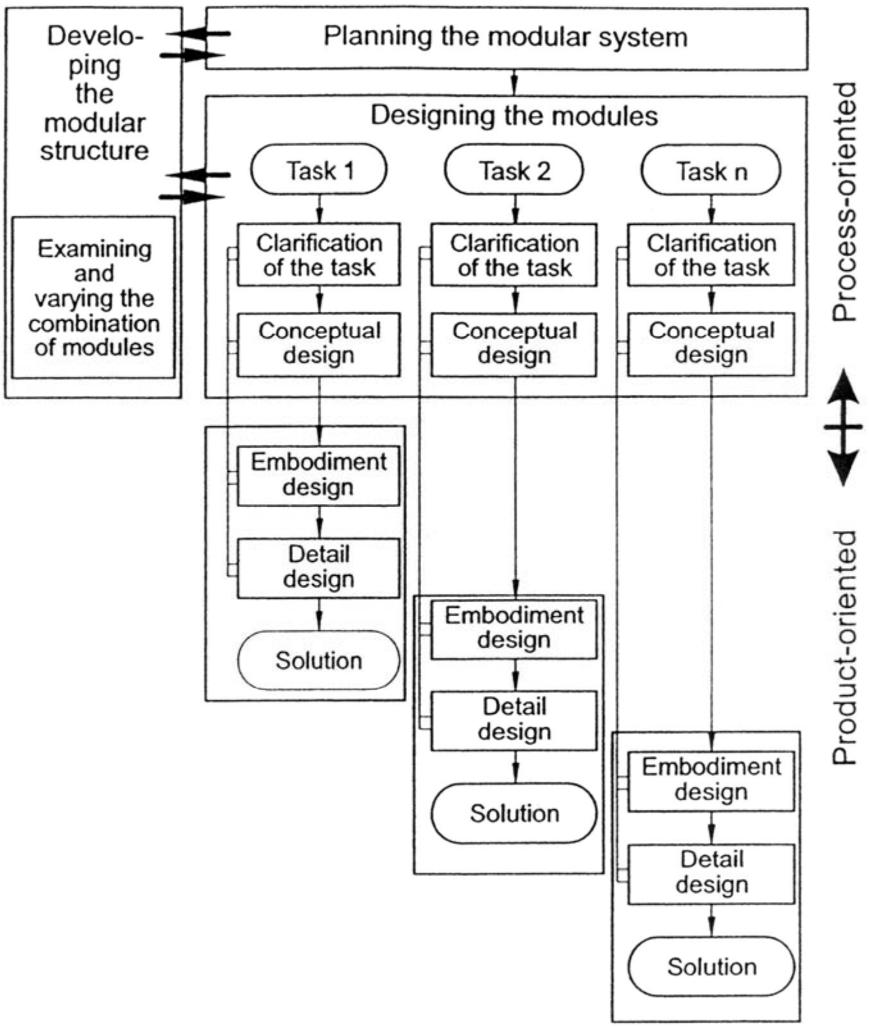


FIGURE 145. The general approach to the development of a modular system, according to Nils Kohlhase and Herbert Birkhofer [Kohlhase & Birkhofer 1996]

This research does not completely separate itself from the function-based approach, as no particular initial method of defining the modular system is selected (the alternatives seem to be the assembly-based or the function-based method, both generally known). Instead, in the optimization of the modular structure, the criteria arises from the business environment and the customer requirements (or, according to the terminology used in this dissertation, from the value chains). The difference in the task of designing a modular structure is compared to product design, and it is taken as a separate process to be carried out simultaneously with product design. The problem of the process order occurring in new product design (see the proof of Hypothesis 1) is ought to be solved with iteration supported by the design support system.

Guenther Schuh, Michael Gruenenfelder, and Adrian Hofer approach modularity from the strategic viewpoint in the spirit of Balwin and Clark. [Schuh & al 2000 and Hofer & Gruenenfelder 2001] they argue that product architecture must be defined on the basis of the criteria set by the market, the technology, and the production. They suggest the following as the methodological framework model:

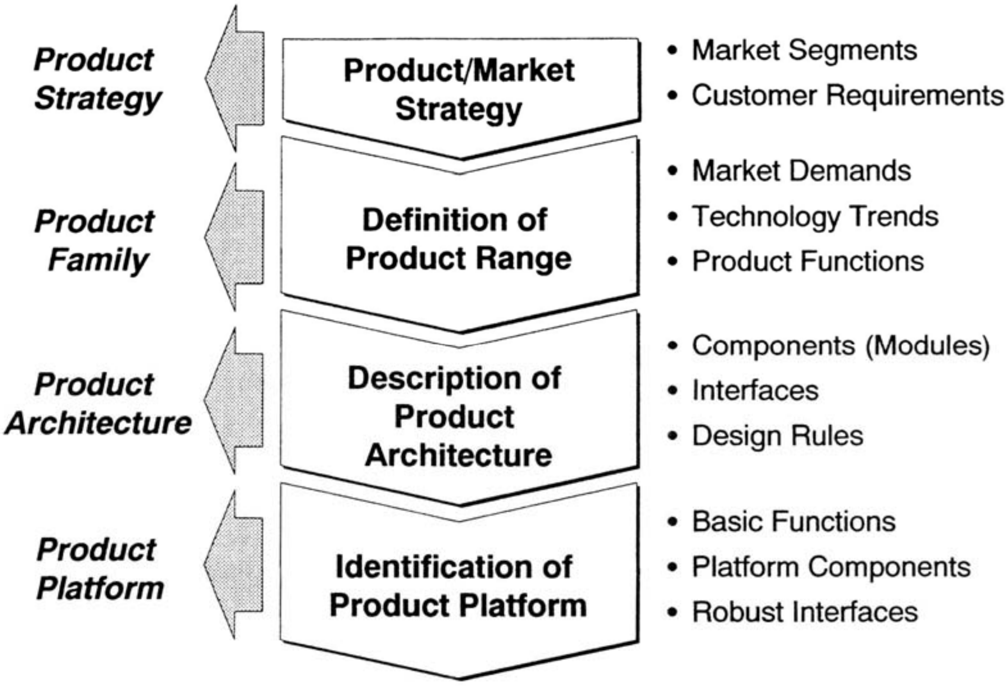


FIGURE 146. The methodological framework model to develop a platform-based product structure [Schuh & al 2000]

The most important criteria for forming the product structure presented in this framework model arise from the market environment. Functionality is only mentioned as one element. Similarly to Baldwin and Clark, the relation between standardization and modularity is not defined, and thus no difference between a module and a component is made. As proved earlier in this work (see Chapter 12, ”the design of a new modular product”), this will in practice lead to the fact that no modular system is created out of the product range, which in turn leads to losing some advantages of modularity in the variant product. In other respects, this approach is valid.

12.1.6 Looking for standardization and optimization

A particular type of modularity research consists of the methods of platform research in which optimal size ranges and dimensions are sought in the product range to be able to cover the technical requirements and the customer requirements with a minimal number of variants. These methods can in principle support new product design, even though the sample cases usually analyze an existing product range. Research of this type usually leads via standardization to a component platform. The result is not a modular system; in fact, we may even encounter non-desired issues for the creation of a modular system, as shown earlier in this dissertation in section 5.4 on *product ranges, model laws, feature-basedness, and modularity*. Research conducted by using this approach most often remains outside the scope of the present dissertation, but as this is not always the case, we will briefly introduce one of the methods in the following.

PPCEM (Product Platform Concept Exploration Method) is a method in which the correct dimensions are sought and defined for the variant product family via calculatory means. The phases and tools of this method are shown in the figure below [Simpson & al 2001].

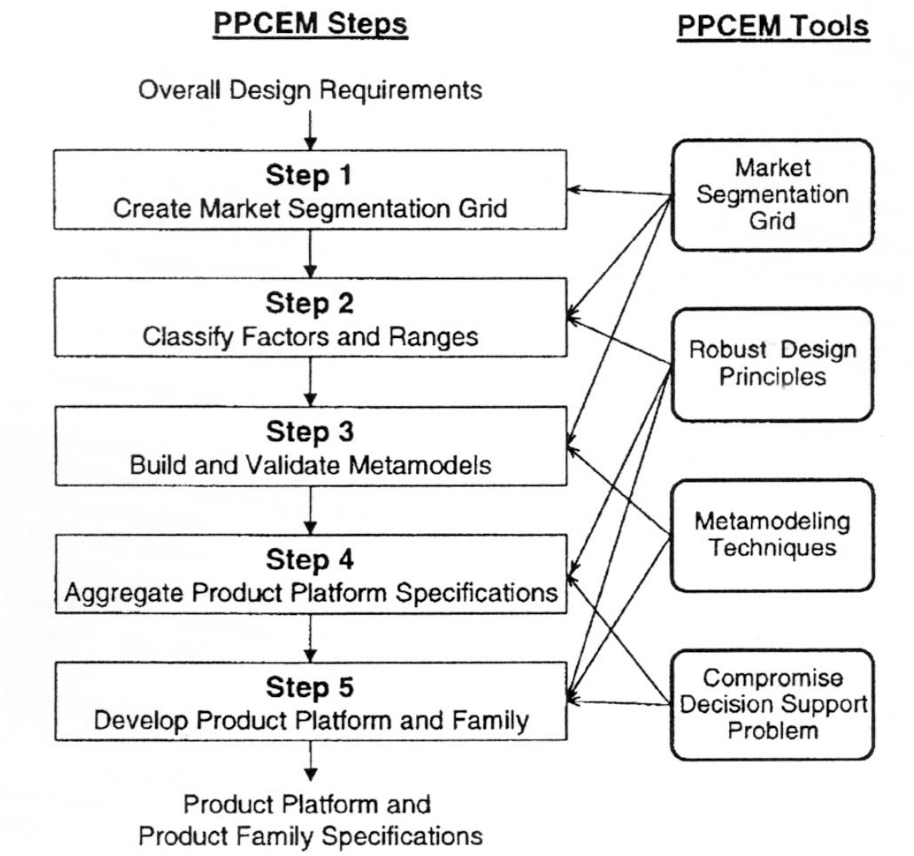
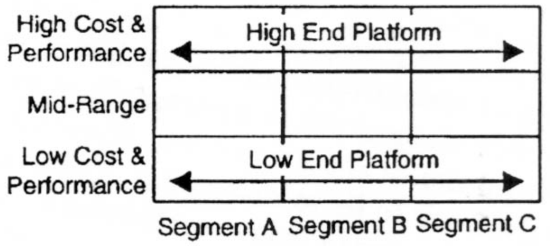
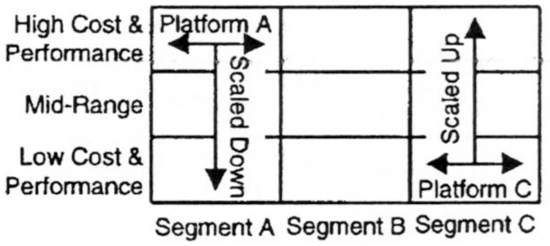


FIGURE 147. The steps and tools of the Product Platform Concept Exploration Method PPCEM methodology [Simpson & al 2001]

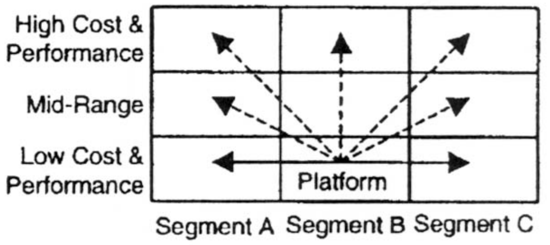
The most interesting tool of this method is the *market segmentation grid* [Meyer 1997]. It defines that product variation can be achieved in two ways: via *parametric* and *configurational* variation. The latter term cannot be explained by its semantical meaning – we are talking variation that affects the generic assembly structure via changing parts in the product. In a market segmentation grid, the market segments are drawn vertically on the X axis, and the power, size, and value classes horizontally on the Y axis. Thus we can state that vertical variation can primarily be controlled by using parameters, while horizontal variation usually requires configurational changes. These lead to platform strategies, as shown in the figure below.



(a) Horizontal Leveraging



(b) Vertical Leveraging



(c) Beachhead Approach

FIGURE 148. Various strategies for developing the platform as principal solutions (,The strategy of separate product segments "Niche" is not included in the figure.) [Meyer 1997 and Meyer & Lehnerd 1997]

The "Design for variety" methodology by Mark Valeton Martin and Kosuke Ishii aims at creating a standardized product architecture with a modularity. The aim is to create a product platform in which future changes and modifications are considered [Martin 1999, Martin & Ishii 2002]. The process of the method is illustrated below.

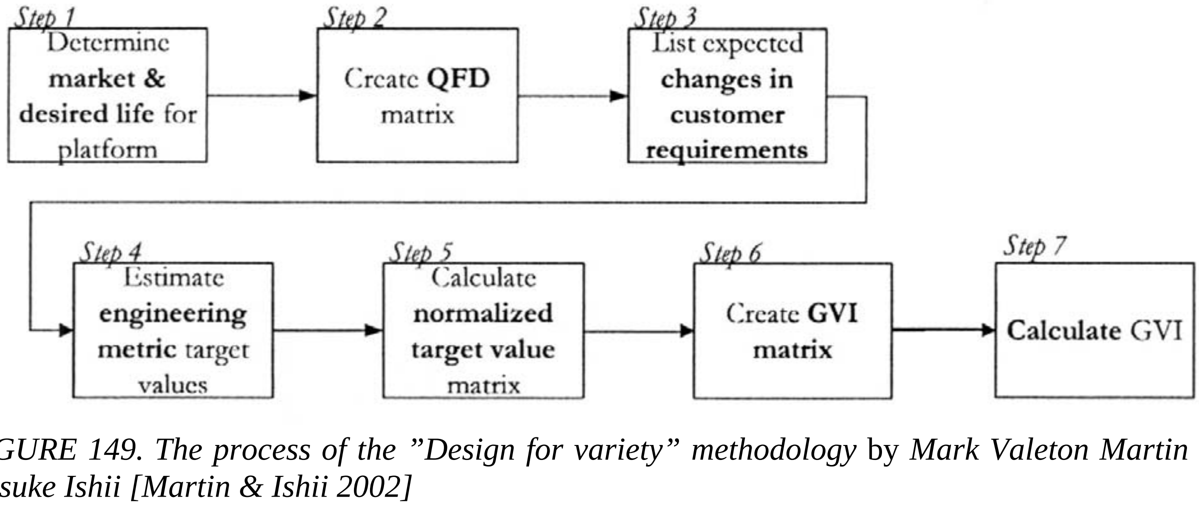


FIGURE 149. The process of the "Design for variety" methodology by *Mark Valeton Martin and Kosuke Ishii [Martin & Ishii 2002]*

This method also starts from the charting of the market situation and the product strategy of the company. The weights and dependencies from the product elements of the various requirements are defined with the well-known Quality Function Deployment method (QFD, see e.g. [Clausing 1994]). After this, the focus is shifted to the expected changes in the customer requirements. After this, the design values are evaluated and in the next phase normalized, so that the change in the various values can be proportioned. These are used to create the *Generational Variety Index* GVI which estimates the scope of the effect of the external pressures for change on the product element. Defining the pressures for change shows (according to the developers of the method) which parts of the product ought to be formed as ”modules” and which can be manufactured via ”standardization”. The terminology and the contents of the concepts here differ from those used in the present dissertation to the extent that there is reason for placing the terms in quotes.

Modular systems can be developed by following the steps of the method, but the method does not guide us in that direction and does not in fact even define a modular system. In any case, this method also includes the idea of a *target architecture* of the product structure, which is not based on the functional structure.

12.1.7 Algorithm-based modular division

Converting the design of a modular division into algorithms is a tempting goal when approaching modularity from the function-based viewpoint. Research conducted by Victor Kreng and Tseng-Pin Lee shows how this could be done. The method is based on calculation performed via means of the intra-domain and the inter-domain matrices in which the dependencies of the product-internal structure are compared to the requirements by using a list of the module drivers. The module drivers in this research are collected from earlier research (it also includes Erixon's MFD). There are 14 module drivers on the list shown below. We will not evaluate the reasons for selecting these particular items as module drivers here; the justifications can be found in [Kreng & Lee 2004]. The problems of such lists from the scientific viewpoint have been discussed earlier in connection with Erixon's methods.

1. Carryover
2. Technology evolution
3. Planned product changes
4. Standardization of common modules
5. Product variety
6. Customized products
7. Flexibility in use
8. Product development management
9. Styling
10. Purchasing industrial components
11. Manufacturability refinement and quality assurance
12. Quick services and maintenance
13. Product upgrading
14. Recycling, reuse and disposal

The Kreng and Lee method begins with the determining of the dependencies of the internal components of the product. The amount of mechanical and functional dependency is examined: they are summed together with the weight factor of 0.5. The strength of the dependency is evaluated with a pseudo-logarithmic scale of 1-3-9 resembling the QFD. Full dependency (9) thus only occurs with parts that are attached to each other and share a function.

After this, the effect of the customer requirements on the module drivers is evaluated. From here, we proceed to calculating the relative importance of each module driver (in relation to the customer requirements and the related development requirements). After this, a table is written in which the effect of each module driver on each product component is evaluated. The data for this table must be collected manually.

After this, the GGA (Grouping Genetic Algorithm) is used that seeks the grouping optimum which forms modules with a similar module driver profile and a minimum number of component-level dependencies outside the module. The initial values of the genetic algorithm are the minimum and the maximum number of modules. According to the nature of a genetic algorithm, various module combinations are formed of the components within the limit values, and the maximum value is sought for the function indicating the number of modules imperatively (=via systematical trial).

$Z(Y) = w_r I_r(Y) + w_c I_c(Y)$

in which $I_r(Y)$ is the total of all ”intra-modularity” created between the components based on the similarity of the module drivers. $I_c(Y)$ indicates the total of all ”intra-modularity” created of the strength of the physical and functional dependencies within the same module. ”Intra-modularity” is the method-internal calculatory value, an index that does not exist in the real world. Coefficient w_r is the coefficient for the effect of the module driver profile. Coefficient w_c is calculated as 1- w_r , which means that these coefficients are used to set the weight value between the physical structure and the module drivers.

The calculation algorithm is not explained in any more detail, as the correctness of the calculation is not the most crucial factor here: the value of the results ought to be evaluated in the light of the initial evaluation data. This data contains the number of physical and functional dependencies between the components, a list of module drivers, and information on their importance. In principle, it is possible to suggest an optimal structure for the product with this initial evaluation data. The correctness of the results depends on the correctness of the initial evaluation data and the correctly defined coefficient w_r for the effect of the module drivers. The results of the analysis are in principle better than those acquired with the MFD method, but considering the difficulties related to the gathering of the material, several opinions can be formed on the matter. An apparent source of errors lies in considering the physical and functional dependencies as equal, which is not true in all products. In any case, the method meets the criteria for breaking free of a purely functional approach – functionality only forms a half of the internal dependency, and the weight value of the physical and the functional dependencies are separately defined. The existing examples are not new product design, but performing the analysis on the concept level is theoretically not excluded.

12.1.8 Further developments of the MFD method

Roger Stake and Michael Blackenfelt have aimed to extend the Modular Function Deployment method with a corporate strategic viewpoint [Stake & Blackenfelt 2000]. In his dissertation, Stake suggests three new analysis elements [Stake 2000]:

1. Strategic Module Map (SMM)
2. Module Driver Hierarchy (MDH)

3. Concepts by Cluster Analysis (CCA)

The purpose of a strategic module map (SMM) is to clarify at the beginning of a product development project *the company's goals that are aimed at via modularity.* As is proved in this dissertation, this is an extremely essential phase, as the structure of a modular product is not defined on the basis of any natural law but is very goal-dependent. Stake suggests placing the module drivers in the process, customer, and product areas as an analysis tool, as shown in the figure below:

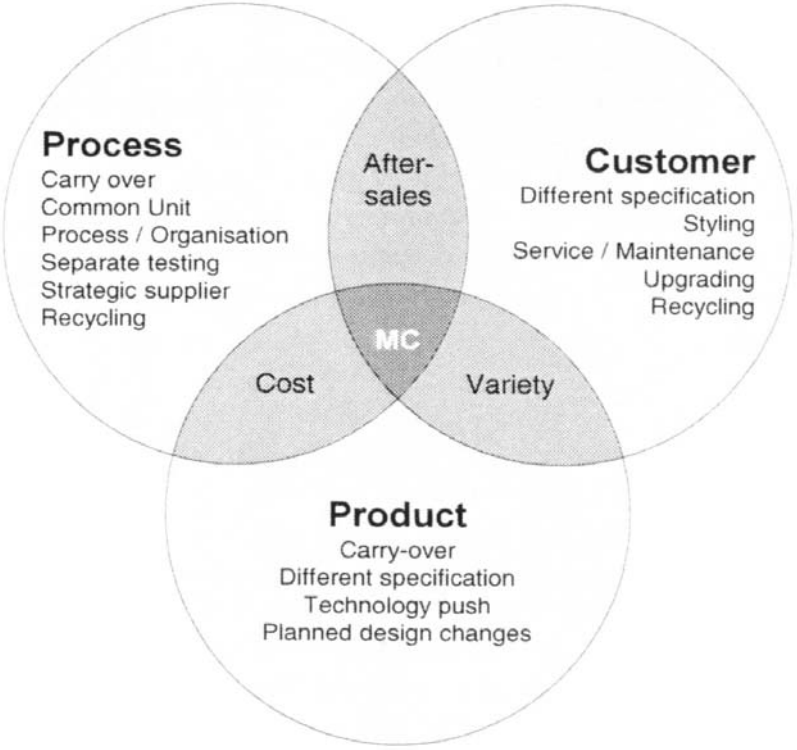


FIGURE 150. The Strategic Module Map (SMM) suggested by Stake [Stake 2000 p. 74]

In the Module Driver Hierarchy (MDH) analysis, Stake suggests dividing the module drivers into those related to the formation of the product family and those related to its functionality. These are valid views in the formation of a modular structure.

The last tool, forming Concepts by Cluster Analysis, does not considerably differ from corresponding methods discussed in section 5.7 *Tools for the synthesis of modularity*. Stake is aware of the challenging nature of such an analysis, and suggests the analysis method for supporting design in providing the designer team with possible solutions to be examined.

Pär Lanner and Johan Malmqvist have introduced the idea of combining the function-based matrix method and Erixon's business-oriented module driver approach. In the so-called ”Lanner matrix”, a vector indicating the importance of the module drivers of each element is entered on the diagonal line of a directed dependency matrix [Lanner & Malmqvist 1996]. A calculation software is required to support this matrix, that is probably similar as the Kreng and Lee algorithm discussed earlier. We also meet the same problems here: how to define the relative order of priority of the elements?

12.1.9 Views on the effects of modularity in a subcontractor chain

The dissertation ”Modularization in New Product Development: Implications for Product Architectures, Supply Chain Management and Industry Structures” by Juliana Hsuan Mikkola strongly highlights the effect of the business environment on modularity. [Hsuan Mikkola 2003] The model on modularity presented in Hsuan Mikkola's dissertation suit very well the proposed CSL-framework model of modularity presented in the present dissertation. Important observations include, for example, those on the effects of the business relationships in the subcontracting chain on the opportunities to utilize modularity. This is shown in the figure below. In our framework model (see Chapter 9), this would be placed on the bottom right corner (organizational structuring) and it would have a limiting effect on the opportunities for selecting the value chains and would thus require cutting down the modular structure into smaller pieces or changing the subcontracting strategy).

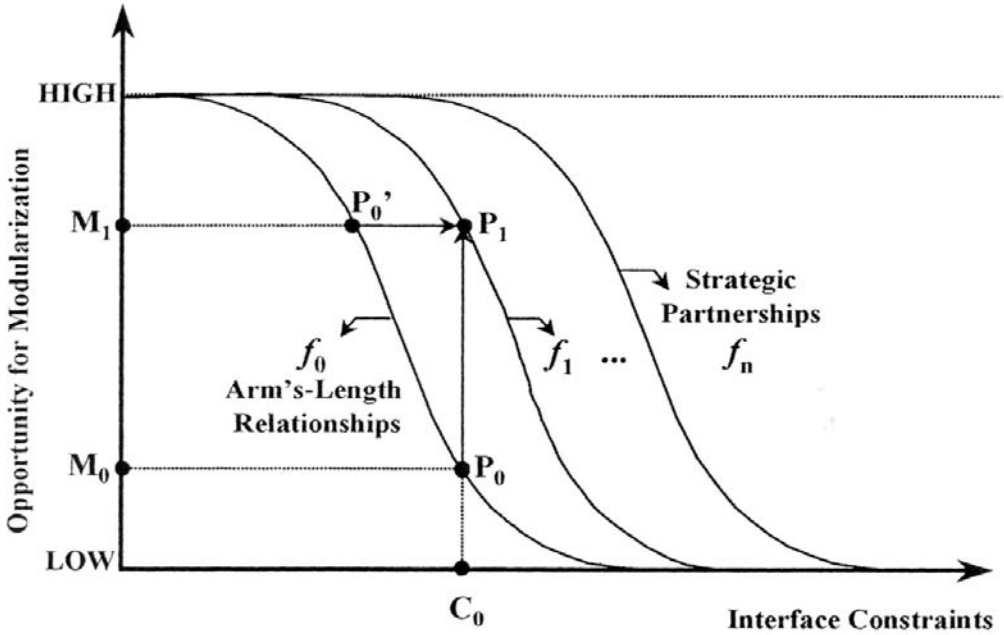


FIGURE 151. According to Juliana Hsuan Mikkola, the business relationships in the subcontracting chain affects the opportunity to utilize modularity. The size of the modules increases on the horizontal axis, which is described as the increasing complexity of the interfaces. Strategic partnership between companies enables the managing of much more complicated interfaces than a poor contractual relationship. [Hsuan Mikkola 2003 p. 226]

12.2 Research based on the function-based approach

US textbooks on product development

In the United States, two well-known textbooks of product development are ”Product Design and Development” [Ulrich & Eppinger 2000] by Karl Ulrich and Steven Eppinger, and ”Product Design” by Kevin Otto and Kristin Wood. The former is a very compact and factual presentation. The views of Ulrich and Eppinger on the development of modularity have been discussed in this work in connection with examining the hypotheses of developing theories.

The book by Otto and Wood is much more thicker, the wide scope is its greatest merit. The width of the scope is clearly visible when Otto and Wood present their own views on the development steps in the history of Design Science. Their quest begins in on approximately the year 2500 BC. This period of examination is considerably longer than that of the present dissertation. As the present dissertation follows the hermeneutic approach, we need to evaluate whether our period of examination is too short. This can be evaluated by examining whether some of the mentioned development steps outside our period of examination are essentially related to standardization or modularity. According to Otto & Wood, LeBlanc in France was the first to suggest interchangeable parts in 1785. The next step is the autobiography by James Nasmyth in 1883 [An Autobiograbhy, J. Murray, London, 1883] which discusses the ideas of Henry Maudslay on machine design (”Maudslay’s Design Maxims”, developed since 1807). The history of standardization is background material for our dissertation, which means it is well justified to exclude these two from the scope of the present work.

The part of the book by Otto & Wood on the design of modularity, pages 357-409, is written in co-operation with on Robert Stone, and the modularity methodology carrying his name is utilized in the book. The book also follows the method of systematical design ”according to the pragmatic school” (research conducted by Pahl & Beitz is mentioned as one of the great advances in Design Science) and refers to the research of Ulrich and Tung. Otto & Wood define that there exist two types of product architecture: integral and modular. Integral (according to Cutherell) is a product

”... where all of the subfunctions map to single or very small number of physical elements”.

According to Ulrich and Tung, a modular structure is defined as the similarity of the physical structure and the functional structure. The definition of the types of modularity presented in the book differs from the Abernathy-Utterback-Ulrich presentation. Otto & Wood present less types and suggest a new type called Mix modularity (this is different from the mix modularity method presented by Pine), based on the joining of the elements via a network. An example of this is the Tinkertoy series* in which the parts are joined by using standardized pins and bars. Another example is the army in which the troops, helicopters, and other military equipment are related to each other (!?). Generally, this kind of modularity based on mere fitting organs is not accepted as modularity in research (see e.g. Brannkamp and Herrman in section 5.2.).

Otto and Wood suggest two design methods for modularity: the clustering of function-based elements and the ”Advanced Functional Method”. The first one of these is discussed earlier in the present dissertation. The latter is much more interesting for the scope of this work. The method is based on analyzing the functional structure in relation to three heuristics. The first heuristics is to discover the Dominant Flows in the functional structure which come from the outside of the product and return to the outside. The other heuristics is to discover the ”branching flows” or the functional groups that branch off the main flows. The third method is to look for ”transformation-transmission modules” in which the energy or the material changes form. The following three figures show the example of a handheld battery-operated screwdriver manufactured by SKIL, as presented in the book. The first figure shows the main flow module candidates, the next figure shows the branching flow module candidates, and the last figure shows the transformation-transmission module candidates. The figures are drawn using the description method presented by Stone.

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* Tinker Toys is a constructional toy system patented by Charles Pajeu in Chicago in 1914. He patented the system after having observed how children created constructions by joining reel of thread with pencils [Jaffé 2006 page 110].

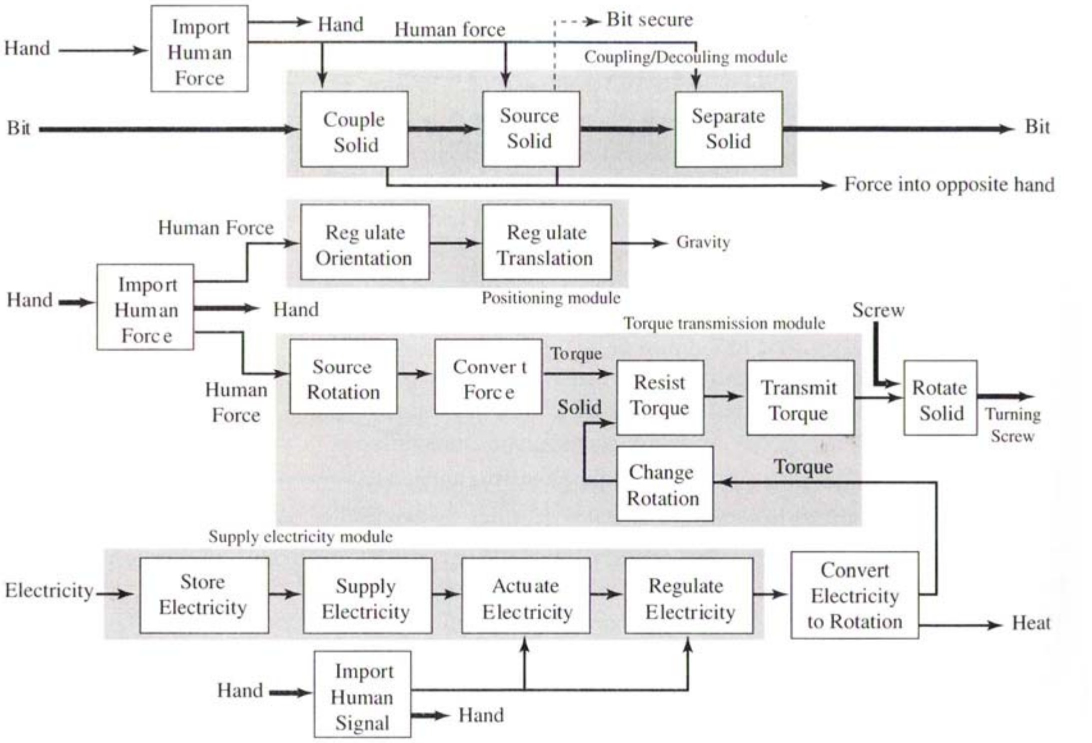


FIGURE 152. The suggested modules in a handheld battery-operated screwdriver manufactured by SKIL, following the "main flow" heuristics, are indicated by a grey background. [Otto&Wood 2001 p. 382]

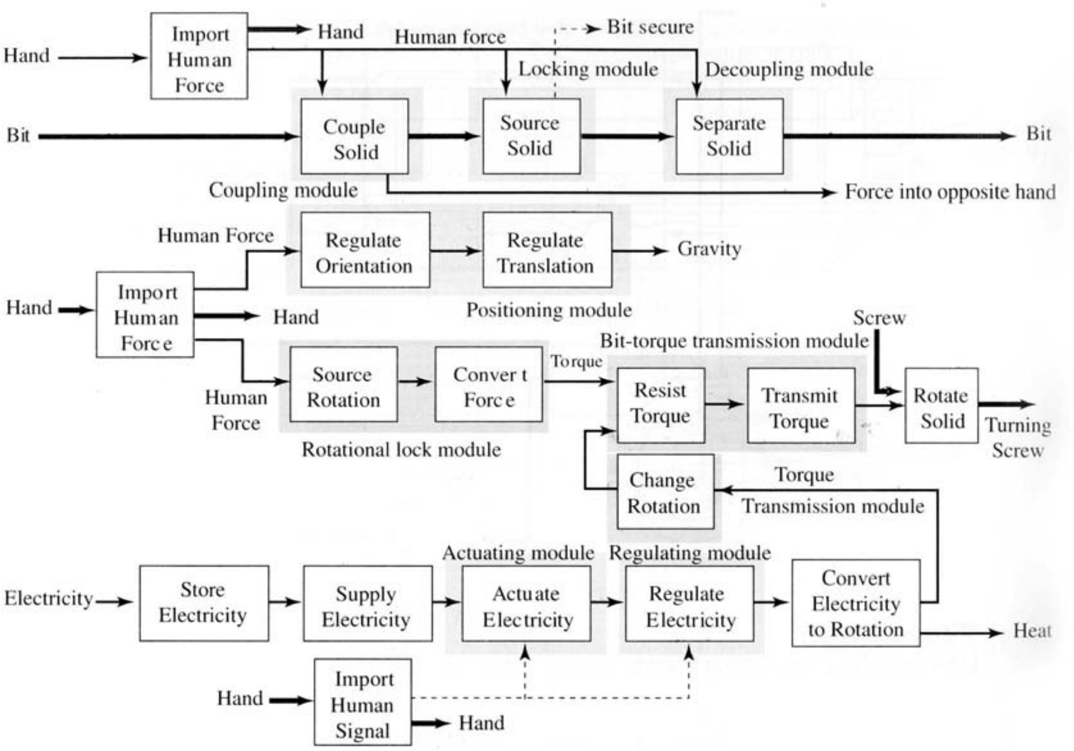


FIGURE 153. The suggested modules in a handheld battery-operated screwdriver manufactured by SKIL, following the "branching flow" heuristics, are indicated by a grey background. [Otto&Wood 2001 p. 386]

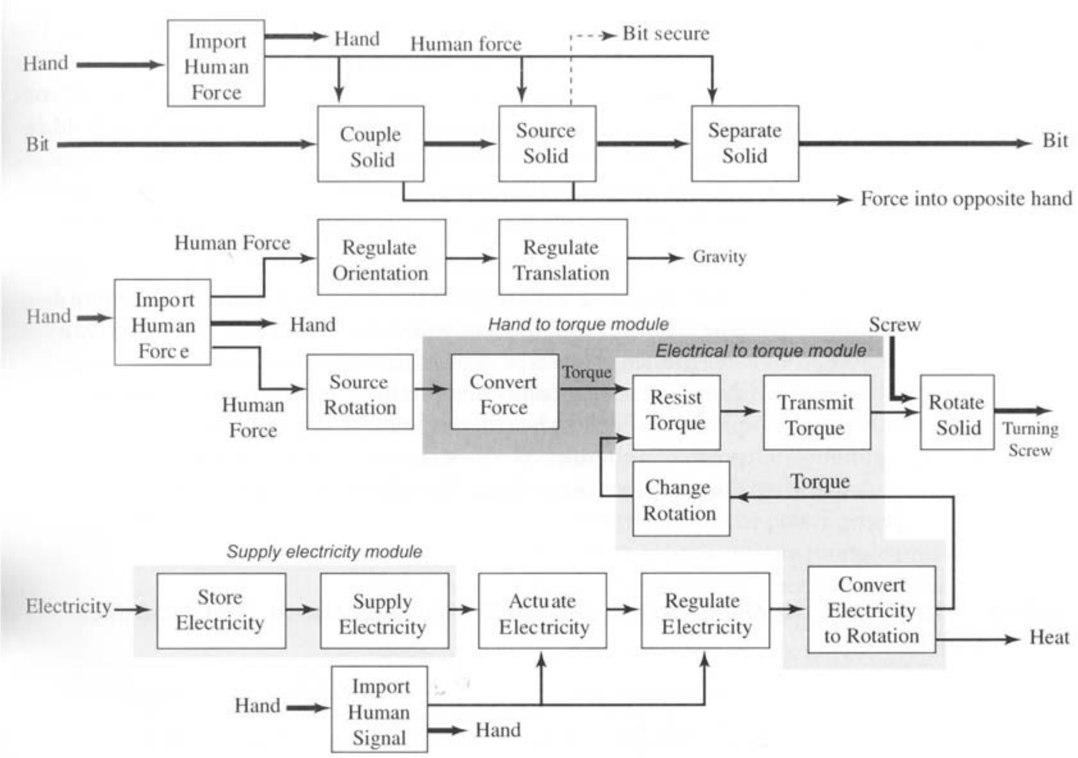
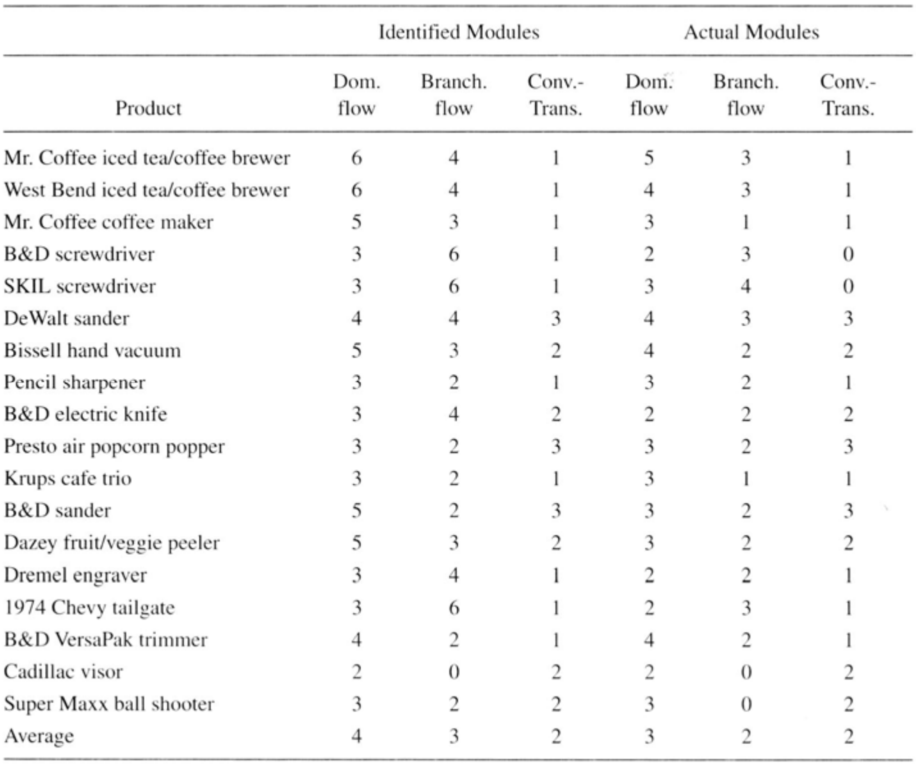


FIGURE 154. The potential conversion/transmission modules in a handheld battery-operated screwdriver manufactured by SKIL are indicated by a grey background. Note the overlapping module suggestions. [Otto&Wood 2001 p. 389]

The method shows more modules than can be found in the implemented product. In some cases, the difference is considerable, for example, in this case the actual product did not have either of the two transformation-transmission modules suggested. The developers of the method (Stone, Wood, and Crawford) have sought to verify the functionality of the method by dissembling and analyzing 70 different products. The products have been mostly hand tools and household appliances, but they also include the tail gate of a 1974 Chevrolet station wagon. Of these, 18 products are presented in a table format in Otto & Wood. The table shows how many modules were proved by the method and how many modules the researchers recognized in each product. The results are shown in the table below:

TABLE 4: The module variants shown by the different heuristics in the functional structure and the number of "modules" in the implemented product detected by the researchers [Otto&Wood 2001 p. 390]



	Identified Modules			Actual Modules		
Product	Dom. flow	Branch. flow	Conv.-Trans.	Dom. flow	Branch. flow	Conv.-Trans.
Mr. Coffee iced tea/coffee brewer	6	4	1	5	3	1
West Bend iced tea/coffee brewer	6	4	1	4	3	1
Mr. Coffee coffee maker	5	3	1	3	1	1
B&D screwdriver	3	6	1	2	3	0
SKIL screwdriver	3	6	1	3	4	0
DeWalt sander	4	4	3	4	3	3
Bissell hand vacuum	5	3	2	4	2	2
Pencil sharpener	3	2	1	3	2	1
B&D electric knife	3	4	2	2	2	2
Presto air popcorn popper	3	2	3	3	2	3
Krups cafe trio	3	2	1	3	1	1
B&D sander	5	2	3	3	2	3
Dazey fruit/veggie peeler	5	3	2	3	2	2
Dremel engraver	3	4	1	2	2	1
1974 Chevy tailgate	3	6	1	2	3	1
B&D VersaPak trimmer	4	2	1	4	2	1
Cadillac visor	2	0	2	2	0	2
Super Maxx ball shooter	3	2	2	3	0	2
Average	4	3	2	3	2	2

Of the sample cases in the present dissertation, modules were sought with a method corresponding to the main flow heuristics in the ambulance case (section 10.7.). This can, therefore, be considered a valid starting point for defining the modules from the functional structure, but the approach is not a new one. Why, then, are branching flows and the transformation-transmission modules considered important bases for forming a module? No theoretical justifications for this are presented.

We can criticize the method in three respects. The method requires a functional structure drawn on such a detailed level that it is not even possible in the concept phase. As a detailed functional structure describes a specific product, this is a question of outlining the modular boundaries in the product, and it could lead only to minor layout changes. In the case of verification performed on 70 products, we could question whether the "modules" found in the products really were modules? The biggest shortcoming, however, was related to the setting of goals. What was the role of modularity in the products? What was the role of modularity in, for example, the tailgate of the 1974 Chevrolet (research published in 1998-99)? From the Borowskian viewpoint presented in this dissertation, this example is almost absurd!

One reported benefit of the advanced function-based method is that it is not a blind module search such as clustering, but it shows modules with respect to, for example, the product families. This goal remains mere words, and the issue is not expressed in the explanation of the method or the examples. A "dominant flow", a "branching flow", and "transformation" are all internal issues in the transformation of the product and the technical system, and no extrapolations can be made from here to the business environment. The method thus highlights no essential new issues for the dissertation.

However, this issue has been revisited by the research team of Jeffrey Dahmus, Javier Gonzales-Zugasti, and Kevin Otto. In their article ”Modular product structure”, the expand the method to cover the design of product families [Dahmus & al 2001]. This is carried out by examining the product family and by recognizing the shared functions and the unique functions. Of these, shared functions can be divided for a large part of the product portfolio. Unique functions are only product or product-group specific. These are sought by using a matrix whose horizontal axis indicates the functions, the vertical axis the products in the product range, and ”modules/components” is written on the columns of the matrix. The method is not very original and does not provide new information for modularity.

12.3 Modularity research based on other premises

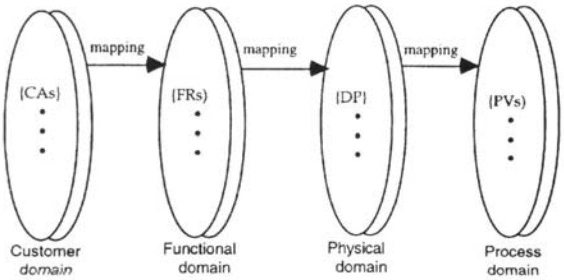
In the field of design sciences, there are not many big theoreticians who had aimed at creating comprehensive presentations on the level of Hubka's Theory of Technical Systems. Nam Pyo Suh is one if the few alternatives that can be considered as the theory base of the TTS. Suh comes from outside the German school. His books and articles, published around the year 2000, do not refer to Hubka. Suh takes a critical stance towards the general level of research conducted in the field. He states that research focuses on engineering science analysis when it ought to focus on engineering science synthesis. He comments on the results:

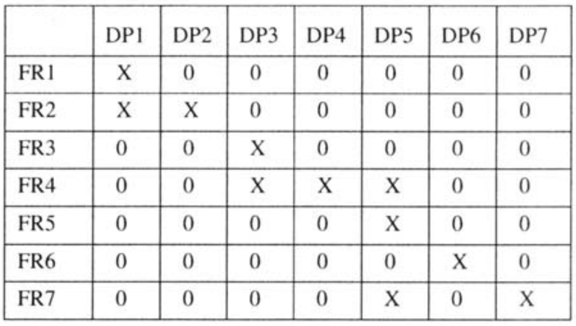
”Consequently, academic researchers have conducted research on optimization techniques and ad hoc theories and methodologies that may lack scientific base.”* [Suh 2001 p. 382]

*ad hoc Latin = for this – usually used in the derogatory sense in connection with theories

To fix the situation, he suggests that product design ought to be based on ”science”, that is, axiomatic design and the natural sciences (Suh 2001, p. 383). Suh's observations on the problematic issues in the development of the field of research resemble in outline those presented in the introduction of this dissertation. Invoking to scientific research is, however, rather without substance, as everyone initiated with methodologies knows that a scientific method guides towards correct knowledge but does not pinpoint it. Developing design methods involve the problem that they describe issues that exist on such levels of abstraction that even the existence of the phenomena studied (outside the theoretical frame) must often be evaluated. In this situation, there is a great risk of selecting issues that have not been tested as required by a scientific method, arising from the researcher's own spheres, as premises. Karl Popper argues in his book ”Logik der Forschung” (1935) that causal explanations require in addition to the initial conditions describing the individual features also a minimum of one universal prerequisite. The potential weakness in Suh's theory is related to the selection of the universal prerequisite, as will be explained later on.

Nam Pyo Suh suggests linking the elements in the functional and the physical domain with a matrix presentation in axiomatic design. [Suh 2001] According to Suh's axiomatic design, the *design world* consists of four *domains* in which the issues involved in the same product occur as different elements according to the context of examination. The domains are the customer (requirement), the function, the physical (=part structure), and the process (of development and production). This is shown in the figure below, next to which there is an example table on the linking of the elements. Such a matrix is not a square matrix unless by coincidence.





	DP1	DP2	DP3	DP4	DP5	DP6	DP7
FR1	X	0	0	0	0	0	0
FR2	X	X	0	0	0	0	0
FR3	0	0	X	0	0	0	0
FR4	0	0	X	X	X	0	0
FR5	0	0	0	0	X	0	0
FR6	0	0	0	0	0	X	0
FR7	0	0	0	0	X	0	X

FIGURE 155. The four domains in the design world, according to Nam Pyo Suh, and the Inter-Domain matrix that links the elements in the different domains (in this case, the functional and the physical). [Suh 1999]

Suh's theory externally resembles Hubka's ideas. Despite the outer similarities, the ideas behind Suh's presentation differ to a great extent from those of Hubka's. According to the author's personal experience, Suh's presentation does not provide an improvement to Hubka's, as it lacks the view on the proceeding of the design process, and the solution principle is not accepted as a separate domain. Highlighting the customer/requirement domain is an advantage compared to Hubka, but it (in the author's view) does not compensate for the mentioned weaknesses.

One of the cornerstones in Suh's theory is the theory of good design properties. He presents an independence axiom which in simplified terms means that the matrix that links the functional and the physical domain becomes a bottom triangle matrix. In addition, the more dependencies on the diagonal line only, the better. Anyone initiated in managing product development projects sees immediately that this means a ”cascade model”, that is, a decision order that does not require iteration in the design process can be found. In a pure cascade model, dependencies only exist on the diagonal line, in which case the one-on-one dependency between the function and the function carrier is implemented. *This also implements Ulrich's definition of product modularity.*

At the beginning of this chapter, we mentioned Popper and the requirement of one universal prerequisite in causal explanation. The idea of a good design is the universal prerequisite in Suh's theory. Suh states:

”Products that violate the Independence Axiom are not good products in terms of quality, reliability and functional robustness.”

This is true when we examine things from the *viewpoint of design data management and the management of the requirements*, that is, looking at the issue with the eyes of designers and design managers. The most important feature of the product is, however, not always easy designability and the easy maintenance of the design data. Suh's axiom leads to the identical form of the function structure tree and the element structure tree, which has been observed to lead to increased weight and costs and reduced performance in connection with modularity. Certainly, it is easy to understand the structure of such a product, it seems logical (is this quality?), it is easy to maintain (reliability), it is easy to configure, and a defect in one function does not necessarily affect the others (functional robustness). The importance of these considerably depends on the area of application, but the independency axiom is not very comprehensive to be used as a universal prerequisite.

As was explained above, Suh's theory as such contains ideas that also ”ac hoc researchers” have associated with modularity. However, Suh's definition of a module differs already for its starting points from the one presented in the present dissertation. According to Suh, a ”*module”* is a row in such a design matrix that produces the Functional Requirement (FR) when attaching a ”Design Parameter” (DP) to one or more physical domains. As the ”modules” are thus *relations between the domains*, they do not show in the tree structures unless separately drawn. For this reason, *module junction diagrams* are drawn in the tree structures. There are three junction types: *summing junction*, *control junction*, and *feedback junction*. These are fully analogous with the three dependency types in Steward's matrix methods (and later the Design Structure Matrix tool). This is shown in the figure below. This observation strengthens the view according to which the bases for Suh's method can be found rather in project management than in the theoretical modelling of a technical system. On this basis, we have reason to assume that the results of this dissertation would not improve if we changed the theory base from Hubka to Suh.

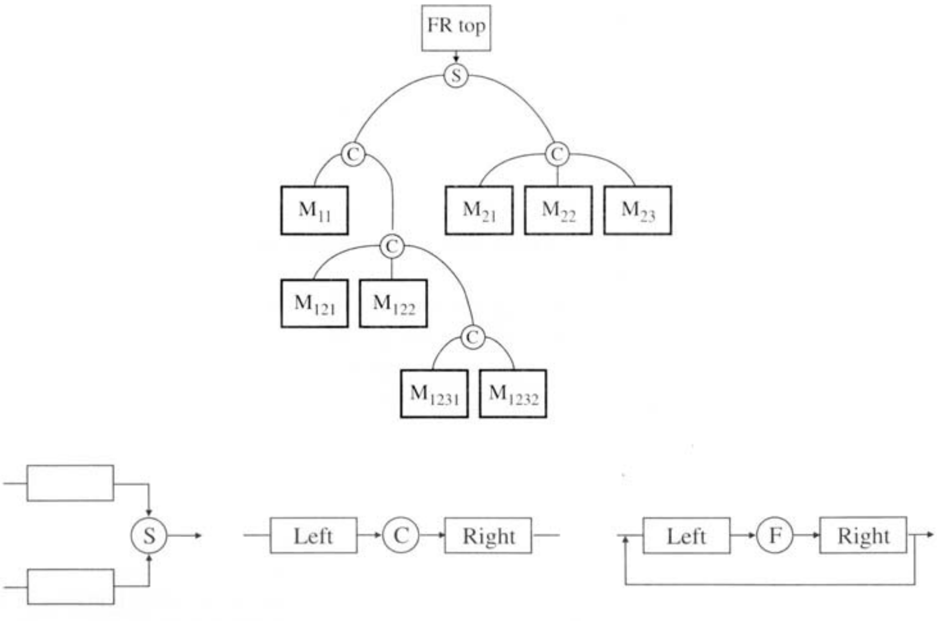


FIGURE 156. The module-junction diagram by Suh and the three ”crossroad types” under it. On the left, summing junction (DSM: independent tasks); in the middle control junction (DSM: consecutive tasks); and on the right feedback junction (DSM: coupled tasks). Suh does not refer to Steward or the matrix methods, but the comparison is added by the author. [Suh 1999 p. 211]

12.4. Summary of the comparison to other research

When comparing the results of previous research to the results and the premises of the present dissertation work, we can state the following:

1. The alternative approaches do not provide new insights to the issue, which means that, the reference material of the theoretical part of this dissertation is correctly selected. (See section 12.3.)
2. No function-based method is able to discover a way around the problem in the new product design presented in this dissertation. Therefore, the proof of Hypothesis 1 is valid. (See section 12.2.)
3. The observations on product development in the industry presented in this dissertation are also noted in other research. In principle, suggestions resembling the design process presented in Chapter 11 have also been presented. Therefore, the proof of Hypothesis 2 is confirmed. (See section 12.1.)

No results could be found in the other research in the field that would question the results of the present dissertation. Instead, we were able to discover material to support the results. To prove the fact that the ideas presented in this dissertation are not a separated island remote from actual core research, the design process of a new product can be illustrated by using existing methods and tools from other research. When aiming to use existing tools, the process is divided into two paths according to whether design is carried out on the basis of an existing product structure ”top down” or whether a new structure is created (see Chapter 11 ”the design process of a new modular product”).

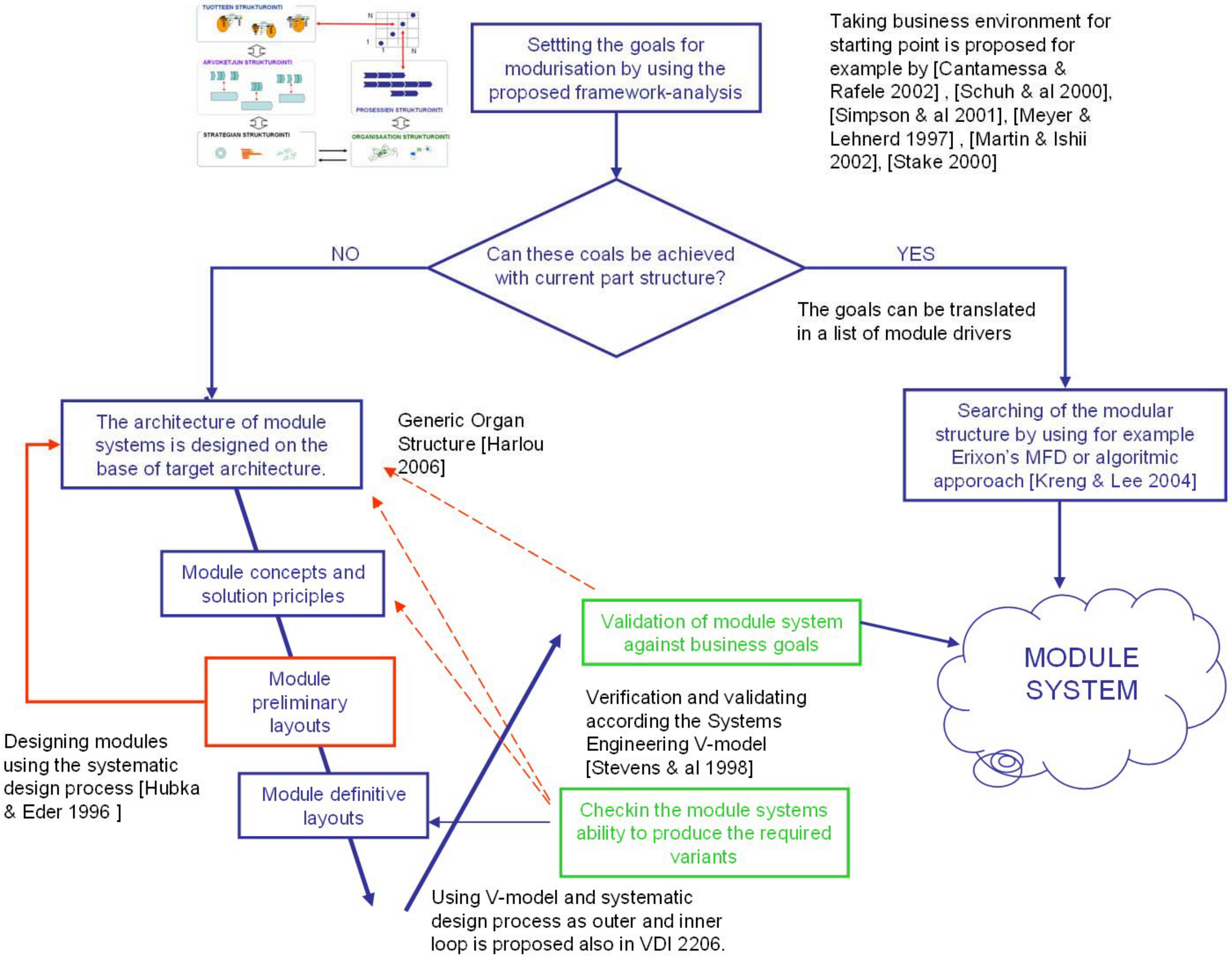


FIGURE 157. The design process of a modular architecture for a new product, using tools developed in other research, is divided into two alternative paths. All phases of the V model and relations therein are not included in the figure for clarity's sake.

The figure shows that the company strategic landscape framework model is the only completely new method of analysis that is absolutely necessary for the design process suggested in Chapter 11. In some methods, it is replaced by QFD analysis (e.g. [Martin & Ishii 2002]). However, Quality Function Deployment compares the goals to product parts, which is not applicable in the design of a new product.

13. Discussion – the importance of observations for modularity research

The scope of the research and applicability

This dissertation discusses the design of a modular structure in new product design following the definition of Design Science. Even though methods resembling the process of new product design are rarely used in industrial product development, the method is important as the basis of a theory. The process of new product design is also important because is it taught in engineering classes at universities in the Nordic Countries and in Germany as the basic method of product development to which other methods are compared. For this dissertation, it is also important to be able to define the proceeding order of the processes, which is enabled by the process of the new product design (in which the design knowledge is ideally considered to be created during the process). The proofs presented in this dissertation are, then, only valid in the (theoretical) development process of a new product. However, we can see from the industrial examples that the presented regularities and the tool suggested on their basis also seem to be valid in practical development tasks. The results are thus valid in a larger scope than proved, even though this cannot be proved in this dissertation due to the insufficient theoretical base.

The research methods

Even before this dissertation, research in Design Science was full of studies of modularity which present more or less arbitrary definitions and assumptions of modularity. In this dissertation, the role of arbitrary definitions is minimized with the hermeneutical historical perspective. In Chapter 4, we have aimed to show what modularity *de facto* is with the help of historical industrial examples. In Chapter 5, this was compared to what has been written about modular-type systems in previous research. As the starting point of the work has been to evaluate the problems in reaching research results, the examination is critical and some of the theories considered in the reference sources are discarded.

The part of the dissertation that contributes to the field in terms of new issues introduces a specific module definition (M-modularity). The definition is not arbitrary, but it limits the scope to system-based modularity. We base the selection on the work of Karl-Heinz Borowski that is nearly always mentioned as the basic source in modularity research. In this dissertation, Borowski is also rather precisely followed. For example, the key idea of solution levels has often been neglected by researchers referring to Borowski. Of research conducted in the United States, we have only included the set theoretical model of structures containing interchangeability.

The presented *company strategic landscape framework* is not a theory that could be derived directly from certain empirical material. Developing such a theory would require actual modelling the relationships between the elements, which is not possible due to the wide scope and the multiple dimensions of the issue. The CSL-framework model is thus a rough generalization of how things ought to affect each other. For this reason, its value can only be measured by its usability. Eight of the presented industrial examples show that the tool is a useful design tool and it is able to highlight issues that have arisen in practice.

The results of the research

In this dissertation, we have defined what kind of an idea of modularity is formed by further developing Borowski's Baukastensystem. Via means of theoretical advances (the theory of the development of modular product structures) and industrial examples, it has been proved that modularity of this type in particular (M-modularity) enables the issues aimed at in most of today's industrial modularity projects: design reuse, systematical product configuration, and a platform-based product. Our purpose is not to prohibit the use of the word 'module', for example, in dividing a large construction into blocks for transport, but this dissertation shows that such a mere physical division does not bring about the good properties often associated with modularity, as these benefits are not created of modules but of the module system. *In these cases, a module system does not exist.* For this part, the arguments in the theory are directly bound to practical goals.

In this dissertation, we have also proved that functionality cannot be taken for granted as the starting point for developing a modular division. This is proved theoretically by examining the systematical design process and by analyzing the elements that implement the goals. On this basis, we present the *design process of a new modular product* in which the requirements of the business environment guide the internal structuring of the product. This corresponds ideas that have been presented elsewhere in the field of research, but changing the order of priority in design has not previously been introduced or justified. The design process presented in this dissertation also operates on a more tangible level than the previous models.

The contribution of the dissertation to research and the focusing of further research

A function-based approach sometimes yields results in developing modular structures. At times, it does not yield any results or emphasized issues that are eventually not relevant for the goals of the real world. It seems that the suitability of the function-based approach depends on the ”inherent type” of the product structure. Electronic products to be grouped in cabinets equipped with terminal blocks are of the *bus-modularity* type to begin with, and as the electronic cards to be attached to them often perform a function, function-based modularity is very applicable in these cases. Process-intensive products (power plants, production lines) are also often divided into modules based on the process phase. In power plant structures, however, the including of auxiliary systems in the modular division often disturbs the clear comprehensive view. In products with a number of main functions and in which variation is related to parameters – such as in the case of a tunnel drilling rig – the functional division is not very interesting on the product family level. Products thus differ in terms of modularity. An interesting research question for further research would be whether classification could be developed here. The example material in this dissertation was not sufficient to serve as the basis for developing a classification.

According to the positivistic view, it has often been considered that a modular structure following Ulrich's definition would be beneficial as such. Obvious benefits can certainly be pinpointed in a modular structure, for example, in the product maintenance. This approach does not, however, consider the major requirements set for the products by a product structure that is organized according to the main function and does not contain unnecessary independencies. On this basis, there has even been reason to ask whether modularity reduces the performance of the product and increases the costs without providing much benefit in return. A good example of this is the application of modularity in the case of a diesel locomotive in section 10.3.

We could present a number of pseudo-rational examples on the superiority of an integral product compared to a modular one. For example, some years ago, the author taught modularity at Edutech, the education centre of the Tampere University of Technology. At that time, he entered an interesting discussion with Professor Asko Martio, who was lecturing the course. Martio, who had previously worked at Kone elevators, showed that in a traditional elevator engine room, separating the functional units (the brakes, the engines, the gear system, the coils) as functional modules increases the amount of material and the congestion in the engine room, and causes costs without providing any real benefits for the business operations. Slightly earlier, Kone Oy had developed a success product in which the entire machinery was assembled as the moving counterweight in the elevator shaft. The case was a typical example of what modular products are traditionally reproached for: expensive, heavy, and suboptimal in efficiency.

The issues highlighted in this dissertation do not remove the fact that a modular product is not the solution for all business situations. Instead, in the case of Kone Oy, we would never suggest discarding the implemented modularity. Professor Martio's observations on the effect of modularity were applied to a product in which traditional function-based modularity was used. We believe that the ideas presented in this dissertation will lead to the realization that modularity can be more than the mere building of functional machine elements as separate assemblies.

Conclusions for researchers and teachers of product development

As we operate on the Design Science field and are thus ready to evaluate the results on the basis of their usability, we end up with the conclusion that the approach emphasizing the function-based division and modular independence does not meet the requirements set for a universal approach. The reason for this is not the erroneousness of the observations but rather the unrealistic attempt to solve a multi-dimensional and difficult issue via simple means. When operating in the real world, we must not forget our goal, and, unfortunately, the goals vary considerably. In extremely few cases, the customer wishes to buy a product because of its modularity. Instead, most often modularity enables certain characteristics desired by the customer. Modularity is often also an internal competitive edge for the company, the importance of which for the customer is created via economic mechanisms.

However, after all the research conducted in technical systems and the design process it is difficult to believe that modularity would be the only area where no functional theory enabled by a synthesis can be created. The purpose of this dissertation is not to present a theory of *the synthesis of modularity*, even though we are able to list some bases for developing one. Should the theory of *the synthesis of modularity* be based on a division of how the functionality of the product and the need for variation arising from the business environment are related to each other? Should products be divided into types with separate instructions for applying modularity?

This dissertation is a further development of the Theory of Technical Systems by Vladimir Hubka. Perhaps we could conclude by examining in what way thesis view differs from the original. Here, we might revert to Hubka's description of the need for theory [Hubka 1984/88 p 7]:

”When visiting a technical museum, we can see thousands objects and we recognize them as products of technology. Their variety in functions, forms, sizes, etc. tends to obscure the common features and properties among these objects... ...Let us therefore ... attempt to develop a term that conceptually describes all classes of technical objects.”

In what way, then, does our visit in the museum of technology differ from Hubka's? The most important difference is the fact that it is a limited view to consider the technical systems on display at museums. As products enter a museum, they are no longer used, and their existence is justified by their mere existence. In the reality outside a museum, the product must be able to adapt to the requirements set by the business environment to even be born. For this reason, we do not discuss *technical systems* but *products* in this dissertation.

Much too often, a product developer only stares at the product and understands it in the technical context only. Are not researchers guilty of the very same? Even though we are able to describe technical systems and discover synergies between them, is our scope of examination still sufficiently wide? It does not suffice to be able to manufacture functional products; a successful methodology must be able to lead us to developing successful products. TTS is an inherently process-based view; adopting a wider perspective would not thus be impossible. As a professional pedagogist operating in the technical field, I ask myself: do we teach skills that separate successful companies from losers, or do we teach skills that everybody already possesses?

14. Conclusions

In this dissertation, we have examined the bases of the synthesis of the modular structure in new product design. In a number of previous studies, the functional structure of the product has been presented as the primary basis for the modular structure. In this dissertation, we show that this approach is not possible in a genuine new product design process without iteration. In addition, we have shown with hermeneutical historical examination and eight industrial examples that functionality is not always relevant in the design of the modular division from the viewpoint of the business environment. In the arguments at the beginning of the dissertation, we thus show that there is no justification for prioritizing the functional structure over the other motivations for modularity.

As we have thus discovered why a more generally established approach ought to be discarded, we set out to examine the bases to which the synthesis of a modular structure ought to be based, in the constructive part of the dissertation. To enable the examination, modularity is examined in a business environment that is larger than the design environment. We make observations on the changes in the use of modularity over history, and based on these, present a *theory of the development of the modular product structures*. The definition of modularity is examined, and modularity as a phenomenon is divided into two categories: variation related modularity and modularity related to the life cycle of the product. Most of the material and the examples in this study are related to variation related modularity that is called M-modularity in this dissertation. A definition of M-modularity is presented that is based on previous research but is new as a whole.

To chart the reasons for the formation of the module structure, we use the *company strategic landscape framework* introduced by researcher Tero Juuti and analyze eight industrial sample cases with it. In the cases, the effect of function-basedness compared to the effect of the business environment is evaluated. As a conclusion, we state that the analysis process that creates the model is clearly better than the function-based one in five cases ought of eight, probably better in one case, and equally good in two cases.

On the basis of the results, the *company strategic landscape* framework is accepted as the starting point for the *design process of a new modular product* to be presented. The process is formed on the basis of the framework model and the V model presented in the Systems Engineering research and on the process of systematical design used on its bottom levels. The selection of the V model as the design process for the modular system level is justified in Chapter 11, and the same issues arise in the example in section 10.4.

Finally, we discuss the previous research in the light of the results, and are able to prove that the ideas and issues presented in this dissertation have already appeared in previous research as fragmented. In addition, it is proved that it is possible to implement the presented *design process of a new modular product* even with the existing design tools.

The main contributions of the work to Design Science and to practical design work are:

1. Showing the limitations of the functional approach in defining the modular structure (Chapter 5)
2. The division of the phenomenon of modularity into ***M-modularity*** related to variation, and to modularity related to the life cycle of the product (Chapter 7)
3. ***A theory on the development of the modular product structures*** (Chapter 8)
4. Developing a framework model as a tool for practical product structure research (Chapters 9, 10)
5. A suggestion for the ***design process of a new modular product*** (Chapter 11).

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