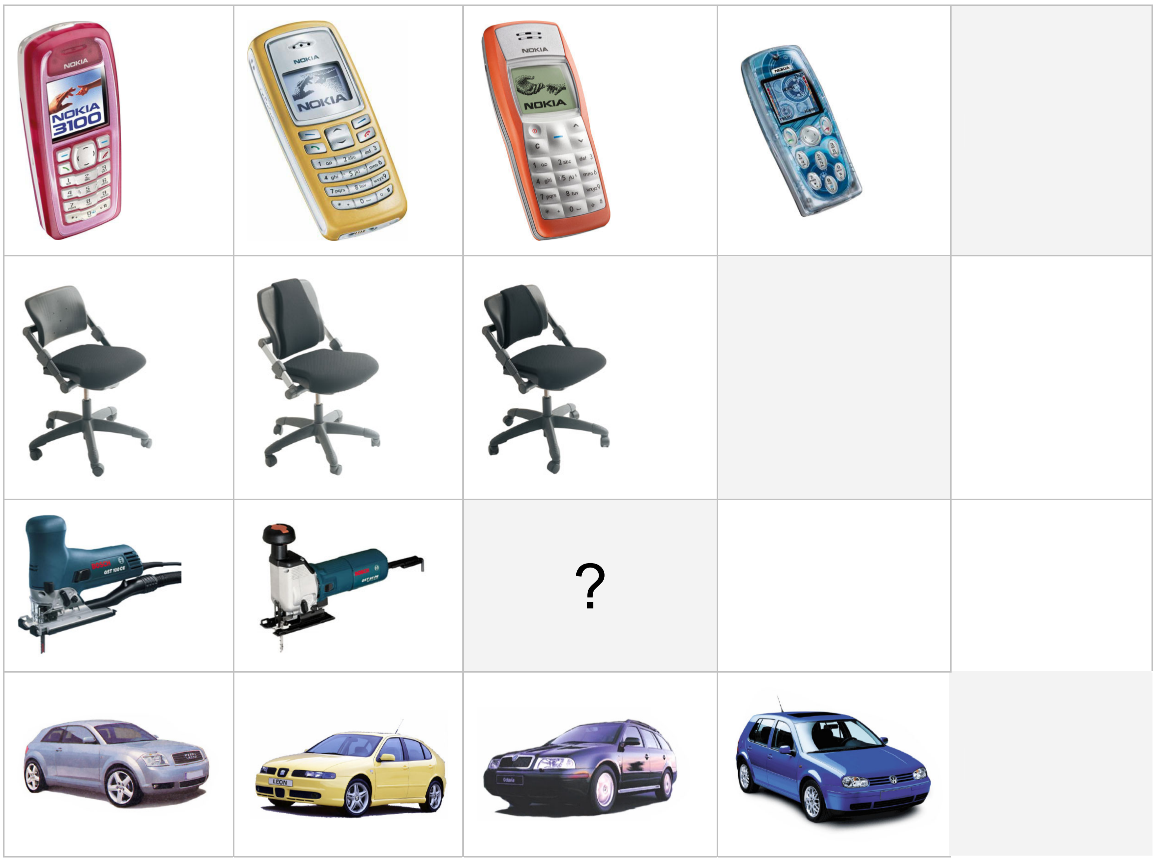
Product Design 9

Modular Product Architectures

Exemplification of the modular concept generation process

When is modularization appropriate?

Øystein Eggen
2003



About this project

This project is written as a part of the course "Product design 9" at the department of product design engineering, Norwegian University of Science and Technology.
Product Design 9 is an in-depth course where the student writes an article on an area of his/her choice within one of the categories eco-design, interaction design, design esthetics, technical analysis and design management. The article is then supposed to serve as the theoretical foundation for an individual project.

I chose the area of design management and wrote an article on modular product architecture. More specifically I described methods of module identification in the concept generation phase of a product development effort. This project is a direct extension of the article, and I have therefore chosen to include the article in the appendix. Throughout this report, I refer to theory described in the article.

Trondheim, 28 November 2003

Øystein Eggen

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1 Summary

This study deals with the concept of modularization. In recent years there has been a shift in the competitive environment for most companies. Globalization and segmentation of markets force companies to diversify. What used to be a large demand for standard mass-market products has fragmented into a demand for different variations of similar products. Manufacturing systems are normally not designed for variety, thus the challenge is to create the desired product variety economically. Modularization has been proposed as a tool to break the product structure into smaller, more manageable units and thereby make mass customization possible.

Several methods for module identification have been proposed. Two of these, each with its own viewpoint on modularization, are combined into one model in an article presented in the appendix of this report. The methods are Modular Function Deployment (MDF), developed by Ericsson and Erixon, and the heuristic methods presented by Stone et. al.. This study presents the whole concept development phase adopted from Ulrich and Eppinger, with special emphasis on modular concept generation. An exemplification of the methodology for module identification is carried out with a compass saw as a physical example.

Although several methodological limitations apply to the study, the results from the two different methods are strikingly similar. One hypothesis is that because the functional decomposition for the heuristic methods also is used as the starting point for MDF, the former method will act so as to adjust the results from the heuristics. This is so because the designers are forced to think through modularization while working with the heuristics, thus leading further execution of the method. Hypothetically the MDF will augment the heuristic methods with a more strategic dimension, but the product tested here is too small to provide any significant results.

The concept of modularization is often advocated as a means to handle complexity by increasing a company's product variety and at the same time facilitate for traditional mass manufacturing (often referred to as mass customization). Much has been written about modularization, and methods for identifying modules. However, there exists no guidance for companies to determine their appropriateness for modularization. The last part of this study gives an overview of the most important dimensions along which appropriateness for modularization can be compared. Modularization is apparently applicable as a strategic tool in various industries, and it seems hard to pin down the exact preconditions for it to be successful. Yet, some important dimensions of the company and product in question may be identified. These are

- Large vs. small companies. Heavy investments are needed
- Complexities of interface management, as well as the importance of knowledge management sets limitations on which company can implement the strategy
- Complex vs. simple products. Complex products with long life-cycles are suitable for platform development
- Evolving vs. mature markets. Mature markets calls for variety.
- Trade-off between economical benefits of modularization and technical performance
- Open vs. closed technical systems. Open systems encourages collaboration and modular product architectures

2 Introduction

Modularization is a relatively new and evolving field of study. Much has been written about the subject lately, and several methods for module identification have been proposed. I wanted to explore the field to gain a better understanding of the different concepts as well as how to implement the theory in practice.

The purpose of this project is twofold: the first part of the project is carried out as an exercise in modular concept generation. I intend to clarify the concepts and methods, and present them in an educative way. Along this path, the method of module identification described in the article “Modular product development” included in the appendix will be exemplified with a compass saw. The assumption is that the two different methods incorporated in the model will yield complementary results. This might be useful because both technical and economical aspects are taken into consideration.

Second, a critical view of the concept of modularization will be presented. While modularization seems to be widely accepted as the method for handling the complexity of mass customization for the global market, there is not a particularly wide spectre of best practice case studies found in literature. Most of the examples that I have encountered are recurring in several articles. Furthermore, few seem to have had a proactive modular product strategy, but only found to fit the strategy theoretically. There exists no guidance for companies to determine their appropriateness for modularization. Questions that will be asked are: Where is modularization appropriate? And where is it not applicable?

3 Background

This chapter will give an introduction to the concept of modularization, product platforms and product families.

In recent years, project management literature has focused on the need for companies to diversify their product lines and continuously create new products for increasingly selective and segmented consumers. What used to be a large demand for standard mass-market products has fragmented into a demand for different variations of similar products. The niches are becoming the market, shifting power to buyers who demand higher-quality goods that more closely match their individual desires (Sundgren, 1999). The challenge is to create the desired product variety economically. Modularization has been proposed as a tool to break the product structure into smaller, more manageable units and thereby make mass customization possible (See Figure 1).

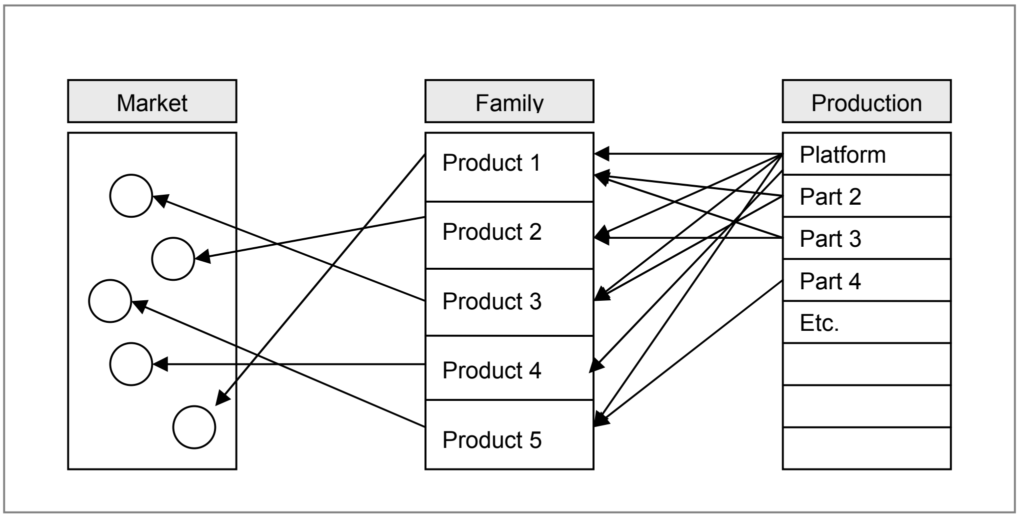


Figure 1 - Challenges that companies face and how modularization tries to solve those challenges. The market is increasingly segmented, forcing the companies to diversify. This diversification creates complexity for manufacturing. Well-defined product structures with specified interfaces are what manufacturing needs. This is where modularization can work. By clearly separating the parts that should vary from the parts that should be kept as common units, variety can be accommodated at the same time as complexity is kept manageable. A total redesign of the product is no longer needed every time a new product variant is introduced.

The definition of a module used in this report is as follows: A module is a structurally independent building block of a larger system with well-defined interfaces. A module is fairly loosely connected to the rest of the system allowing an independent development of the module as long as the interconnections at the interfaces are well thought of.

A special case of modularization is that in which a platform is developed as a basis for product variation. The product platform encompasses the design and components shared by a set of products. An effective platform is the core of a successful product family, and serves as the foundation for a series of closely related products. Products that share a common platform but have specific features and functionality required by different sets of customers form a product family. A product family typically addresses a market segment, while specific products within the family target niches within that segment. Product development thus becomes an integration activity, focusing on re-using assets in the form of platforms and differentiating features (BASYS, 2002). Figure 2 illustrates the concept of product families and platforms.

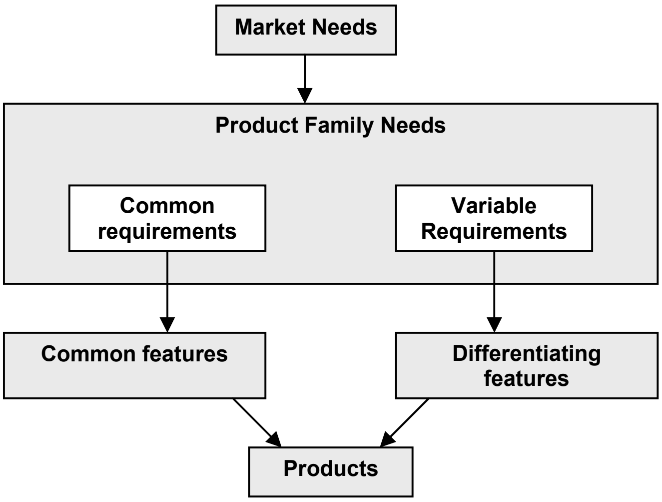


Figure 2 - Developing product platforms (BASYS, 2002)

Several methods for module identification have been proposed. In the article in the appendix, “Modular product development”, two of the most recognized methods are combined into one model. The first, based on Stone et. al., introduces methods to cut out a module from function structures using module heuristics. A function structure is a functional decomposition block diagram of all the product’s functions with material, energy, and information flows between them. The second method, Modular Function Deployment™ (MFD™) based on Erixon and Ericsson is more management and less engineering oriented. It is also based on functional decomposition, but in this method, other modularity drivers than functionality are considered. There are twelve modularity drivers in MFD™.

For more on modularization, the theoretical benefits of a modular product strategy, and the methods of module identification, please refer to the article in the appendix.

4 Concept generation and module identification

In this chapter a test of the method for module identification outlined in the article will be carried out. First, the main assumptions and limitations will be described. Then, the task of module identification/concept generation will be put into a broader context by presenting its place within the product development process. The main part of the chapter is comprised of the different steps in the modular concept generation model. The assumption is that the two different models will yield complementary results. This might be useful because both technical and economical aspects are treated. A compass saw will be used as a physical example.

4.1 Limitations

This chapter will explain main assumptions and limitations underlying the project.

To exemplify the module identification model, a compass saw will be used as a physical example. This undertaking is not so much to develop a new concept for a compass saw as it is to explore the methods of modularization described in the article in the appendix. A compass saw was chosen because it is a manageable product that fits well within the scope of this project.

For modularization methods to function as intended, a thorough knowledge of the company, market and product family in question is required. This knowledge is not available for this student project which has been carried out independently. Assumptions on these and other factors have for that reason been made based on common sense, as well as discussions with fellow students. Ideally, persons with a high degree of technical competence as well as product design experience within the particular field of power tools should have participated in the project.

This limits the validity of the results from the module identification procedure. However, as long as the assumptions are used consistent, the idea is that the methods can be compared almost as intended. Furthermore, the indicated limitations will not represent a big problem for the achievement of the goal of the project which is to gain an understanding of the concepts and methods of modularization as well as to explore the limitations of the theory.

4.2 The concept development phase

This chapter will give an overview of the product development process. It is important to have a clear understanding of the different activities in the design process as well and their relations to each other.

The model presented in Figure 3 is adopted from Ulrich and Eppinger.

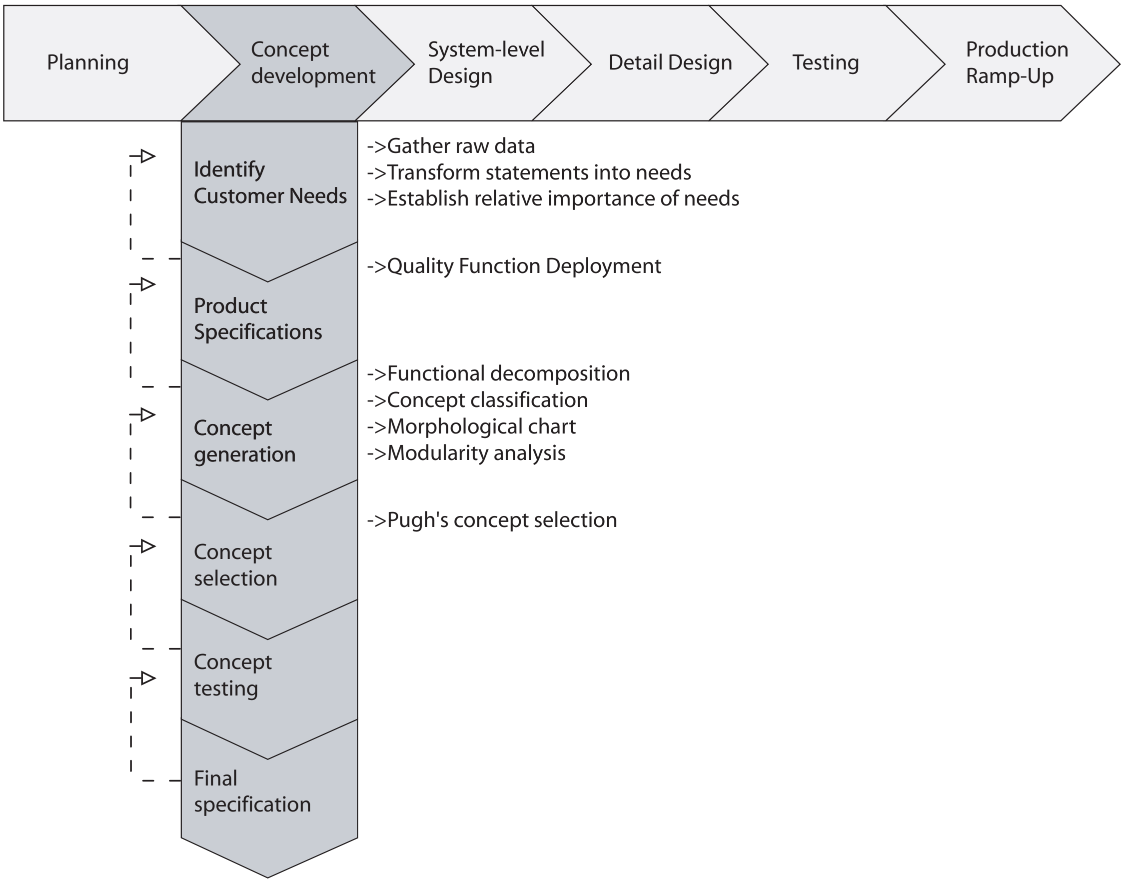


Figure 3 -The product development process, detailing the concept development phase (Ulrich and Eppinger, 1995)

The first four steps are directly involved in the module identification procedure suggested in the article in the appendix (Figure 4, page 10).

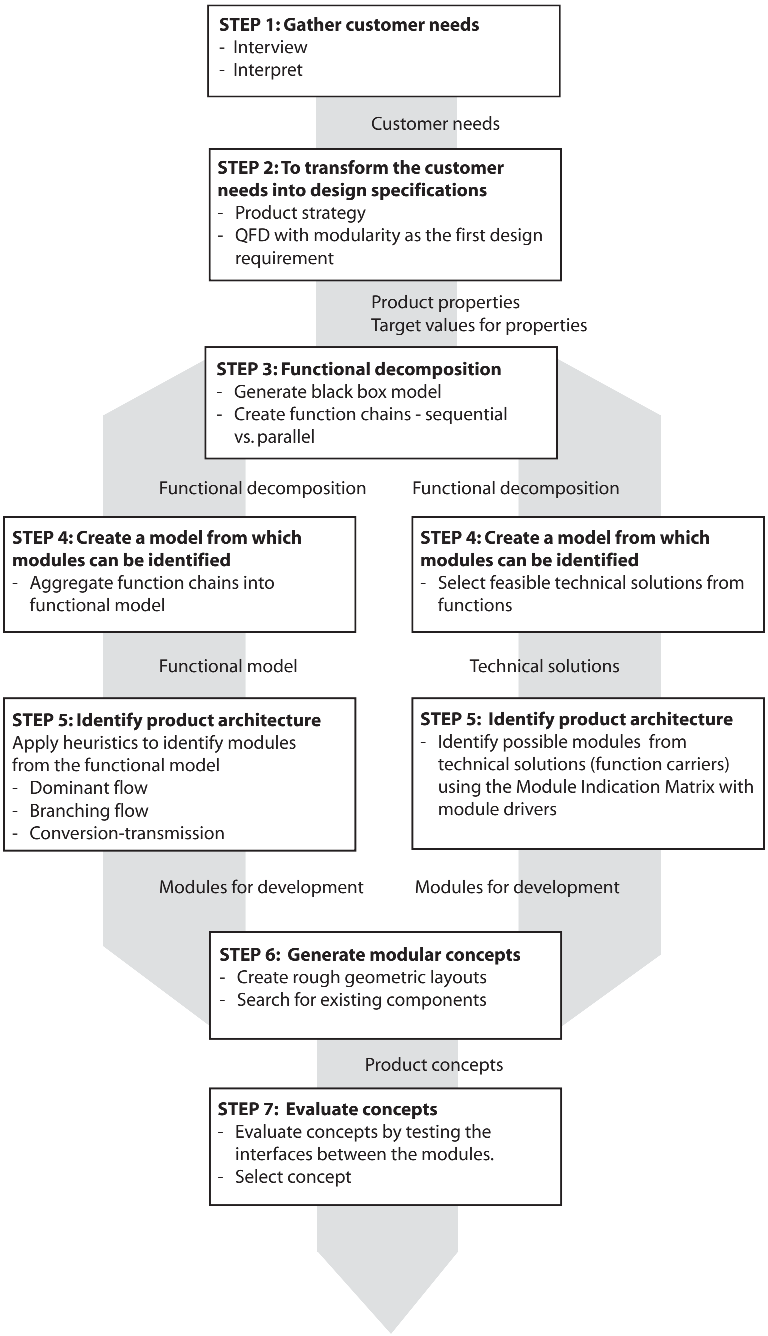
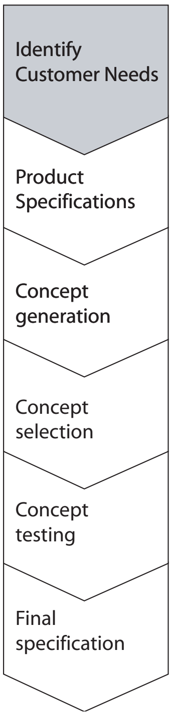


Figure 4 - Model for modular concept generation adopted from Modular Function Deployment (Ericsson and Erixon, 1999) and Heuristic methods for module identification (Stone et. al., 2000)

4.3 Example: Modularization of a compass saw

This section will build upon the methodology of Figure 4. Brief explanations of the tools and techniques for each step in the methodology are provided. For further information on the different steps, please refer to the article in the appendix. A compass saw is used as an example because it contains several material flows and because it is a relatively simple product that still will provide a sufficient level of detail.

4.3.1 Step 1: Gather customer needs



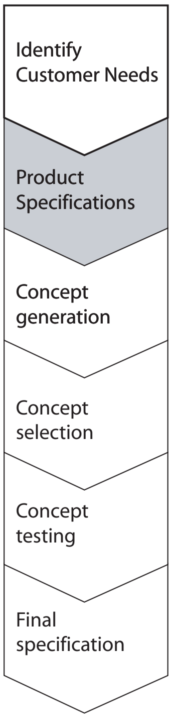
Before any redesign or new design project is begun, areas such as company objectives, core competence, and potential markets need to be well defined since they strongly influence the modular structure (Erixon and Ericsson, 1999). As a first step, a mixture of customer requirements and company needs must be gathered. The product strategy and wanted brand image must be defined. Questions that may be asked at this stage are:

- What is the product vision of the future?
- What is the profile/image of this product on the market?
- Who are the most important customers?
    - What do they expect in a product?
- Who are the major competitors?

A good understanding of user needs requires a thorough investigation of the market situation and customer identity. User surveys should be carried out to elicit all needs. Typically, nine or more customers are interviewed for small consumer products (Griffin and Hauser, cited in Otto and Wood, 1996). Weighting as well as the relative importance of the needs should also be established to help the design team to make trade-offs and allocate resources (Ulrich and Eppinger, 1995). For this project, only a brief investigation of user needs was done by means of short interviews with fellow students. After all needs are gathered, they must be converted into user requirements and weighted by users according to importance. Typical requirements for the compass saw might be:

- High performance
- Stability, easy to manoeuvre
- Oblique sawing
- Saw close to edges
- Remove sawdust
- Adjustable speed
- Low price
- Low noise level
- Easy maintenance
- Easy storage
- Secure
- Low vibration
- Good visibility of sawing
- Good grip

4.3.2 Step 2: Transform needs into specifications



Product specifications spell out in measurable detail (a metric and a value) what the product has to do. The base for establishing product specifications is an awareness of the relative importance of each customer need, because trade-offs will eventually be necessary (Ulrich and Eppinger, 1995). The goal for this step is to set target specifications for the product to be developed and contains three steps:

- Prepare a list of metrics corresponding to the various needs, several metrics may be needed to reflect a single need
- Collect competitive benchmarking information
- Set target values for each metric

These steps are taken into consideration in the Quality Function Deployment method, which systematically refines the input customer needs into the weighted scores of the product specifications. After the important characteristics have been identified, the development team can easily set meaningful performance targets. The core of QFD is a matrix called the House of Quality (Figure 5). The process involves constructing a collection of sub-matrices, each containing information related to the others (Salonen and Kauhanen, unpublished).

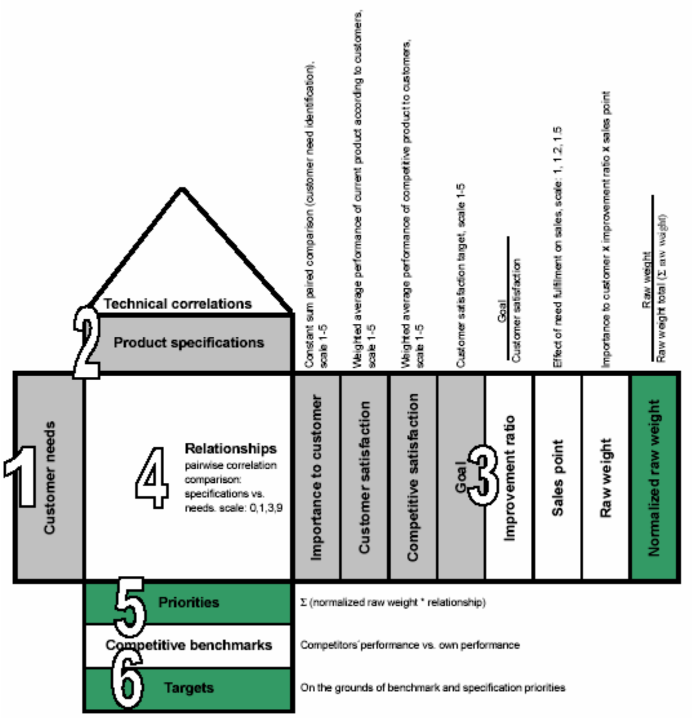


Figure 5 - The House of Quality (Salonen and Kauhanen, unpublished)

Some of the most important product metrics for the compass saw might be:

Metric	**Units**
Vibration	Subjective
Size	m^3
Shape	Subjective
Weight	g
Noise level	dB
Power output	kW
Stroke length	cm
Cutting capacities for different materials	cm
Material	List
Ease of disassembly	Subjective
Instils pride	Subjective

Table 1 - Important product metrics for a compass saw

Because a complete concept development of a compass saw is outside the scope of this project, and to prevent going into too much detail, a simplified QFD matrix is used here to relate the customer requirements with the identified product metrics (**Table 2**). For further details on the house of quality, see the article with the same name by Hauser and Clausing (1988).

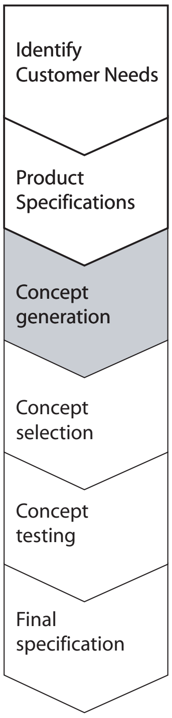
Product attributes Customer requirements	Need weights	Variance of weight	Modularization	Size	Shape	Weight	Noise level	Power output	Vibration	Instills pride	Cutting capacity for wood	Material	Ease of disassembly	Sum
High performance	5				1	1	1	9		9	9		1	31
Stability, easy to maneuver	5				3	9			9			3		24
Oblique sawing	4				3				1					4
Remove sawdust	3						1	1	3				1	6
Adjustable speed	2							1			3			4
Low price	4			9				9		1		3		22
Low noise level	1						9					1		10
Easy maintenance	3			9	3								9	21
Easy storage	2				9	1								10
Secure	4				1			1	3					5
Saw close to edges	3				9				1					10
Low vibration	5				1	3		3	3		3	3		16
Unrestricted view of blade	5				3									3
Good grip	5				9				3	3		3		18
Sum				63	155	67	17	105	103	13	15	58	35	

Table 2 – Simplified QFD matrix for the compass saw. The relations are graded with a point system where a strong relation is equal to 9 points, a medium relation, 3 points, and a weak relation 1 point. The grade is then multiplied with the customer demand weight before it is summarized vertically. An empty row indicates that a customer requirement is not taken care of by the proposed product properties, while an empty column indicates a redundant property.

The matrix in Table 2 is augmented by the column labelled “variance of weight”. This is meant as an aid in using the modularity column. A high variance of a particular weight (weights are gathered by means of customer surveys) indicates a requirement for product variance for this particular need and thus product modularity.

After targets have been set, the actual concept generation can begin by splitting the product into sub-functions.

4.3.3 Step 3: Functional decomposition



The concept generation process begins with a set of customer needs and target specifications and results in a set of product concepts from which the team will make a final selection (Ulrich and Eppinger, 1995). This project is primarily concerned with modular concept generation and will focus on the methods that are relevant to achieve that goal.

Most concept generation approaches begin with a functional decomposition of the problem at hand[1]. Functional decomposition is the process of breaking the overall function of a product into smaller, easily solvable sub-functions. The sub-functions are related by the flow of energy, material or signal passing through the product to form a functional model. The functional model for the compass saw was created by the reverse engineering method of Otto and Wood (1996). The purpose is to provide a form-independent model of the product that relates directly to customer needs.

Generate Black Box Model

As the first step in a functional decomposition, a black box model of the product is created based on customer requirements, identifying the input and output flows of materials, energies, and signals, as well as the global function of the product. The intent is to understand the overall product function, while maintaining little knowledge of the internal components of the product. This avoids a biased view of possible product solutions at this stage. Figure 6 shows the black box model created for the compass saw.

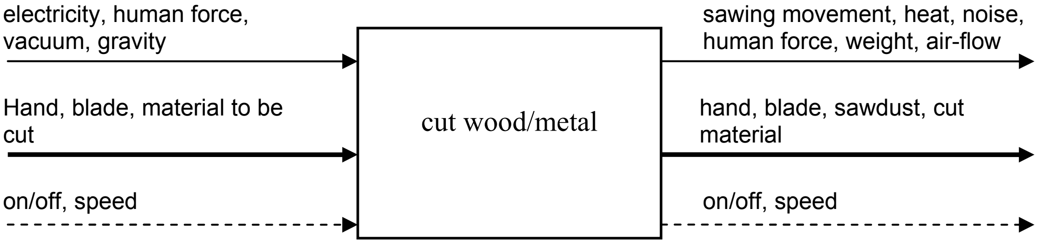


Figure 6 - Black Box model of a compass saw

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[1] If it is a redesign effort, it should start with decomposition of the existing or competing product. This will provide detailed information regarding component function, assemblability, manufacturing processes and an intuitive understanding of the product. (Otto and Wood, 1996)

Functional modelling

Each flow identified in the black box model is traced through the product, as it would flow during use, through a sequence of sub-functions that change the flow. A subfunction is formed by pairing an active verb with a noun that represents a product operation.

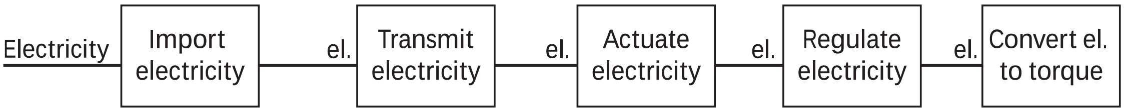

Figure 7 - Function structure for the flow electricity

To get started with the functional modelling, it might be useful to create a function diagram for an existing product (Ulrich and Eppinger, 1996). While tracing the flow, the designer should "become" the flow as it is transformed through the product (Stone, et. al., 2000).

4.3.4 Step 4: Create a model from which modules can be extracted

A central task in the module identification process is to create a model from which modules can be extracted. As can be seen from Figure 4, the model branches at this step requiring two separate models to be constructed. Because both branches emphasise the functional decomposition of the product, the function structure shown in Figure 8 is used as a common input.

Complete the functional model

After all flows have been traced through the product, the different sequences of subfunctions are aggregated into a complete function structure. It may then be necessary to connect the distinct chains together, sometimes by adding new subfunctions. Figure 8 shows the complete functional model for a compass saw[2].

The function structure can also be used as a check too verify that all needs have been taken care of. Needs not covered by the function structure require further analysis and added functionality.

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[2] As mentioned, the required technical experience, as well as company specific knowledge is not available. Thus, the function diagram may not represent an exhaustive list of functions, but hopefully a fair approximation of the most important ones.

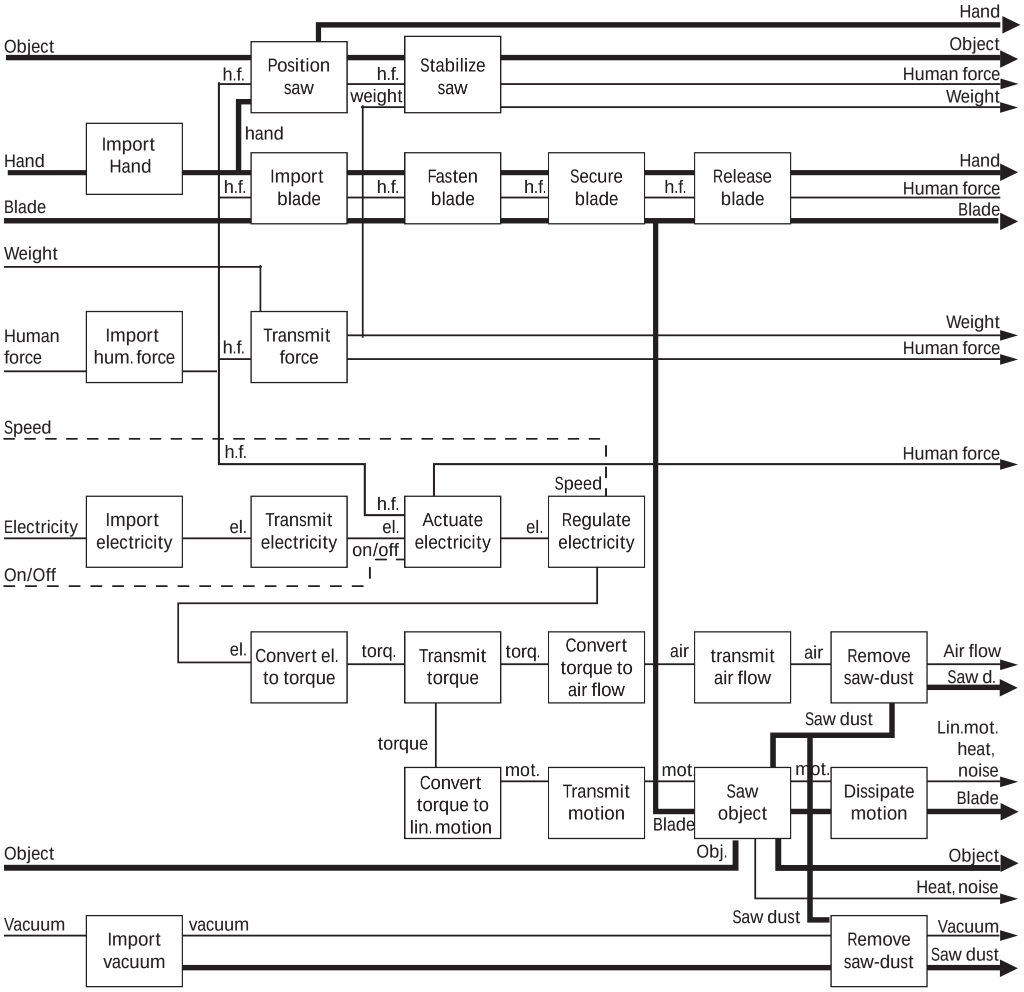
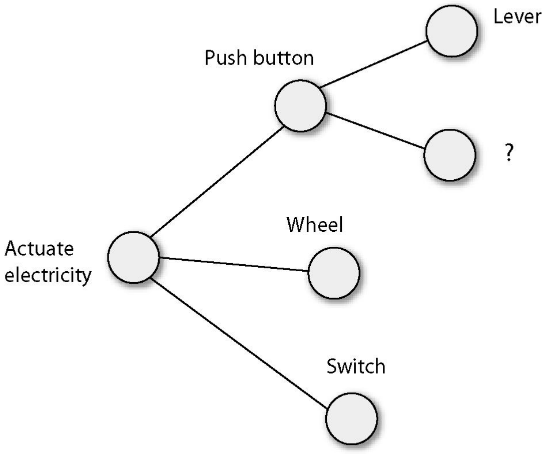


Figure 8 - The functional model for a compass saw

Convert subfunctions to technical solutions

To extract modules, the MDF requires that actual technical solutions are identified in a functions/means tree. A concept classification tree can be used to search for different solution principles to the various subfunctions of a product. An example of a concept classification tree for the function “actuate electricity” is shown in Figure 9. Unpromising branches can be pruned. A morphological analysis can then be used to generate concept proposals by systematically selecting ideal combinations of solution principles (Figure 10).



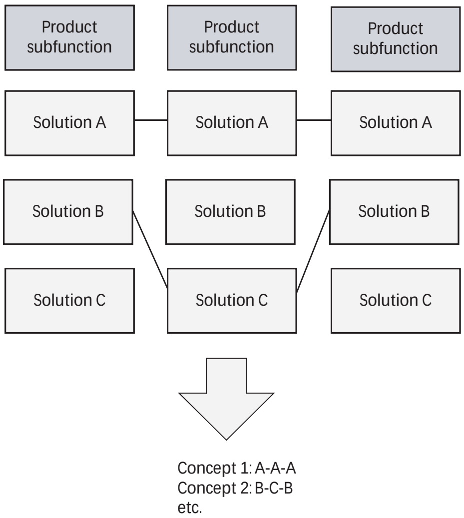


Figure 9 - Incomplete concept classification tree for the function actuate electricity

Figure 10 - Creation of concept proposals with a Morphological chart

For simplicity, only the current technical solutions for a compass saw are listed here (Table 3).

Function	Technical solution (Function carrier)
Position saw	Adjustable base plate to accommodate for sawing close to edges and oblique sawing
Stabilize saw	Solid anchoring of footplate to chassis
Import blade	Slot for saw blade
Fasten blade	Locking mechanism
Secure blade	Locking mechanism
Release blade	Locking mechanism
Transmit force to sawing	Casing
Import electricity	Socket
Transmit electricity	Cord
Actuate and lock electricity	Push lever with lock
Regulate electricity	Wheel
Convert electricity to torque	Electrical motor
Transmit torque	Transmission
Convert torque to air flow	Fan
Transmit air flow	Pipe leading from fan to saw-blade
Remove saw dust	Air-flow from fan
Convert torque to linear motion	Rotating eccentric with rod of different lengths depending on product
Saw object	Moving saw blade
Dissipate motion	Casing, human force
Guide sawing	Roller guide
Import vacuum	Socket for vacuum hose
Remove saw dust with vacuum	Vacuum nozzle

Table 3 – Function vs. function carrier for a compass saw

4.3.5 Step 5: Identify product architecture

It is now time to identify the actual modules from the functional model developed in the previous step. The three heuristic methods will be explored first.

Heuristics

The heuristics define possible modules, and the three different methods may suggest overlapping modules. It is up to the designer to choose which ones makes sense. Because it is not an algorithm, designer insight and good judgement are required.

Dominant flow

The dominant flow heuristic examines each non-branching flow of a function structure and groups the sub-functions the flow travels through until it exits the system or is transformed into another flow. The identified sub-functions define a module and the interface with the rest of the product. Any flows that cross the boundary are interactions between the module and the rest of the product (Stone et. al., 2000). Figure 11 shows the modules identified by the dominant flow heuristic.

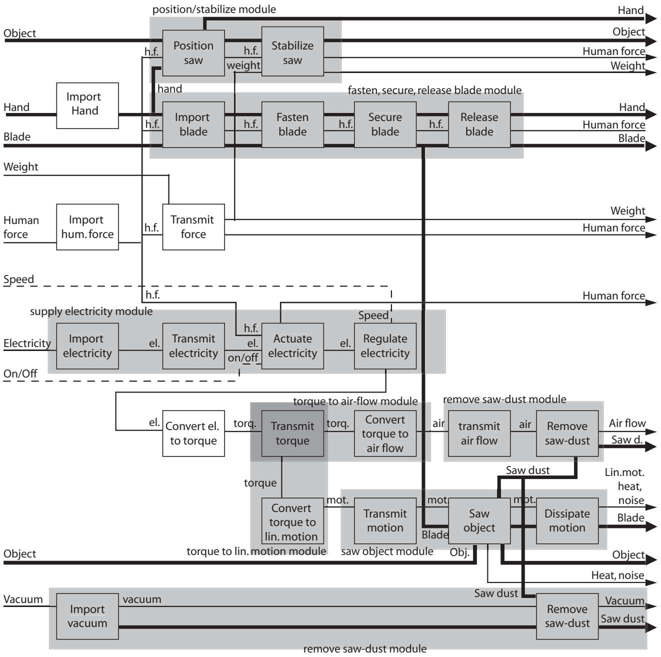


Figure 11 - Modules identified by the dominant flow heuristic

Branching Flow

Each limb of a parallel function chain defines a potential module. The modules identified will interface with the product at the flow's branching point. Branching flows will typically identify modules capable of component swapping or bus modularity (Stone et. al., 2000). See Figure 12 for identified modules for the compass saw.

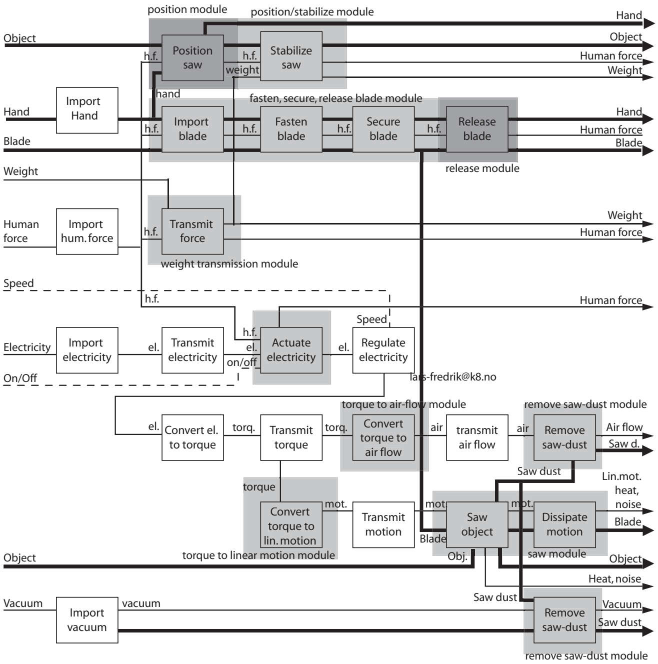


Figure 12 - Modules identified with the branching flow heuristic

Conversion-Transmission

Conversion sub-functions accept a flow of material or energy and convert the flow to another form of material or energy. These sub-functions are in many instances already modules, for example an electrical motor. Transmission is added to the module if the conversion sub-function is linked with a transmission sub-function. Interfaces and interactions are defined in a similar manner as those for a dominant flow module. Figure 13 shows the modules identified by the conversion-transmission heuristic.

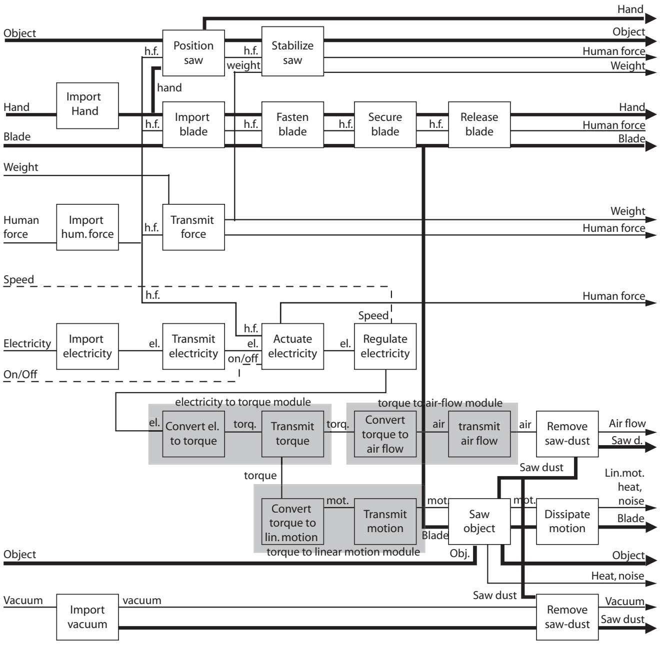


Figure 13 - Modules identified by the conversion-transmission heuristic

As a help in deciding on which modules to implement, the indicated modules from the three heuristics are overlapped in Figure 14.

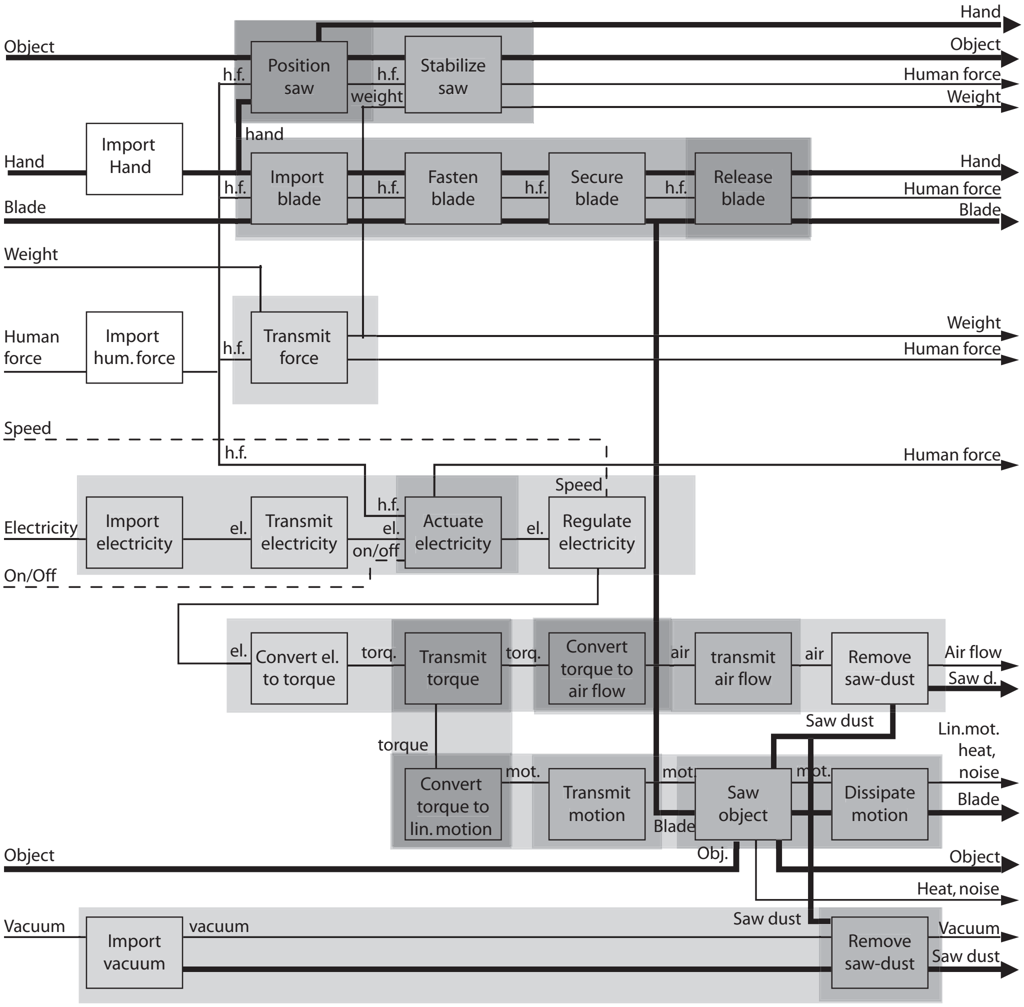


Figure 14 - Overlap of all the modules identified by the three heuristic methods

Design- and manufacturing as well as knowledge of company-specific capabilities are now required to select the actual models from Figure 14. Nevertheless, a general rule is to select the smallest number of functions where there is overlap in keeping with the philosophy that modules should be easily identifiable with a particular function (Stone et. al., 2000).

The modules selected for the compass saw are:

Module	Functions	Heuristic	Technical solutions
Position saw module	Position saw	Branching flow of hand	Adjustable base plate to accommodate for sawing close to edges and oblique sawing
Change saw blade module	Import, Fasten, secure and release blade	Dominant flow of blade, branching flow of hand. The release blade subfunction is too linked with the fasten and secure blade subfunctions to be left alone as a module by itself.	Locking mechanism for blade
Weight transmission module	Transmit force	Branching flow of human force	Casing
Electric motor module	Convert electricity to torque, transmit torque	Conversion-transmission	Electric motor with transmission
Fan module	Convert torque to air flow module	Overlap between conversion-transmission heuristic and dominant flow	Fan
Convert torque to linear motion module.	Convert torque to linear motion, transmit linear motion	Overlap between conversion-transmission heuristic and dominant flow	Rotating eccentric with rod of different lengths depending on product
Sawing module	Saw object, dissipate motion	Overlap between branching flow and dominant flow	Saw-blade
Vacuum module	Import vacuum, remove saw dust module	Dominant flow	Attachable vacuum hose with connection to vacuum nozzle

Table 4 - Modules selected for a compass saw by using heuristic methods

MDF

The technical solutions from Table 3 are now transferred to a module identification matrix (MIM) to be used as the basis for identifying modules. The technical solutions are listed on one axis and the module drivers on the other. A fellow student with “above-average” technical competence completed the MIM for a compass saw, shown in Table 5. The design driver “product planning” was left out because no company specific information was available. A different approach would be to postpone selection of technical solutions until after the modularity analysis, so as to facilitate a more thorough modularity of the design. A trade-off is that the modularity analysis would then be harder to complete (Salonen and Kauhanen, unpublished).

Function carrier / Module Driver	Adjustable base plate	Anchoring of base plate to casing	Slot for saw blade	Locking mechanism for blade	Casing	Electrical cord and contact	Push lever with lock	Regulating wheel	Electrical motor	Transmission	Fan	Pipe from fan to saw blade	Rotating eccentric rod	Saw blade	Device to guide saw blade	Socket for vacuum hose	Nozzle by saw blade	Total
Carryover	9	9	9	9	3	9	9	3	9	9	9	3	3	3	9	9	9	123
Tecnology evolution	3		1	3	1		1	1	1	3			3	3	3		1	24
Different spesification						9	1	1	3	1				3				18
Styling					9	1	1	3						1			3	18
Common Unit	9	9	9	9		9	3	1	9	9	9	3	3	9	9	9	9	118
Process/Organization	9	9	3	9	9				9	9	3	1	3	3	9	1	1	78
Separate Testing				3	1				9	1			3	9	3	1	1	31
Supplier Availability						9	9	9	9	3	9		1	9		3		61
Service and Maintenance	3	1	3	9		1	9	3	9	3			1	9	3			54
Upgrading	3	1												9	3			16
Recycling	3	1	1	1	3		1	1	3	3	1		1					19
Total	39	30	26	43	26	38	34	22	61	41	31	7	18	58	39	23	24	

Table 5 - Module Identification Matrix (MIM) for a compass saw

Many and/or unique module drivers, highly weighted, indicate that the technical solution in question has a complicated requirements pattern and is likely to form a module by itself, or at least, the basis for a module (Erixon and Ericsson, 1999). These are:

- Base plate
- Anchoring of base plate to casing
- Locking mechanism for blade
- Electrical cord and contact
- Push lever with lock
- Casing (unique pattern)
- Electrical motor
- Transmission
- Fan
- Saw blade
- Device to guide saw blade

However, by treating every single function carrier as a separate module there is a risk of getting a non-optimized product (Erixon, 1996). If the scores in the MIM are followed horizontally, functions that have the same or non-contradictory module drivers are candidates for grouping. *Grouping or integration* of functions to the module candidates can now be executed. Functions not among the module candidates should be considered first.

Regarding the number of modules, Erixon and Ericsson suggest that the ideal number of modules is approximately the square root of the number of parts or assembly operations. The estimate is based on optimizing the assembly lead time of the whole product (Erixon and Ericsson, 1999).

Table 6 shows the final modules from MDF.

Module	Function (s)	Most important Module Driver	Technical solutions
Position and stabilize module	Position saw, Stabilize saw	Carryover, common unit, process/organization	Adjustable and replaceable base plate. Anchoring of base plate to casing.
Change saw blade module	Fasten, secure and release blade, slot for saw blade	Carryover, Common unit, Service and maintenance, Process and organization, Maintenance	Locking mechanism for saw blade combined with slot for saw blade.
Import electricity module	Import electricity, transmit el.	Supplier Availability, Different Specification	Electrical cord with contact.
Electric motor module	Convert electricity to torque	Carryover, Common unit, process/organization	Electric motor
Fan module	Convert torque to air-flow	Carryover, Supplier Availability	Fan
Transmission module	Convert electricity to torque	Carryover, common unit, process/org.	Transmit torque
Sawing module	Saw object	Carryover, Common unit	Saw-blade
Guide saw blade module	Guide saw blade	Carryover, common unit, process/org.	Roller guide

Table 6 - Modules, their drivers and technical solutions for a compass saw

The next step would be to evaluate the identified modules in terms of the interfaces between the modules as outlined in the article in the appendix. This is not done here, because of limited knowledge of assembly technology. Furthermore, the heuristics have already indicated interfaces between different modules.

The three last steps of the concept development process will not be covered here.

4.4 Conclusion

This chapter will draw some conclusions regarding the modular identification method that has been detailed above. The methodological limitations have already been mentioned and will not be discussed.

The two different methods of modularization, namely the heuristic methods and modular function deployment produce strikingly similar results for the modularization of a compass saw. This may be a consequence of two underlying factors.

1. Because the input to both methods was the same functional structure, and because the heuristic methods were performed first, thus guiding the implementation of MFD. That is, the process of identifying modules with the heuristics forces the designer to think through the technical aspects of modularization, of what is possible and what is not. That way, MDF can be used so as to adjust the results from the heuristics rather than suggest a radically different set of modules.

2. Because the product is too simple, or because the functional decomposition was not detailed enough. As a result, the modularization could have been guided by preconceptions of how the final result ought to be from the very beginning of the process.

In a study by Holtta and Salonen, three different methods (Design Structure Matrix, the heuristics and MDF) are compared and found to partition the same products rather differently (Holtta and Salonen, 2003). The inconsistent results were attributed the differing viewpoints of the methods. The function structure heuristic method minimizes interactions between the modules while MFD looks at strategic factors for modularization, but leaves module interaction choices to the designer. Choice of method is therefore dependent on the case at hand.

A compass saw may be a simple product, but is still representative for a vast array of consumer products. Table 7 shows the final set of modules chosen for a compass saw.

Module	**Technical solutions**
Position and stabilize sawing module	Adjustable and replaceable base plate. Anchoring of base plate to casing.
Change saw blade module	Locking mechanism for blade combined with slot for saw blade
Styling module	Casing
Electric motor module	Electric motor with transmission
Fan module	Fan
Convert torque to linear motion module.	Rotating eccentric with rod of different lengths depending on product
Sawing module	Saw-blade
Vacuum module	Attachable vacuum hose with connection to vacuum nozzle
Guide saw blade module	Roller guide
Import electricity module	Electric cord with contact

Table 7 - Final modules selected for a compass saw

4.5 Research questions

To gain a better understanding of when and how to use the method of module identification exemplified above, more examples are needed to explore the variance of the results from MDF and the heuristics. The examples should vary considerably in type of industry as well as in technical complexity.

Hypothetically the two methods should complement each other. The MDF should augment the heuristic methods with a more strategic dimension. However, more complex product should be tested to provide significant results.

5 Discussion

The concept of modularization is often advocated as a means to handle complexity by increasing a company's product variety and at the same time facilitate for traditional mass manufacturing (often referred to as mass customization). Much has been written about modularization, and methods for identifying modules. Some companies seem indeed to be very successful in implementing the modular strategy. The Sony Walkman, Swatch watches and the desktop computer are often cited as examples of how well a modular product strategy can work[3]. However, the case studies are almost always written in retrospect, if success has been achieved and found to fit the modular approach. There exists no guidance for companies to determine their appropriateness for modularization.

This part of the study go through theory and case studies found in literature, and relate those and other examples to each other according to various dimensions that will be identified in the following. Central questions are: Where is modularization appropriate? And where is it not applicable?

5.1 Where is it appropriate?

A fundamental prerequisite for modularization is a product line/product family environment, where several product family members can be built as derivatives of a common, domain-specific platform. At least, there should be a need to upgrade or repair the product easily. However, further refinement is necessary to determine a company's appropriateness for modularization. *"A number of factors within the four areas purpose, product, process and market must be considered. The purpose of modularization is of superior importance and there must be a fit between the company's products, processes and market in order to carry out the modularization concept successfully"* (Hammar & Heimgård, 2001). But when can this "fit" be achieved?

5.1.1 Trade-off between economical and technical aspects

Malmström and Malmqvist suggest that there is a need for a method to evaluate the trade-off between economical and technical aspects when using modularization. Modularization may well lead to increased variety and faster product development, but the trade off can be degraded technical performance and subsequent reduced customer satisfaction. The hypothesis is that there exists a relationship between the use of modularization and the overall benefits (see Figure 15). The benefits can be variables such as development cost and time-to-market. The optimum degree of modularization will vary depending on product and company specific factors (Malmström and Malmqvist, 1998). However, they do not specify what those factors are.

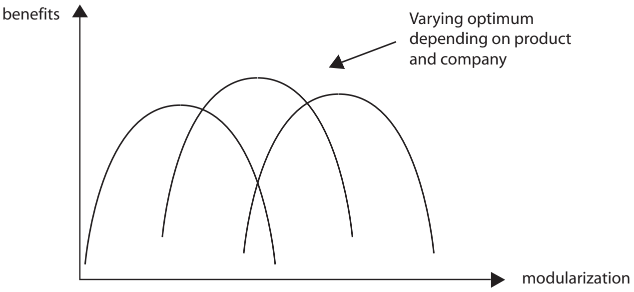


Figure 15 – Modularization trade-off curve (Malmstrøm and Malmqvist, 1998)

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[3] See the appendix for more examples of successful modularization

Interface complexity is the main reason why this trade-off between economical and technical aspects of modularization occurs. Too much modularization will result in an increasing number of interfaces, and thus a more complex design (Sako and Murray, 2000).

5.1.2 Interface management

An essential feature of a modular product architecture is that the interface specification have been standardized and not allowed to change during the commercial lifetime of the product (Sanchez and Collins, 2001). The personal computer is the prime example of this feature. A PC accepts variations in components as long as each variation conforms to the standardized interface specifications for that type of component.

However:

> *"It turns out that modular systems are much more difficult to design than comparable interconnected systems. The designers of modular systems must know a great deal about the inner workings of the overall product or process in order to […] make the modules function as a whole. And while designs at the modular level are proceeding independently, it may seem that all is going well; problems with incomplete or imperfect modularization tend to appear only when the modules come together and work poorly as an integrated whole" (*Baldwin et al., cited in Langlois, 2000).

Sundgren (1999) presents the concept of interface management in new product platform development. Interface management is the process of developing and defining the interfaces between the platform and different subsystems to facilitate the derivation of a product family.

One of the companies that he studied focused on bringing the first product to market as soon as possible, thus skipping some test cycles for the platform interfaces. This led to deficient functionality for two of the family's products. It is clear that technical aspects where traded for the economical aspect of rapid development and market introduction. The other company studied employed a different strategy. The products involved were of a complementary character and required a simultaneous release in the market. Consequently, focus was placed on maximizing the number of platform elements and ensuring functionality of all the products in the family. The results were a slight decrease in one product's performance and a considerable increase in development time. However, the company managed to reduce production costs. Again technical performance was traded with economical aspects.

Miller (2000) describes the modularization efforts of a company providing consultancy services for the pharmaceutical industry. He argues that the company has not yet harvested all the potential engineering benefits of modularity. Not because of technical problems, but because architectural knowledge was not formulated explicitly and used for conscious design of a common modular architecture. The formulation of architectural knowledge as rules for modular design requires a lot of experience

5.1.3 Product dimension

Apparently, if the products are associated with heavy investments and a long life-cycle (for example in the automotive industry), modularization should be implemented around a robust platform with clear interface specifications. The goal is here to release future products without costly changes to the product platform, that is, to leverage fixed investments over multiple products.

5.1.4 Market dimension

Increased variety is normally used to better serve a mature market (Malmström and Malmqvist). However, if the product is not complex and neither its market nor the underlying technology is changing rapidly, the cost of modularization may not be justified (Cebon, Hauptman and Shekar, 2002).

Furthermore, if the goal is to release the product as soon as possible, the interface management process may be reduced to save time. This may be the case for products that are built on evolving and unstable technologies in immature markets (for example portable music players based on different codecs, like mp3). In such cases it will be difficult to define those components that are likely to change and those that will remain stable. However, some degree of modularization may still be viable if the company can anticipate what changes that are likely to occur, and can accommodate for those changes in the interface specifications (Sanchez, 2002).

5.1.5 Open vs. closed systems

Open system modular strategies disclose the interface specifications so that other firms can develop components for its product architecture. On the other hand, closed systems, have proprietary specifications. The degree of system openness is related to the company’s degree of collaboration with outside suppliers. According to Hsuan, the success or failure of modularization in new product development is expected to vary depending on the nature of the supplier-buyer partnerships. She concludes that higher opportunities for modularization can be attained through a more collaborative form of supplier-buyer partnership (Hsuan, 1998). Supplier involvement in product development can be characterized by the degree of functional specification and detailed engineering responsibilities carried out by the supplier. Success with modularization may be attributed to early involvement of customers and suppliers.

Alternatively, firms may collaborate to establish industry standards that define the type of functional components they will use and the interface specifications that will apply to each type of component (Sanchez and Collins, 2001). During these circumstances, creation of product variety can be cheap and fairly simple as the products are assembled from standardized components that can be combined into different products in numerous ways, almost like Lego® (Sundgren, 1999). An increasing number of industries today consist of different firms that each develops one specialized component. This evolution has happened in the computer industry, where previously vertically integrated hardware companies have outsourced much to external suppliers (like Intel and Microsoft as well as the plethora of complementary developers around them). The reasons industries evolve this way are widely discussed, but a central tenet of many theories is the concept of modularity (Cebon, Hauptman and Shekar, 2002, Langlois, 2000).

At first, IBM worked hard to keep interfaces proprietary and to prevent others from supplying compatible modules, but subsequently this strategy was changed and the company managed to set the industry standard for personal computers. On the other hand, however, Apple is still to some extent vertically integrated, and seemingly thriving in its position. A trademark of Apple computers is that they are very high in performance; undoubtedly because they are built on a more integral architecture than their competitors.

5.2 Conclusion

Modularization is apparently applicable as a strategic tool in various industries, and it seems hard to pin down the exact preconditions for it to be successful. However, as pointed out in the above discussion, some important dimensions of the company and product in question may be identified.

1. **Company Size**: One of the most fundamental aspects to take into consideration is company size. Modularization requires heavy investments in equipment as well as time and effort. Furthermore, the strategy needs a new way of thinking about knowledge management in order to take advantage of the same method in subsequent projects. *"The formulation of architectural knowledge as rules for modular design requires a lot of experience"*. This may be hard to achieve in small to medium sized companies.

2. **Type of product:** A fundamental prerequisite for modularization is a product line/product family environment, where several product family members can be built as derivatives of a common, domain-specific platform. As a minimum, there should be a need to upgrade or repair the product easily. Furthermore, the product should exhibit a certain degree of technical complexity.

3. **Type of performance:** A superior performance product should probably not be modularized because of technical trade-offs that have to be made. At least, careful considerations regarding the benefits of modularization should be carried out.

4. **Type of market:** Mature markets need more variety and thus modularity.

5. **System openness**: Closed systems may be internally modularized, but modularization will become much easier if customers and suppliers get involved at an early stage. Standardized systems create the best opportunities for modularization.

5.3 Research questions

A more systematic approach should be carried out to explore the concept of dimensions for modularization and provide ample examples of both successful and unsuccessful modularization efforts. That is, along what dimensions is the modularization strategy a viable option? These dimensions can provide better guidance for companies when they develop new product architectures, and prevent mistakes from repeating.

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7 Appendices

1 MIM questionnaire

Design and Development

3		
Are there	[ ] strong [ ] medium [ ] any	reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations?
Technology push		
Is it	[ ] a great risk [ ] a medium risk [ ] some risk	that this part will go through a technology shift during the product life cycle?
Planned design changes (Product Plan)		
Are there	[ ] strong [ ] medium [ ] some	reasons why this part should be a separate module since it is the carrier of attributes that will be changed according a product plan?

Variance

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

Manufacturing

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

Quality

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

Purchase

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

After Sales

Service/maintenance		
Is it possible that	[ ] all [ ] most [ ] some	of the service repair will be easier if this part is easy detachable?
Upgrading		
Can	[ ] all [ ] most [ ] some	of the future upgrading by simplified if this part is easy to change?
Recycling		
Is it possible to keep	[ ] all [ ] most [ ] some	of the highly polluting material or easy recyclable material in this part (material purity)?

2 Examples of product modularization

Many of these examples can be found in a list gathered by Sundgren (Sundgren, 1999).

- NCR's Dundee ATM (automated teller machine) Division created a platform that helped NCR to fulfill the major share of the worldwide ATM market.

- Swatch has developed hundreds of wristwatches based on a few platforms

- Aircraft manufacturers such as Boeing and Airbus Industries use common wings and nose and tail components to leverage many models by using different fuselage modules to create crafts of different lengths and passenger/ freight capacities.

- Rolls-Royce (RR) created a high-powered aeroengine family during the 1970s

- The automotive industry provides several examples of how to utilize one of the most expensive parts of a car, i.e., the platform, in a whole range of different models. Some argue that the development of the platform can be as expensive as up to 60% of total development cost. For example, the Volkswagen Group is striving to reduce their number of platforms from 16 to 4. Consequently, the different brands in the group (Audi, Volkswagen, Seat, and Skoda) will have to share platforms.

- Sony HandyCam™ evolved from a basic and common architecture to become a notable commercial success. The first product, M8, specified the basic product architecture and interfaces serving as a platform for four additional models that were introduced into the market within 26 months. This advantageous evolution was made possible by the intelligent design of the product architecture, mainly the platform.

- Sony created and dominated the market for personal stereos (the Sony Walkman) with a worldwide market share around 40% for over a decade

- With the ThinkPad PC product line, IBM provides a good example of the strategy of using common parts and the same basic industrial design concept to develop unique end-products.

- Black and Decker approach of creating a new heat gun derived from an electric drill is the essence of transferring core designs to create something completely new. The new heat gun design was based heavily on the current electric drill architecture. Black and Decker only replaced the transmission and chuck subassemblies with the new heater element and nozzle. The fact that two thirds of the parts carried over from the electric drill (i.e., motor, fan, case, and switch) were all at hand and thoroughly tested reduced the potential problems and development costs associated with an entirely new product.

Modular product development

A review of modularization objectives as well as techniques for identifying modular product architectures, presented in a unified model.

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ABSTRACT

Due to the increasingly segmented world markets, modular product architectures are being implemented for new product designs in a growing number of companies. This article is primarily written for product design engineers who need a broad overview of the concept of modularization to be able to manage the concept generation processes. It covers a review of the basic definitions, and gives an account of the strategic advantages that may follow from implementing modular product architectures. To illustrate a complete process for identifying concepts for modular product architectures, the author combines two main branches of literature into one unified model. It is argued that the basis models (Modular Function Deployment and the heuristic methods) complement each other in ways that renders the unification of the models possible.

KEYWORDS

Modular product architecture, methods for identifying modules, modularization objectives

1 INTRODUCTION

In an increasingly competitive and segmented global marketplace, the need to diversify is greater than ever before. Advances in production technologies has rendered out many of the differences in product quality, and thus changed the competitive environment companies find themselves in. Traditional mass production has in the past decade been replaced by the concept of mass customization, mass production of customized products. To overcome the great complexity that customization potentially creates in the manufacturing systems, modularization is used as a tool to break the product structure into smaller, manageable units (Ericsson and Erixon, 1999).

Modules are defined as physical structures that have a one-to-one correspondence with functional structures. They can be thought of quite simply as building blocks with defined interfaces (Ericsson and Erixon, 1999). Modular products may be defined as machines, assemblies or components that accomplish an overall function through combination of distinct building blocks or modules (Stone 2000).
A modular product development is one in which the input and output relationships between components, that is, the component interfaces, in a product have been fully specified and standardized (Liang, Huang, 2002).

To exploit the benefits of modular product development, it is crucial to have modularization in mind from the start of the design process, and not only as an afterthought when all components are developed. If modularity is identified and exploited in the initial conceptual or reverse engineering effort, the immediate product design reaps benefits in several strategically important areas to be described later in the article. Modularization methods must therefore encompass the entire concept generation phase. The research issues associated with modular products can be divided into those associated with the identification of modules, the design of modules, and designing with modules (Liang, Huang, 2002). This paper is primarily concerned with the first area of identification of modules.

There are many different ways to modularize a product. Two companies manufacturing the same type of product could end up with different modularized product structures, depending on their product strategies. One branch of literature (Stone, 1999, Dahmus et. al. 2001) introduces methods to cut out a module from function structures using module heuristics. These methods identify modules from a functional model of a product, create rough geometric layouts and group products into families based on function. Erixon (1996) presents Modular Function Deployment (MFD™) which is also based on functional decomposition, but in this method, other modularity drivers than functionality are considered.

Industrial designers are usually occupied with defining the spatial interfaces of components in a product architecture, that is, the space a component will occupy in a product design-and with the user interfaces that define how a user will interact with a product. Technical designers, on the other hand, are commonly concerned with defining the attachment, transfer, control and communication, and environmental interfaces for components in a product architecture (Sanchez, 2002). The specifications and concerns of the two groups may have significant implications on each other. Product design engineers should thus be able to manage the interactions between technical and industrial design and must therefore possess a clear understanding of modularization issues. This paper is written with this in mind and aims to give an overview of what modularization is, what advantages firms can achieve with modularization and finally present a method for modularization that tries to unify two main branches of literature.

The remainder of the article is organized as follows. The next two sections will give a review of the terminology and motivation for modular architectures, and what advantages can be attained by effective deployment of a modular product development. The last section will then go on to describe a method for modular product development. It is important to bear in mind that the method described here is only an outline, and that to get a more thorough understanding of the different steps, a further study of the original literature is required.

2 MODULAR VS. INTEGRAL ARCHITECTURES

Ulrich (1995) define the architecture of a product as

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

The functional elements of a product are the individual operations and transformations that contribute to the overall performance of the product (Ulrich and Eppinger, 1995). In essence, product architecture design is the transformation from product function to product form (Stone, et. al. 1999).

There are two types of product architecture; modular and integral. An integral architecture includes a complex (not one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components (Ulrich, 1995). A modular architecture on the other hand, has a one-to-one correspondence between modules and functions. It is built up of sub-systems or modules that interact with each other through a set of well-defined rules. Such a modular architecture allows a design change to be made to one module without requiring a change to other modules for the product to function properly. A familiar example of a modular product architecture is the desktop computer, in which a range of variations in microprocessors, memory cards, hard disks, monitors, keyboards and other components can be freely combined to configure a nearly unlimited number of product variations.

Figure 1 and
Figure 2 on page 3 illustrates the difference between an integral and a modular architecture.

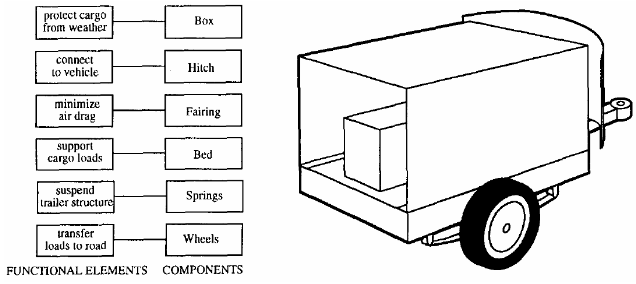

Figure 1 - A modular trailer architecture exhibiting a one-to-one mapping from functional elements to physical components. (Ulrich, 1995)

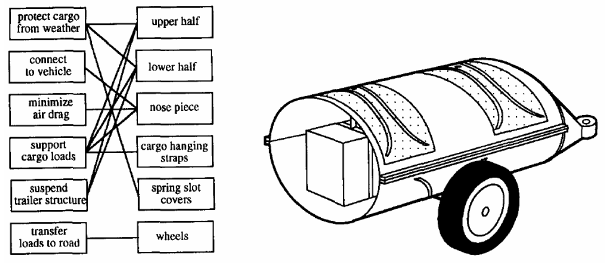

Figure 2 - An integral trailer exhibiting a complex mapping from functional elements to physical components. (Ulrich, 1995)

3 STRATEGIC ADVANTAGES OF MODULAR PRODUCT DEVELOPMENT

Of course, there are different levels of modularization in a product architecture, but when used effectively, modular architectures enables firms to achieve a number of strategically important advantages in competing in product markets. Sanchez identifies four such strategic advantages, namely greater product variety, faster technological upgrading of products, greater speed in developing new products, and cost reductions (Sanchez 1999 and 2002). To clarify all the advantages of modular product development, we will now give an account of these four as well as other more subtle strategic objectives.

3.1 Greater product variety

A modular product design can be partitioned technically so that each product functionality or feature thought to be a significant source of product differentiation in the eyes of users is contained in a single component or a subsystem of components. Variations in functional components (or subsystems) can then be substituted into the modular architecture to create product variations based on different combinations of component-based functionalities, features, and performance levels (Sanchez, 2002).

3.2 Mass customization

Historically, companies chose processes that supported the production of either customized crafted products or standardized mass-produced products (Duray et. al. 2000). To combine customization with mass production remained an unsolved paradox. Mass customization today relates to the ability to provide customized products or services through flexible processes in high volumes and at reasonably low costs (Silveira et. al. 2000).

Many authors view modularity as the key to achieve low cost mass customization. Ulrich & Eppinger argue that products built around modular architectures can be more easily varied without adding too much complexity to the manufacturing system (Ulrich & Eppinger, 1995). For example, Swatch produces hundreds of different watch models, but can achieve this variety at relatively low const by assembling the variants from different combinations of standard modules. In fact, Swatch could develop all these models even before they produced a single watch!

Modularity bounds the degree of customization of the product and distinguishes mass customization from pure customized products. The fact that these parts or modules are standardized allows for mass-customized products to achieve the low cost and consistent quality associated with repetitive manufacturing (Duray et al. 2000).

3.3 Product family

Sony's Walkman is a prime example of how the use of product platforms, a special form of modularity can lay the basis for an entire product family. During the 1980s, Sony introduced more than 250 different models in the U.S. market alone, based on only three different platforms (Sanderson & Uzumeri, 1995). Most of the changes in models were achieved by making small changes in features, packaging and appearance.

3.4 Reduced cost of development - leverage fixed investments over multiple products

Volkswagen claims to save $1.7 billion annually on development and production costs through effective product architecture. Volkswagen is able to take advantage of platform and component commonality by sharing between its four major brands VW, Audi, Skoda and Seat. They also claim that this shared common platform can be effectively differentiated in the eyes of the customer (Dahmus et. al. 2001).

A modular design strategy reduces product costs by partitioning some functions in a product architecture into component designs that will be used in common across product models (and perhaps even across product lines) or that will be reused in future architectures. Such common or reusable components generally provide technically necessary functions that are "transparent" to customers and thus are not sources of product differentiation (for example, a power supply in a personal computer). The greater reliability of reused component designs that have been incrementally improved over time may also help to reduce service costs and claims costs associated with new product introductions (Sanchez, 2002). Furthermore, reduced material and purchase costs may follow from the reduction of part numbers (Ericsson & Erixon, 1999).

3.5 Economies of scale

Production costs may also be reduced through increased economies of scale in producing components, extended economies of learning, and increased buying power for outsourced components. Greater use of common and reused components also reduces parts variety and resulting costs of carrying inventories of parts (Sanchez, 2002).

3.6 Faster technological upgrading

Modularity in product development permits the processes of developing components for the design to be partitioned into tasks. Thus, modular product development can lead to an important form of strategic flexibility (Ericsson & Erixon, 1999), i.e., flexible product designs that allow a company to respond to changing markets and technologies by rapidly and inexpensively creating product variants derived from different combinations of existing or new modules. The key point is that changes in one part of the product will only influence limited parts of the product. This was the key prerequisite for Sony's subsequent releases of Walkman models in the 1980s

Modular product architectures may also be designed to accommodate technologically improved components that are expected to become available during the commercial lifetime of a product architecture. When component interfaces are specified to support the introduction of improved components expected to be available in the future, technologically upgraded product variations may be brought to market as soon as improved components become available (Sanchez, 2002).

3.7 Increasing speed to market

Parallel development activities are possible once the interfaces between the modules have been defined, and subsequent work conforms to the established interface specifications (Ericsson & Erixon, 1999). This reduces overall development time and resource requirements by eliminating the time-consuming redesigns of components that result when component interfaces are not fully defined and standardized during component development processes (Sanchez 2002).

3.8 Decoupling of tasks - Concurrent product development

In a modular architecture, there is a division of labour between architects who first split a product into modules, and those who work within the parameters of a specific module. The latter group needs to know only about the specific module and the 'global design rules' which ensure that the module can be integrated into the larger system, while architects must possess the requisite knowledge of parameter and task interdependencies of the whole product (Sako & Murray, 2000). A clear definition of the components in a product design can for example enable the company to define the required manufacturing equipment at an early stage. Thus, development of process capabilities for producing the new products can be undertaken even before the overall product designs are finalized.

3.9 Subcontracting / Network cooperation

Fully defined and standardized component interface specifications for modular architectures provide, in effect, the system specifications for the components of new products. This enables a distributed network of designers to develop components that will “plug-and-play” in the new product architecture.

Hsuan argues that it also works the other way round. He shows (Hsuan, 1998) that the success or failure of modularization in new product development is expected to vary depending on the nature of the supplier-buyer partnerships. With closer partnerships, the possibilities for modularization increases substantially.

3.10 Ease of maintenance, repair and recycling

With modules, the operations of maintenance, repair and recycling becomes more trivial. For example, a defect CD-ROM player in a personal computer can be replaced or repaired without affecting the whole system. Dahmus et. al defines four main influences on a system engineer when determining product partitioning modules, and which must be considered when making up-front system architecting decisions. Market variance, usage variance (how users need variety after the purchase is made), technology change and Design for X (Dahmus et. al., 2001). The latter defines how design, production, supply and lifecycle criteria factor into consideration when determining product partitioning. For example, to enable a high degree of recycling, the number of different materials can be limited in each module and environmentally hostile material can also be kept in the same module so that disassembly will be easier.

3.11 Handle uncertainty

Modular architectures are used to manage market uncertainty. When future consumer preferences are uncertain, the flexibility to accommodate a range of product variations may be designed into a modular architecture as a means for managing the irreducible uncertainties as to which product variations consumers will want in the future (Sanchez, 2002).

3.12 Better integration of marketing and technical objectives

Because a modular architecture can represent a one-to-one mapping of specific user benefits into a specific technical component, the strategic role of each component can be made clear. Thus, it may be easier to identify possible problems and possibilities with the overall product.

3.13 Limitations

The modularization strategy may be taken too far. For Volkswagen, brand cannibalization is already a problem. As previously touched upon, no fewer than 11 car models are built on VW's A-Platform, ranging from Audi TT Roadster to VW New Beetle to the Skoda Octavia. Buyers are starting to wonder why they should pay $25,000 for an Audi A6 when it looks suspiciously like a $16,000 Volkswagen Passat. (Businessweek, Nov. 1999). This illustrates that modularization can lead to unexpected results if the customers’ perceptions of product functionality is misunderstood. In the case of Volkswagen, the company seems to have focused too much on the notion that buying a car is solely an emotional, not a rational issue.

Sometimes an integral product architecture may be a better solution. For example, to achieve a particular noise/vibration/harshness level in cars at different maximum speeds, engineers need a deep understanding of the subtle linkage between the body, chassis, engine, and drive-train. This means that without the integration capability of vehicle manufacturers, the body, chassis, engine, and drive-train produced by separate suppliers each with their own specialized systems knowledge may not, upon assembly, lead to a workable automobile (Sako & Murray, 2000).

4 METHODS FOR MODULARIZATION

This article will illustrate how the heuristic and modular function deployment (MFD™) methods relate to and complement each other, to achieve an optimal modular architecture. An overview of the combined product architecture design approach is shown in Figure 3. This methodology may work for single products as well as product families and consists of seven steps. A description of each step in the process will follow.

Step 1: Gather customer needs
Step 2: Transform customer needs into design specifications
Step 3: Functional decomposition of the product
Step 4: Create a model from which modules can be identified
Step 5: Identify product architecture
Step 6: Generate modular concepts
Step 7: Evaluate concept

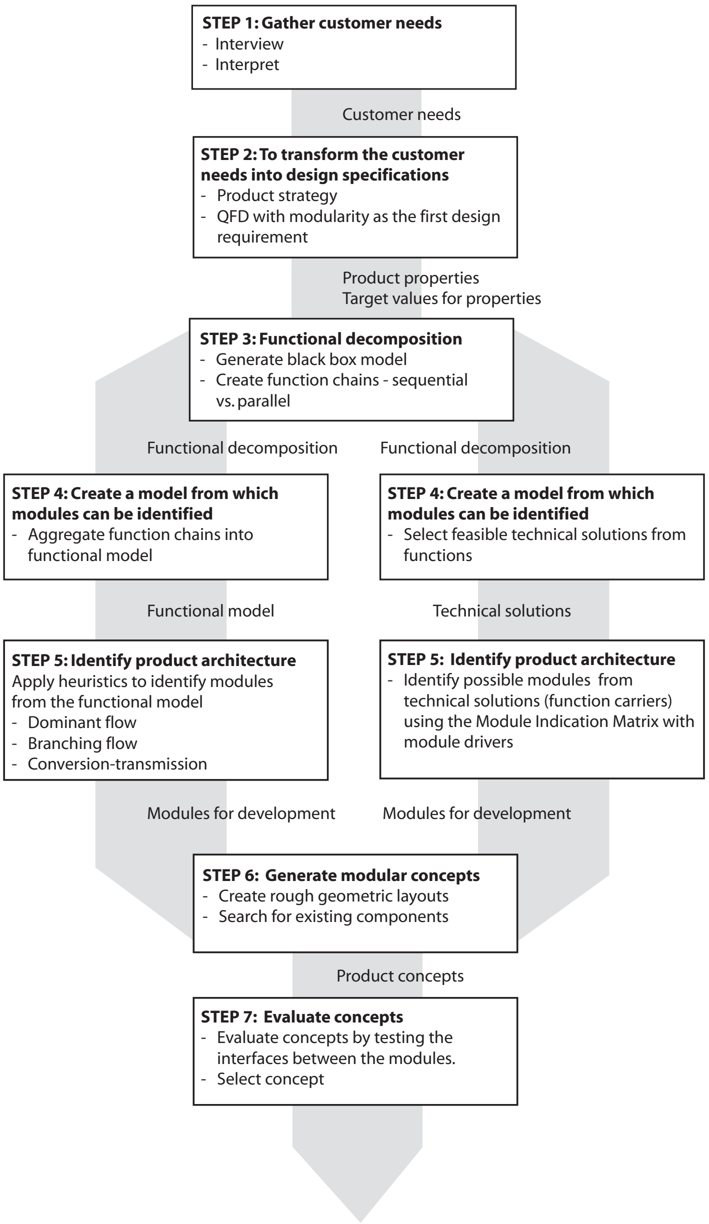

Figure 3 – An overview of the unified product architecture design methodology. Results from each step are shown directly under the respective steps

4.1 Step 1: Gather customer needs

The first step in any product development process is the gathering of customer requirements. A method which has proven to be effective in eliciting needs is the interview.

4.2 Step 2: Transform customer needs into design specifications

Before anything else, the product strategy, including brand image, must be defined. This strategy should provide a reference point for all subsequent decisions.

A simplified version of quality function deployment (QFD) can be used to define the customer requirements so that a specification of the product to be designed can be formulated. MDF™ introduces the concept of modularity at this early stage by putting "modularity" directly in as the first "how" (design requirement). This is done primarily to establish the right "mind-set" of the project team members (Ericsson & Erixon, 1999).

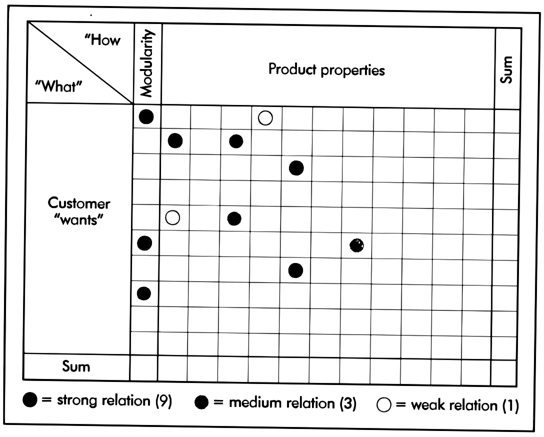

Figure 4 - Simplified QFD for eliciting product spesifications

4.3 Step 3: Functional decomposition

Stone defines functional modeling as the process of breaking the overall function of a product into smaller, easily solvable sub-functions (Stone et. al., 1999). A requirement for achieving an optimal modular design is functional independence. Functional independence makes it possible to achieve robust modular design where interactions between modules are minimal. The stand-alone modules can then be treated independently from each other (Ericsson & Erixon, 1999, Dahmus et. al., 2001). There are several methods for identifying the functions necessary to allow the product to fulfill its overall function.

Otto and Wood present an approach based upon tracing flows. For every customer need, a flow is identified. Stone et. al. names this the black box model of a product's overall function and input/output flows (Stone et. al., 1999). Each flow identified in the black box model is then traced through the product, as it would flow during use, through a sequence of sub-functions that change the flow (Figure 6*)*.

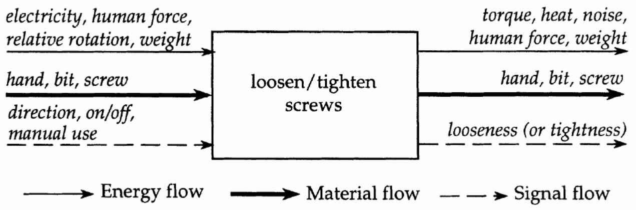

Figure 5 - Black box model for an electric screwdriver (Stone et. al., 1999)

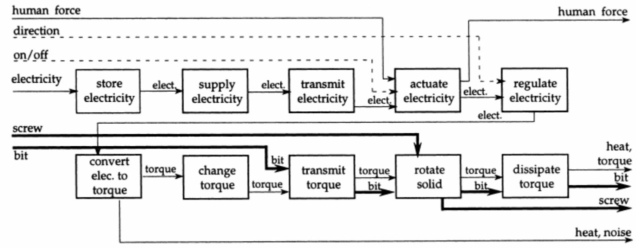

Figure 6 - A sequential function chain for the flow electricity (Stone et. al., 1999)

4.4 Step 4: Create a model from which modules can be extracted

Derive functional model (heuristic methods)
The independent function-chains are merged into a complete function structure network (see Figure 10). Dahmus et. al. expands the heuristic method to cover whole product families by combining functional models of several products into one family function diagram. Common modules for the product family are then selected with the help of a modularity matrix (Dahmus et. al., 2001).

Select technical solutions (MDF™)
Identify feasible technical solutions for the functions identified in step 3. Several technical solutions for a certain function (some functions may have to be clustered) may be found and a choice must be made, for example by using a Pugh matrix[1].

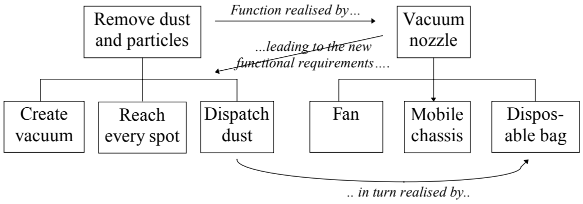

Figure 7 - First levels of the functional decomposition of a vacuum cleaner (Erixon, 1996)

4.5 Step 5: Identify product architecture

This is the central step where the actual modules are identified. We will see that the heuristic methods rely on the functional map of the product, while MDF™ considers specific drivers for modularization of the product in question.

Heuristics (Stone et. al., 1999)
The heuristic methods developed by Stone et. al. are divided into three types: dominant flow, branching flows, and conversion–transmission. (Note that different heuristics may identify overlapping modules or modules that are subsets of others).

The dominant flow heuristic examines flows through a function structure, following flows until they either exit from the system or are transformed into another type of flow. The set of sub-functions through which a flow passes, either until it is converted to another type of flow or until it exits the system, define a module. The identified sub-functions form the boundary, or interface, of the module. Any other flows, in addition to the traced flow, that cross the boundary are interactions between the module and the remaining product (*Figure 8*).

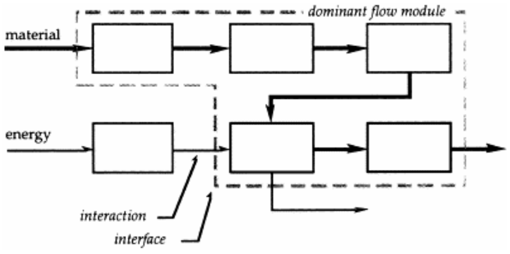

Figure 8 - Dominant flow heuristic applied to a generic function structure

The branching flow heuristic examines flows that branch into or converge from parallel function chains. Each branch of a flow can become a module. Each of these modules interfaces with the product through the point at which the flow branches or converges.

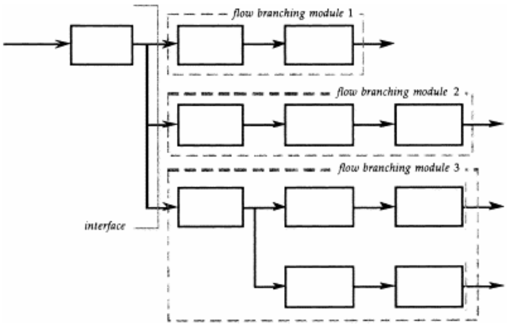

Figure 9 - Flow branching heuristic applied to a generic function structure

The conversion–transmission module examines flows which are converted from one type of flow to another. A conversion–transmission module converts an energy or material into another form, then transmits that new form of energy or material. In many instances, this conversion–transmission module is already housed as a module, as in the case of an electric motor.

Dahmus et. al. present two additional heuristics to find common modules across products in a product family. They find shared functions across products, and unique functions that are found only in one product within the product family and separate them as modules (Dahmus et. al. 2001).

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[1] See for example Pugh, S. 1991. Total Design: ”Integrated Methods for Successful Product Engineering” Reading, MA: Addison-Wesley Publishing Company

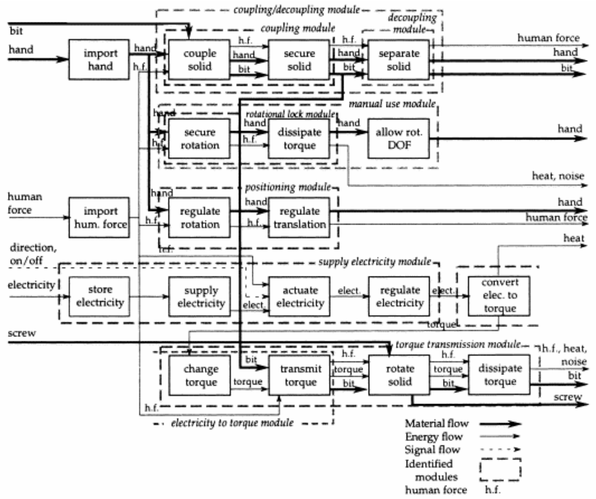

Figure 10 - Function structure of a power screwdriver with modules identified by the heuristic methods

MDF™ (Ericsson and Erixon, 1999)

In the fifth step, the selected technical solutions are analyzed regarding their reasons for forming modules. Module selection in MFD™ relies on twelve modularity drivers. These drivers can be seen as generic but may be complemented by company specific ones such as: strategy, financial limitations, legal restrictions, etc. In the Module Identification Matrix (MIM), each technical solution is assessed against the module drivers (See Figure 11). This method is similar to Quality Function Deployment (QFD) but here modularity drivers are mapped against technical solutions (functions) instead of customer requirements. Many and/or unique module drivers, highly weighted, indicate that the technical solution in question has a complicated requirements pattern and is likely to form a module

Table 1 - Modularity drivers, linked to different functions of a company

Product development and design	**Carryover**	A part or a subsystem of a product that most likely will not be exposed to any design changes during the life of the product platform. Enables heavy investment in production technology.
	Technology evolution	Parts that are likely to undergo changes as a result of changing customer demands or technology shift. It will be important to accommodate the interfaces so that new technology can be introduced and replace the module in question.
	Planned product changes	Parts of the product that the company intends to develop and change. (Sony Walkman’s consecutive model introductions)
Variance	**Different specification**	To handle product variation and customization effectively, a designer should strive to allocate all variations to as few product parts as possible. (An example is different specifications for voltage in different parts of the world)
	Styling	Styling modules typically contain visible parts of the product that can be altered to create different variations of the product.
Production	**Common unit**	Common unit is similar to the shared functions across products described by Dahmus et. al., i.e. parts or subsystems that can be used for the entire product assortment.
	Process and/or organization	Parts requiring the same production process are clustered together. For example, all parts requiring welding may be moved into a single module to enable atomization.
Quality	**Separate testing**	The possibility of separately testing each module before delivery to final assembly may contribute to significant quality improvements, due to reduced feedback times.
Purchase	**Supplier availability**	Purchase standard modules from external vendors
After sales	**Service and maintenance**	Parts exposed to service and maintenance may be clustered together to form a service module to be able to quickly replace and repair/replace it.
	Upgrading	Give customers the possibility of changing the product in the future
	Recycling	The number of materials in each module should be limited. Easily recyclable material can be kept in separate recycling modules.

	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 11 - Completed MIM for a vacuum cleaner (Erixon, 1996).

4.6 Step 6: Generate modular concepts

The module candidates identified in step 5 is here refined into different module concepts. Possible candidates could show a certain degree of overlap between the two approaches of step 5, but this is not an absolute requirement for modularization. Ideally, the two approaches will complement each other.

The lower weighted technical solutions from MDF™ are evaluated as to the possibility of integration with these modules.

The module concepts should contain rough dimensioning and form and a few selected and further detailed. It is important to bear in mind that this phase by no means can be solved by using any method. Product design skills and experience are required to create modular concepts that actually will work!

4.7 Step 7: Evaluate concepts

The interfaces have a vital influence on the final product and the flexibility within the assortment. Fixed interfaces between the modules are a condition for successful parallel activities. An interface might be fixed, moving or media transmitting. Fixed interfaces only connect the modules in a product and transmit forces. Moving interfaces transmit energy in the form of rotating, alternating forces etc. The media can be fluids, electricity etc. From an assembly point of view, two ideal interface principles can be identified: base unit and "hamburger" assembly. These are marked with arrows in Figure 12. All markings located outside the arrows indicating the preferred assembly principles should be subject to further consideration (Ericsson and Erixon, 1999).

An interface matrix, as in Figure 12, gives a good overview of the interface connections for a vacuum cleaner. The modules have been entered into the interface matrix in expected assembly order and the interface relations have been analyzed. The following examples are marked in the figure:

1. A geometric interface connects the electric motor and the chassis (G)
2. The electric motor and the fan are joined by a geometric connection. And, energy will be transmitted from the motor to the fan (G and E)

It is clear that most geometric interfaces follow the upper border of the matrix, indicating a base unit assembly. Independently of assembly order, most modules can be mounted on the chassis.

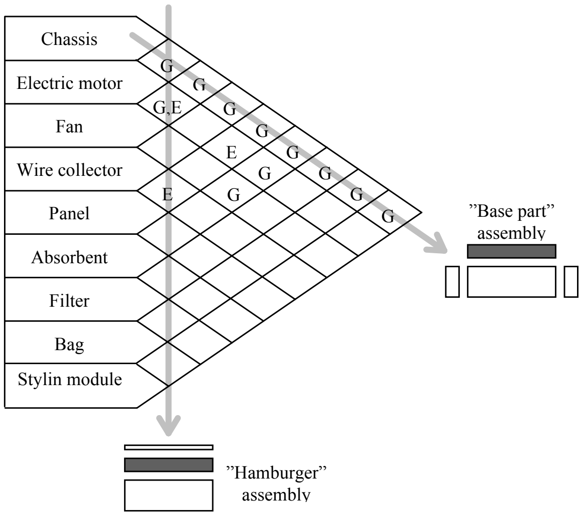

Figure 12 - Evaluation of interface complexity (Ericsson and Erixon, 1999)

5 CONCLUSION

The purpose of modularity is first and foremost to gain flexibility for mass customization, but a modular product strategy enables firms to achieve a number of strategically important advantages. Sanchez identifies four such strategic advantages, namely greater product variety, faster technological upgrading of products, greater speed in developing new products, and cost reductions. This article gives an account of these as well as other advantages of having a modular product strategy.

The heuristic and modular function deployment methods for module identification can apparently play together to create a combined method for modular concept generation. The heuristic methods consider functionality as the only modularization criterion. By integrating the heuristic method with the more management-oriented MDF™ approach, other business related factors are taken into consideration to ensure that the modules meet additional company objectives. The heuristics, in turn, give an important contribution to MDF™ as it is better at identifying interfaces between modules at an early stage.

To verify the model, a product must be modularized and the results compared to those of the individual methods. This will be carried out in the practical phase of this course[2].

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[2] This article is written as a part of a product design course at the department of product design engineering at the Norwegian University of Science and Technology, Trondheim, Norway.

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