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ON THE DEVELOPMENT OF MODULAR PRODUCT STRUCTURES: A DIFFERENTIATED APPROACH

C. Blees and D. Krause

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1. Introduction

In recent years many industries have introduced modularized product structures to cope with rising demand for customized products and increasing requirements concerning lead times, costs and quality. Among others the aircraft industry makes increasing use of such modularized product structures [Whitney 2004]. In this application especially the aircraft interior is a very promising field as the interiors can be found in a high variety and their final assembly is one of the most laborious parts of the production process.

The methodologies supporting the development of modular product structures are basically composed of three steps, which have been proposed first by [Pimmler/Eppinger 1994]:

1. Decomposition of the system into functional or physical elements
2. Documentation of the interactions between the elements
3. Clustering of the elements into modules

According to Pimmler and Eppinger, for the decomposition it has to be considered if it is a novel or an incremental design. For a novel design functional elements are defined in the stage of conceptual design and are developed in more detail in the ongoing design process [Pahl/Beitz 2007]. In the more likely case of an incremental design most of the physical elements of the product, the components, are already known. Subsequent to the decomposition the functional-technical and product-strategic interactions between the elements are mapped and on this basis modules are derived. However, as a result of the multitude of technical-functional and product-strategic interactions this becomes a very complex approach. Therefore, in this paper the approach is made to develop a methodology that enables a separate consideration of the most relevant perspectives of modularization. On the one hand this enables the reduction of the complexity and on the other hand this makes it possible to support the different perspectives in a more appropriate way.

At the beginning of this paper the two most common methodologies for modularization are briefly described. Secondly, the approach of the development of a modular product from different perspectives is presented. Finally, the development of modular products from the manufacturing and assembly perspective is presented which has already been prepared more in detail.

2. Design methodologies for modularization

For the development of modular product structures especially the approaches made by [Pimmler/Eppinger 1994] and [Erixon 1998] are important. Pimmler and Eppinger focus on the development of modules by mapping of technical-functional interactions between components. Therefore they adapt the Design Structure Matrix (DSM) of [Steward 1981]. In the DSM the components are opposed to each other and their interactions are analyzed. This is done by identifying the type of interaction and by giving each interaction a score. The interaction types are: spatial, energy, information and materials. For the evaluation of the interactions a scale of 2 (required), 1 (desired), 0 (indifferent), -1 (undesired) and -2 (detrimental) is provided. An example of a design structure matrix is illustrated in figure 1. After the evaluation of interactions, clustering the elements into chunks can develop modules. Clustering can be achieved by sorting columns and rows. The idea is to combine the interactions predominantly within the chunks and to minimize the interaction between the chunks. For this purpose the authors suggest the use of algorithms.

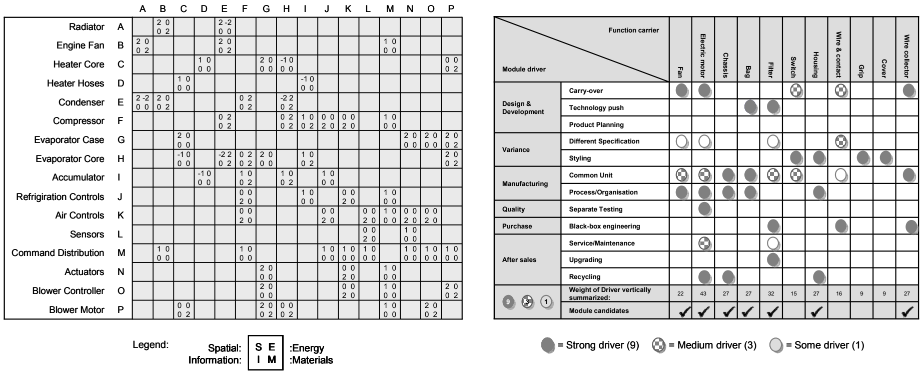

Figure 1. The Design Structure Matrix according to [Pimmler/Eppinger 1994] and the Module Indication Matrix according to [Erixon 1998]

Erixon uses his method, Modular Function Deployment (MFD), for the development of modular product structures. The MFD-method is subdivided in the steps clarification of requirements, selection of technical solutions, generation of modular concepts, evaluation of modular concepts and improvements of modular concepts. The main part of the MFD is the generation of modular concepts using the Module Indication Matrix (MIM).

In the MIM product-strategic interactions between components and so-called module drivers are indicated. An example of a MIM is shown in figure 1. The module drivers from the fields of design and development (carry-over, technology push, product planning), variance (different specification, styling), manufacturing (common unit, process/organization), quality (separate testing), purchase (black-box engineering) and after sales (service/maintenance, upgrading, recycling) are reasons for components to become part of a module. The interactions between the module drivers and the components are evaluated by experts and classified by values from 0 (no driver) to 1, 3 and 9 (strong driver). For building the modules the components with the highest ranking are used as basis. In the ongoing process further components with a similar evaluation pattern are added to these basic components. With this technique several modularized product structures can be developed.

In the following step of the MFD methodology the modular concepts are evaluated. First it is considered, whether an assembly-friendly product structure can be realized using a "hamburger assembly" or "base-part assembly". In the next step the concepts are rated with respect to development (lead time in development, development costs, development capacity), assembly (product costs, system costs, lead time, quality) and after sales (variant flexibility, service/upgrading, recycling). With this evaluation one concept is chosen and further detailed in a final step. For this Erixon refers to the established DFX methodologies.

3. Approach for a differentiated methodology for modularization

From the application of the methodologies of Pimmler/Eppinger and Erixon in the field of aircraft interiors it was realized that the multitude of interactions between the components turns modularization into a very complex task. One major reason for this complexity is that all perspectives

of modularization have to be considered at the same time. Therefore in this paper the approach of a separate development of modules according to the main perspectives is suggested.
An examination of the similarities and interdependencies between the module drivers has already been realized by [Stake 2000]. He suggests a grouping of the drivers in *product family planning* related drivers and drivers related to *functional purity*. In addition he allocates the drivers of the first group to the characteristics *degree of communality* and *time* and the drivers of the second group to the characteristics *location of effort* and *product life cycle*. The resulting representation is shown in figure 2. For the derivation of the most relevant perspectives of modularization this classification is used as a basis.

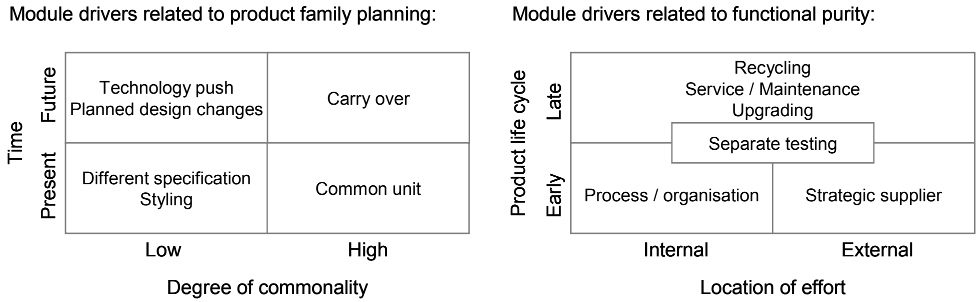

Figure 2. Grouping of module drivers according to [Stake 2000]

All module drivers Stake has assigned to the group of product family planning have very strong interdependencies, and as a result they do not allow a separate consideration. Therefore, the drivers *technology push*, *planned design changes*, *different specification*, *styling*, *carry over* and *common unit* remain together in the *product planning* perspective. The interdependencies of the drivers in the second group are less strong. Thus, the drivers can be adjoined to three different perspectives. The first perspective is the *purchase* perspective which consists solely of the driver *strategic supplier*. The second one is the *manufacturing and assembly* perspective. Beneath the driver *process/organization* the driver *separate testing* has been added as testing is one of the major tasks of assembly [Andreasen 1988]. The remaining drivers *recycling, service/maintenance* and *upgrading* are added to the *after sales* perspective. However, a further decomposition of the *after sales* perspective should still be considered if particularly high requirements concerning recycling or maintenance have to be satisfied by the product.
On the basis of these considerations a differentiated proceeding for the development of modular products can be derived. In figure 3 the main steps of such an approach are presented. At the beginning the goals of the modularization have to be clarified. These could be the variants requested by the product planning or the requirements concerning after sales aspects.
Subsequently, the actual modularization process takes place. At the beginning the product is decomposed into its components. This decomposition is the basis for the following modularization according to the four perspectives that have been derived before. The approach of a manufacturing and assembly oriented proceeding is presented in the next chapter while the development of adapted proceedings for the remaining perspectives will be part of the future work.
Concluding the concepts made from different perspectives have to be combined into the final modular product structure. Therefore it has to be examined whether different modular concepts can be coexistent in the product or not. In the latter case a decision in favor of one concept has to be made.
The water filter of an aircraft galley is a good example to show independent perspectives of modularization. From the *maintenance* perspective the water filter has to be a separate module in order to allow an easy replacement. In addition the *assembly* perspective requires the integration of the water filter in the lower module of the galley to minimize the number of assembly steps in the final assembly line. In this example the different concepts can be coexistent in the product without conflicting with each other.

In contrast to the above example the handrail mounted at the bottom of the hat rack shows a conflict of the perspectives *product planning* and *purchase*. From the *product planning* point of view handrail and hat rack should not be integrated in one module as the hat rack is a common unit while the handrail can vary in terms of color and shape. But, at the same time it is aspired to purchase a standardized hat rack module with all attached parts from a supplier. In this case a strategy has to be developed in order to overcome this conflict. If the goals of product planning are weighted higher, the handrail could be separated from the hat rack module. Contrariwise the hand rail could be standardized and integrated in the hat rack module. Thereby the differentiated consideration of the perspectives of modularization supports an attentive dealing with the conflicting goals in product development.

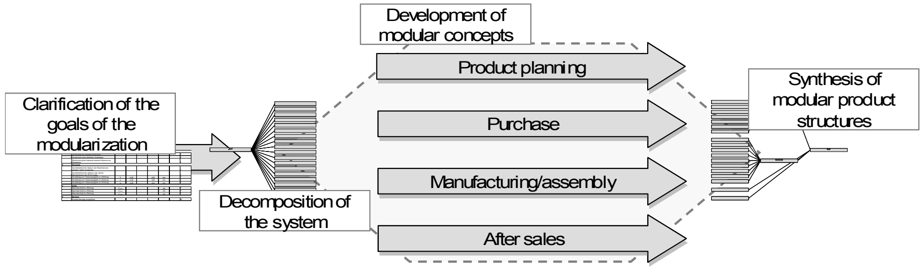

Figure 3. Approach for a differentiated development of modular product structures

4. Modularization from a manufacturing and assembly perspective

Modular product structures are fundamentally important for the assembly as most of the degrees of freedom that can be used for assembly planning are determined by the product structure. Therefore the production perspective has to be integrated into the design phase. In figure 4 the approach of a manufacturing and assembly oriented development of modular product structures is outlined.

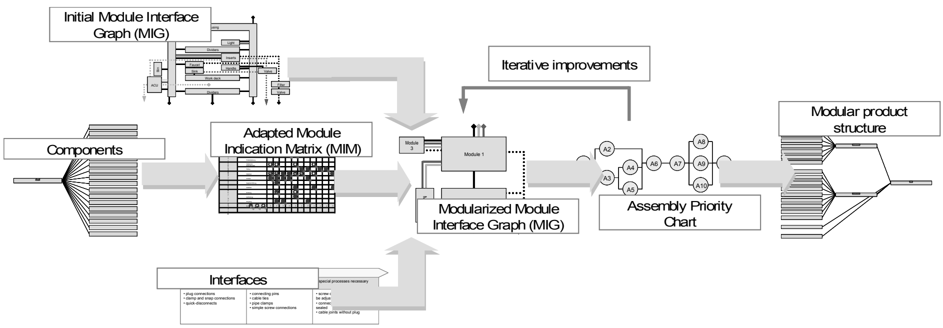

Figure 4. Modularization from a manufacturing and assembly perspective

For the development of a production-oriented modularization the essential inputs are the components, the initial product structure and knowledge of the interfaces. While in the case of an incremental design the components usually can be taken from the parts list, the decomposed product structure has to be mapped to outline the initial state. Therefore the Module Interface Graph (MIG) has been developed. An example is given in figure 5. Here the components are mapped approximately to their geometrical position on the graph. The interfaces are represented by lines between the components with different drawing styles or colors according their type (structural, power-transmitting etc.) together with inputs and outputs. This illustration gives a clear visualization of the initial product structure including the interfaces. For validation the MIG has already been applied successfully to the major systems of aircraft interiors (galley, lavatory, hat racks, personal service channel and panels).

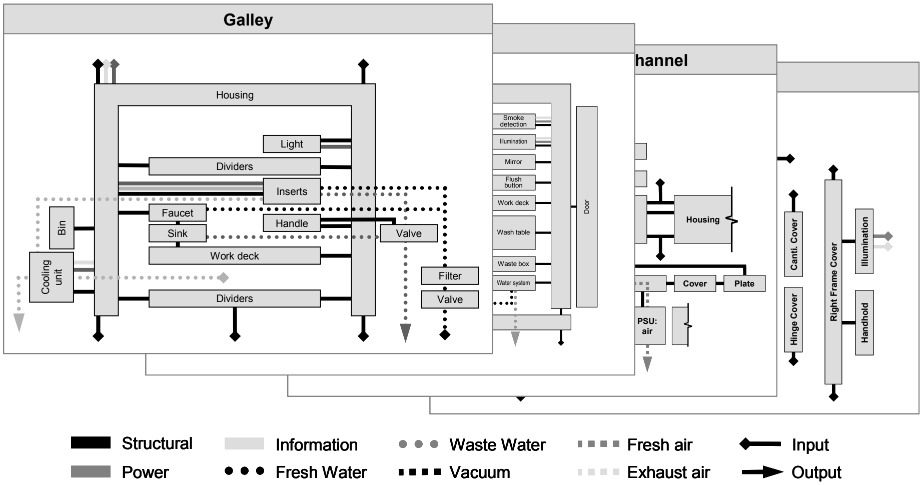

Figure 5. Module Interface Graph (MIG) for a galley and further aircraft interior systems

Furthermore, the interfaces and their design are of vital importance. From the assembly point of view especially the resulting lead time is the crucial factor. Therefore, a classification of interfaces based on their assembly effort is implemented. In the first class interfaces are summarized that can be assembled without tools and separate fasteners. Interfaces that require tools and/or separate fasteners are assigned to the second class. The third and last class contains interfaces that require additional procedures such as adjustments or sealing of split-lines. Table 1 shows common interfaces known from the field of aircraft interiors. In fact, this approach requires a new classification for every different type of product, but once a framework has been compiled it is easy to assign another interface to one of the classes.

Table 1. Classification of common interfaces from the field of aircraft interiors

Rising assembly efforts		
• no separate fasteners required • no tools required	• separate fasteners and/or • tools required	• special procedures necessary
• plug connections • click and snap connections • quick-disconnects	• connecting pins • cable ties • pipe clamps • simple screw connections	• screw connections that need to be adjusted • connections that need to be sealed • cable joints without plug

In the proposed proceeding the Module Interaction Matrix is used again for the actual deployment of modular concepts. However, to support the manufacturing and assembly perspective the module drivers have to be adapted accordingly. On the basis of Erixon and [Bullinger 1986] an adapted set of drivers has been compiled:

- *Work content*: the component has suitable work content for a group.
- *Skills*: special skills are required to assemble the component.
- *Lead time*: the assembly of this component has an especially long lead-time.
- *Automation*: the component can be assembled automatically.
- *Tools*: special tools are required to assemble the component.

- *Separate testing*: the component should be tested separately.
- *Process*: the component requires a special process.
- *Handling*: the component requires a special handling.
- *Storage*: the component should be stored in a particular way.

A further adaptation of the set of drivers is necessary in every application. In the case of the modularization of an aircraft cabin the driver *size* has been added to introduce the requirement that the integration of components and modules has to be accomplished through the passenger door. On the other hand some module drivers have been removed. The adapted MIM used in this application is shown in figure 5.

Module driver \ Component		Housing	Inserts	Light	Faucet	Work deck	Sink	Drain valve	Drain valve handle	Bin	Cooling unit	Water filter	Inlet valve	Dividers
Assembly	Size	●	●			●					●			●
	Handling	●	●			◍					●			
	Separate Testing		●	○	○		◍	●	◍			●	●	
	Process	●				●								
	Lead time	●									●			◍
	Weight of Driver vertically summarized:	36	27	1	1	21	3	9	3	0	27	9	9	12
	Module candidates	✓	✓			✓					✓			✓

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

Figure 6. The adapted MIM – completed for an aircraft galley

In the next step all inputs are combined. The modular concepts pointed out by the adapted MIM are examined. For this purpose the Module Interface Graph is used again. The MIG gives the simple representation of the product structure that is necessary to consider the given spatial adjacency requirements. In addition the line weights of the interfaces are chosen according to their assembly efforts. In figure 7 the initial and the modularized MIG are presented for the example of an aircraft galley.

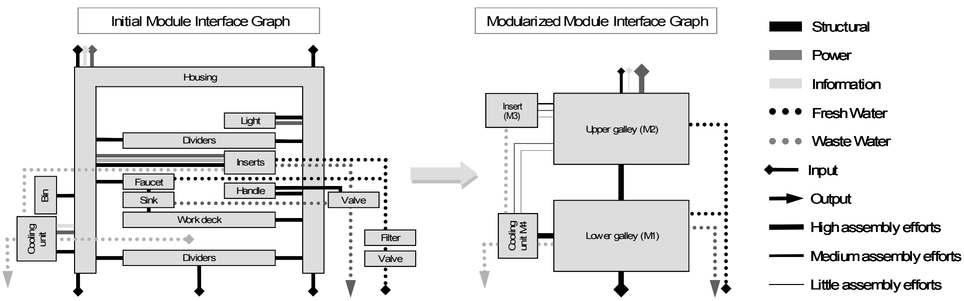

Figure 7. Module Interface Graph (MIG) for an aircraft galley

The last step of the proposed proceeding is the evaluation of the resulting assembly sequence. For this the assembly priority chart is used. An assembly priority chart is a network plan where necessary assembly tasks are represented as nodes and their interdependencies by connection lines. The nodes are plotted at the earliest point of time where the execution is possible, while the connection lines end at the latest possible point of execution. Figure 6 shows a rough assembly priority chart for an aircraft galley.

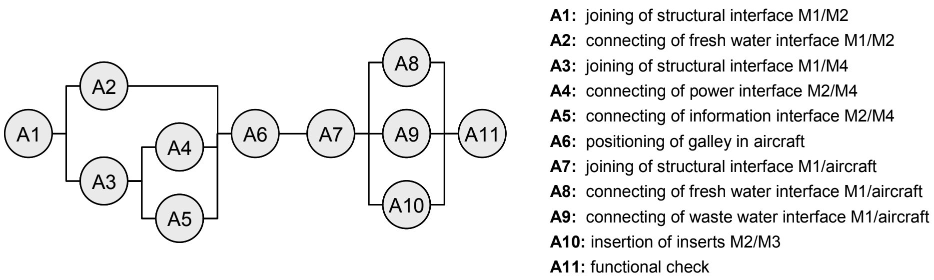

Figure 8. Assembly priority chart for the final assembly of an aircraft galley

The assembly priority chart is the basis for the evaluation of the modularized product structure in terms of lead time, workshop organization etc.. If the results are not satisfying, an iterative improvement of the product structure is required.

5. Conclusion

This paper explains why integrated approaches of developing modular product structures lead to a very complex task. To overcome this difficulty a proceeding is proposed which is based on a differentiated consideration of the *product planning, purchase, manufacturing and assembly* and *after sales* perspective.

Furthermore, the development of modular products from a manufacturing and assembly perspective has been discussed. An adapted Module Indication Matrix and the Module Interface Graph have been presented. In addition the classification of interfaces concerning their assemblability and the integration of the assembly priority chart have been proposed. This methodology has already been applied to aircraft interiors and will be further detailed in future applications.

Besides the manufacturing and assembly perspective the remaining perspectives need to be further examined. Hence, a major part of the future work will be the development of adapted methodologies for these perspectives alongside with the more precise consideration of their interdependencies.

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Dipl.-Ing. Christoph Blees
Scientific Assistant
Hamburg University of Technology,
Institute for Product Development and Mechanical Engineering Design
Prof. Dr.-Ing. D. Krause
Denickestraße 17 (Gebäude L), 21073 Hamburg, Germany
Tel.: +49 (0)40-42878-2784
Fax.: +49 (0)40-42878-2296
Email: christoph.blees@tuhh.de
URL: http://www.tuhh.de/pkt