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 Traditional mass production has in the past decade been replaced by the concept of mass customization, mass production of customized products.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.

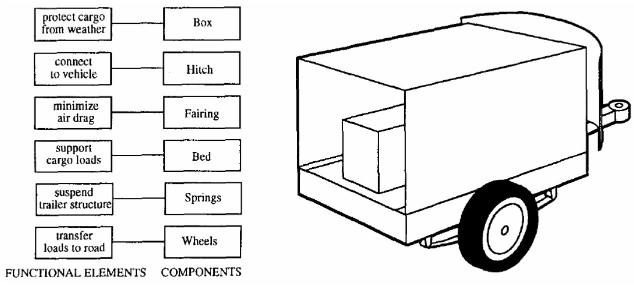

Figure 1 - A modular trailer architecture exhibiting a one-to-one mapping from functional elements to physical components. (Ulrich, 1995)

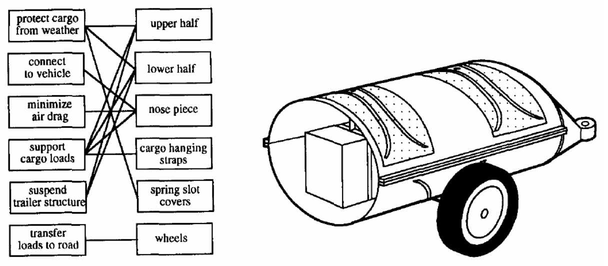

Figure 2 - An integral trailer exhibiting a complex mapping from functional elements to physical components. (Ulrich, 1995)

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

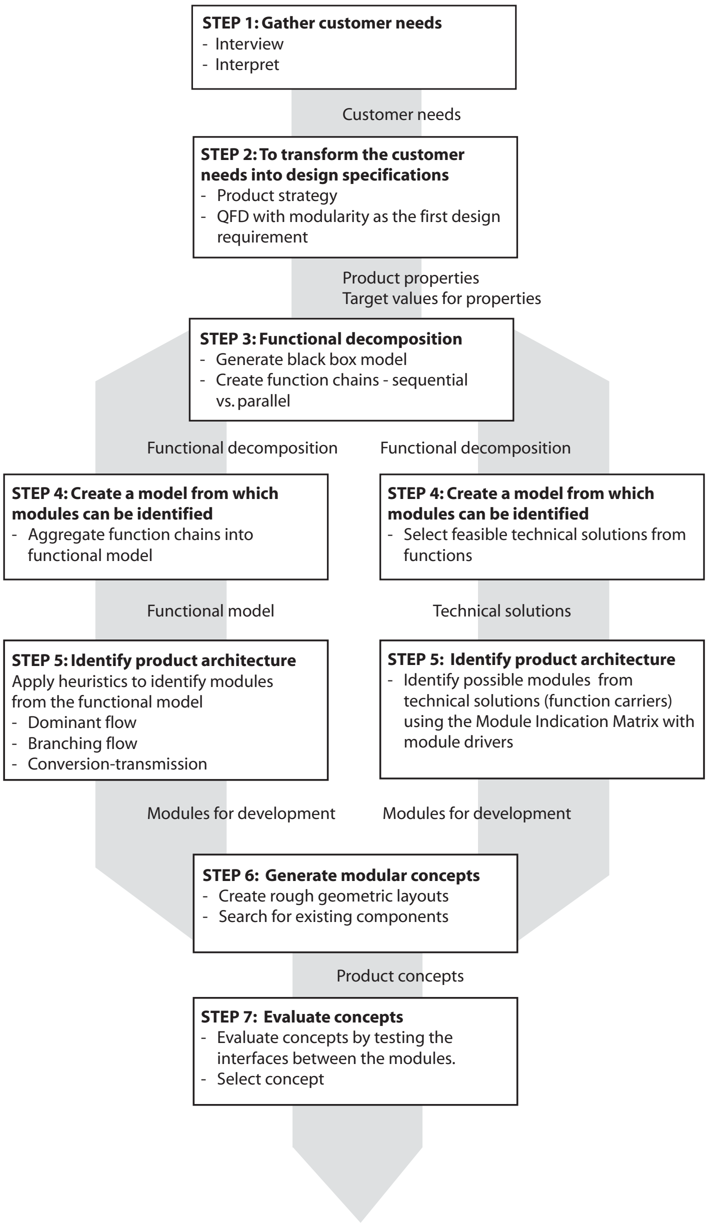

Figure 3 – An overview of the unified product architecture design methodology. Results from each step are shown directly under the respective steps

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).

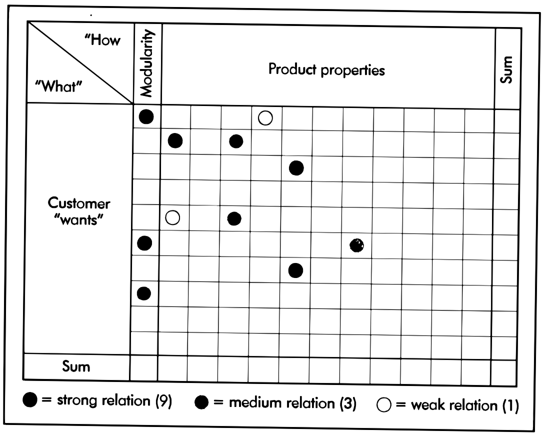

Figure 4 - Simplified QFD for eliciting product spesifications

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*).*

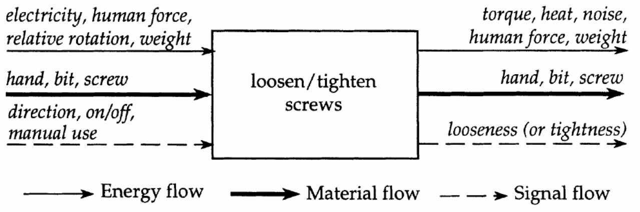

Figure 5 - Black box model for an electric screwdriver (Stone et. al., 1999)

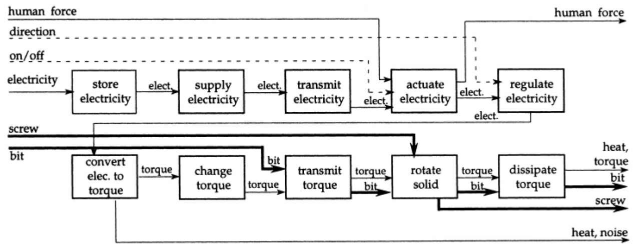

Figure 6 - A sequential function chain for the flow electricity (Stone et. al., 1999)

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].

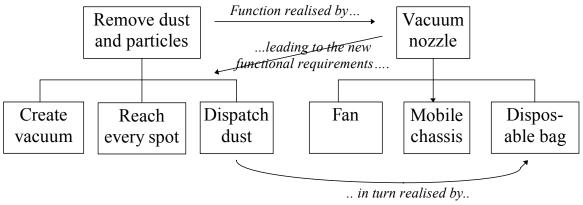

Figure 7 - First levels of the functional decomposition of a vacuum cleaner (Erixon, 1996)

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*).

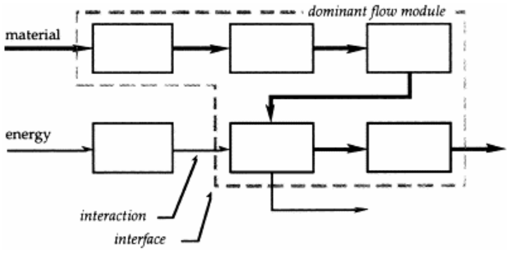

Figure 8 - Dominant flow heuristic applied to a generic function structure

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.

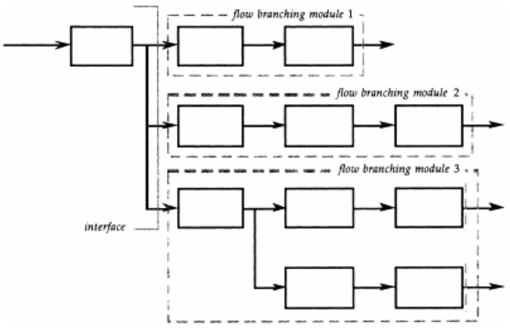

Figure 9 - Flow branching heuristic applied to a generic function structure

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

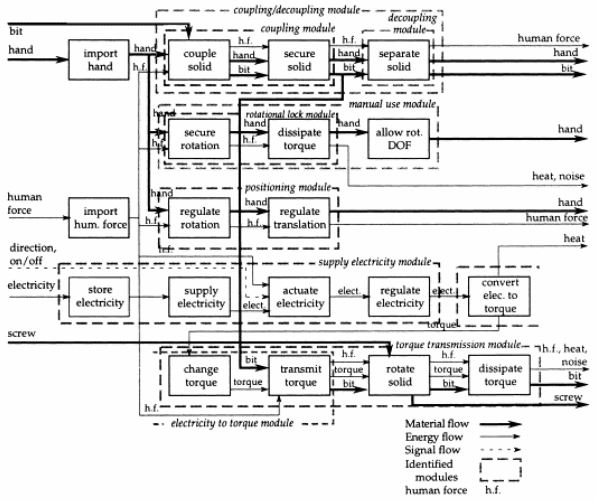

Figure 10 - Function structure of a power screwdriver with modules identified by the heuristic methods

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.

	Module driver \ **Function carrier**	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.

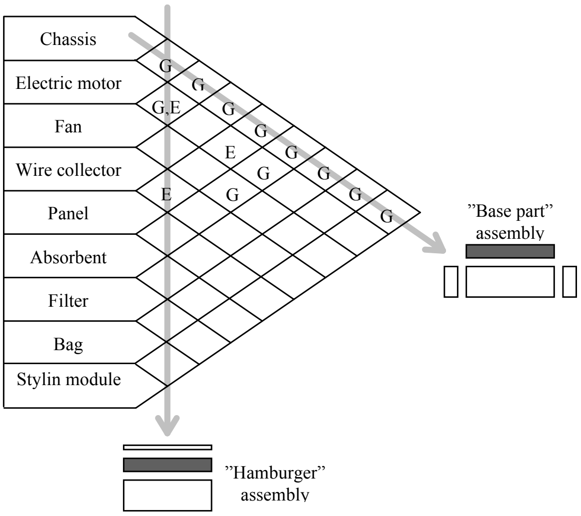

Figure 12 - Evaluation of interface complexity (Ericsson and Erixon, 1999)

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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