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Target-oriented Modularization– Addressing Sustainability Design Goals in Product Modularization

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Abstract

Through modularization, a large range of sustainability goals can be addressed in design, e.g. environmentally friendly end-of-life or improved MRO (maintenance, repair and overhaul) processes. The development of methods for product modularization raised increasing interest in recent years. However, published methods for product modularization still lack of flexibility and standardization. Numerous methods have been developed that are defined for one or a given list of design goals. As a result, it is still difficult for engineers to find and apply the right method for a defined set of design goals. In this paper, the field of modular product design methods has been analyzed with the aim to develop a Target-oriented Modularization Method that allows defining modular product structure according to user-defined design goals. The introduced method is demonstrated on the example of a Garrett GT2860R turbocharger.

Keywords: product modularity; modular product design; sustainable design; product design; design methods

1. Introduction

In order to cope with the challenge of creating sustainable value without comprising traditional success factors such as time to market, cost and quality, new solutions for virtual product creation are needed [1]. In broadest terms, product modularization represents an approach for organizing complex products and processes efficiently, by decomposing complex tasks into simpler ones [2]. The scheme according to which product components and functions are arranged into *chunks* or *modules* and by which they interact with each other are defined in the product architecture [3]. The choice of product architecture has significant effect on the further steps of the product development process and on the whole product lifecycle. For complex products like automobiles or airplanes, several alternatively/equally relevant product architectures may compete, which makes the definition of the product architecture a complex yet critical task in product development.

The efficiency of a product architecture varies depending on the goals pursued in the product development process. Consequently, a challenge for product design teams consists in disposing of the relevant criteria for clustering product components and functions into modules according to a given set of design goals. Various measures have been identified that allow defining these design goals concretely and support the process of grouping elements into modules and defining interfaces [4]. Also, numerous modularization methods have been developed which use these measures in step-by-step procedures. However, each one of these methods has been developed for one or a defined list of design goals, such as mass customization or reduction of development time. This constitutes a limitation in the support these methods can offer to the use of product modularization in the development of sustainable products. In reaction to this, the present article introduces a generic approach where methodological aspects (how to implement modularization?) are separated to motivational aspects (what are we implementing

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modularization for?). It introduces the concept of a Target-oriented Modularization Method (TOMM) which can be implemented regardless of user-defined design goals. It allows product design teams to pursue their own goals already in product modularization, enabling the consideration of life-cycle and sustainability issues.

2. State of the art in modular product design

Three essential aspects of product modularization are covered in this section: Goals, which can be achieved through product modularization, measures which have been used to translate goals into practice and methods that use these measures and assist the product modularization process.

2.1. Achieving design goals through product modularization

Modularization has been found to support a broad range of design goals. Amongst academic literature, some authors introduced the concept of module drivers, defined as design goals product modularization can contribute to (e.g. [5, 3]). The provided lists of drivers, however, are not exhaustive and may vary between authors. Other authors describe similar advantages of product modularization and label them differently

Several authors point out that product modularization has a positive effect on product variety for mass customization (e.g. [6, 7, 8]). It allows decreasing internal variety by standardizing parts in a mass customized product [9]. Breaking down product complexity in order to facilitate design tasks and reduce development time through enabling parallel development, shorter time-to-market at lower cost, is another cited approach [10]. Leveraging postponement and delayed differentiation through product modularization is also expected to reduce production costs (e.g. [11]). The reduction of interface complexity may simplify communication between development teams facilitates design changes (e.g. [12]).

Next to classical cost and time driven design goals, researchers also point out that product modularization can contribute to addressing sustainability design goals. Product modularization is an important factor when it comes to product maintenance allowing separate diagnosis of product components and isolation of wear parts [13]. Modularity also fosters upgrade, adaptation and modification of products or components for an extended service life that may result in a reduction of environmental load [7]. As modular design influences the disassembility of a product, it indirectly influences the treatments potentially applicable at its end-of-life and may help reducing its environmental impact (e.g. [14]).

2.2. Modularization Measures

Researchers have described metrics which intend to measure to what degree components should be clustered in the same module. Gershenson et al. suggested that the affinity of components to be grouped together can be expressed through the generic properties of independence and similarity – two properties that can be measured for each pair of functional carriers within a product. Depending on the desired goal, the generic properties can be instantiated through more specific measures [15].

Independence is described as the measure of relations among components inside a module versus relation between components outside a module [16]. In other words, independence between modules means that changing the design of a component in a module has a minimal effect on other modules. Different instantiations of the concept of independence measure have been introduced: component position pattern [17], assembly dependency [16], accessibility [18], cost of reusability [19], interface openness [20] and interface design effort [21].

Similarity is used to denote resemblance in processing or the ability to be processed in a similar way [16]. The literature provides different metrics expressing similarity in modular product design, including assembly process similarity [16], maintenance frequency [13], component connection pattern [17], post life intent [22] and production cost [18].

2.3. Methods for product modularization

Methods in product modularization can be divided into two different groups. The first group of methods aims for the modularization of one product. Here, a single decomposition is conducted and a single product architecture is created. The second group consists of methods for product family modularization. These methods decompose multiple individual products and aggregate the elements to a family product architecture.

Methods for single product modularization

Pahl and Beitz integrate their modularization procedure in their generic view of the product development process [23]. The detailed approach stretches from product planning, where customer needs are identified and requirements derived to the definition of the product architecture and the specification of interfaces in embodiment design. Pimmler and Eppinger suggest a less detailed procedure which focuses primarily on the tasks of product modularization, integrating the usage of the interaction matrix and a clustering algorithm [24]. Lange and Imsdahl build on the previous work by Erixon [25]. Their approach ranges from the clarification of customer requirements to Design for X, utilizing a range of different matrices [5, 25]. Lanner and Malmquist leave out activities for requirements definition and start with the establishment of an organ structure. Alternative proposals for the product architecture are generated through the Interaction and Lanner Matrix [26]. Kusiak and Huang present a method for the design of modular products for testability in the presence of testing modules [27]. Similarity and dependency are the central concepts for clustering modules according to Gershenson et al. Relative modularity is calculated via a Modularity Evaluation Matrix . Lai and Gershenson's method ranges from the creation of the respective similarity and dependency matrices to checking the assembly feasibility

[16]. The concept of different drivers is addressed by Voß and Birkhofer. Starting out from the generation of a Driver Selection Matrix, the component vector is calculated in order to receive the component combination impact [4]. Qian and Zhang's approach has a simple structure, divided into three steps: similarity analysis, independency analysis and evaluation via algorithms [28]. Schmidt introduces a procedure for effective clustering of car bodies. The author proposes the conception of basic and variant modules [29].

As described in this paragraph, the current field of methods for product modularization is limited to one or a defined list of design goals. The majority of these goals address the economic dimension of sustainability, e.g. mass customization or reduction of the product development time. Methods addressing the environmental dimension of sustainability are less represented in the academic literature, while the social dimension has not been found represented at all.

Methods for product family modularization

Dahmus et al. start their product development method with developing separate function structures for each product in the product family. These are merged into a single family function structure in the next step. Using these functions a modularity matrix is created, which aids in constructing different possible product portfolio architectures [30]. Kimura et al. propose a similar procedure, where functional dependency modules are described in a graph structure and then superimposed [31]. Kong et al.'s detailed procedure contains 14 steps in an extended V-model, including product family planning and the identification and definition of interfaces [32].

3. Problem Statement

Three major findings have been identified through literature research:

1. Various design goals addressing the economic and environmental dimensions of sustainability can be addressed through the design task of modularization;
2. For a significant amount of them modularity measures have been developed;
3. Current methods for product modularization are specifically focused on addressing one or a defined list of design goals

In this paper, the Target-oriented Modularization Method is introduced. This method allows defining modules according to user-defined design goals and measures. It is defined independent of any modularization measure and can therefore be adapted to any design goals and can contribute to more sustainable performance of the final product.

4. Research Methodology

Within the scope of this research, existing modular product design methods have been analyzed. Their procedures have been extracted and compared systematically. Distinctive steps and methodological concepts have been extracted and examined regarding the question: *Can this step be utilized for a generic method, which allows taking arbitrary modularizations measures into account?*

The useful elements which have been identified were rearranged to Target-oriented Modularization Method (TOMM). The method has been tested on a Garrett GT2869R turbocharger.

5. Method Conception

In this section, the development of the proposed method Target-oriented Modularization Method is described. The results of the analysis of existing methods are stated in section 5.1. The procedure of TOMM is specified in section 5.2.

5.1. Identification of suitable steps for Target-oriented Modularization Method (TOMM)

Researchers widely agree that an essential task in product modularization is breaking down the product into elements. Several approaches for this task, such as the one by Pahl & Beitz, Lanner & Malmquist, Gershenson et al. and Ulrich & Eppinger have been defined in the academic literature [3, 12, 23, 26]. For TOMM, we selected "Decomposing the system into elements" by Pimmler & Eppinger. The advantage of their approach consists in allowing a decomposition in either physically or functionally described elements.

In early stages of the product development process, it can be more useful to describe the product in functional elements, using a function structure, since most of the physical elements have not been defined yet. In later stages, physical elements or components can be used. In the majority of cases, however, a mixture of both will be applied.

Two approaches for merging structural diagrams of several products into one structural product family diagram have been identified [30, 31]. For TOMM we decided to use the approach of Dahmus et al. since it is described in more detail.

The only concept described in literature which takes user-defined measures into account is the one by Gershenson et al. [16]. Therefore a product representation in the form of similarity and dependency matrices was chosen for TOMM. These matrices list physical and functional elements of the decomposed products on both axes. Their cells contain either similarity or dependency relationships between the elements of the product. The goal of similarity and dependency representation is to quantify and visualize the element-to-element relationships in the cells of the matrices [16].

In order to cluster the elements into chunks, rows and columns of developed similarity and dependency matrices have to be reordered by an algorithm, so that the highest values are located closer to the diagonal. This way, product elements which should rather be clustered in the same module are located next to each other after the algorithm has clustered the matrix. The heuristic swapping algorithm used by

Pimmler & Eppinger or the one developed by Kusiak can be applied [24, 27].

5.2. Application of Target-oriented Modularization Method (TOMM) to a turbocharger

In this section, we present the concept for a six-step approach for product modularization which allows the consideration of goals and measures by the product design team. In order to test it, the method has been applied in the redesign of a Garrett 2860R turbocharger.

In Step 1 of TOMM, the products which are subject to the modularization task are decomposed into smaller elements. The elements are represented in one scheme, i.e. a hierarchical diagram modeling the functional or physical elements of a product. [24]. A product scheme represents the product design team's understanding of the constituent elements of the product [3].

Table 1: Procedure of TOMM

Step	Task	Result
1	Decompose products into physical or functional elements and represent in schemes	Product schemes
2	Union multiple product schemes into a single product family scheme	Product family scheme
3	Identify goals and related modularity measures	List of goals and modularity measures
4	Determine value of modularity measures	Similarity and dependency matrices
5	Use algorithmic support to reorder the matrices	Alternative proposals for product architectures
6	Choose final product architecture by comparing the different product structures created in step 5	Product architecture

In figure 1 the developed scheme for the Garrett 2860R is presented. The product has been decomposed into 6 separate elements. Since the scheme has been developed within a redesign process, the elements are described physically. The changes which will be performed to the product within this process are incremental and take place on the component level. At this point of the product development process, the design team already knows which functions are fulfilled by which physical element, so they can be described through components.

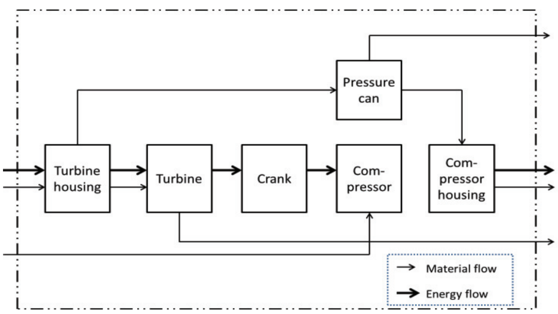

Figure 1: Scheme of a Garrett 2860R turbocharger

In Step 2 the diagrams which have been developed for each product in Step 1 are merged into a single diagram using the procedure described by Dahmus et al. [30]. The product family scheme represents a single diagram showing every functional or physical element of the considered products in the product family. If the TOMM is applied on a single product, only one scheme has to be developed and Step 2 can be skipped. In the case of the Garrett 2860R only one product is subject to the redesign process. Thus, no family product scheme has to be developed.

In Step 3, the product design team decides upon the goals and related measures for product modularization. For this step, the design team is provided with a database of standard modularity metrics where design teams can find the right metric corresponding to their design goals. The detailed presentation of this database is not in the focus of this article and will be the subject of a future publication. For means of this example, the design goals *decrease development time*, *improve end-of-life treatment* and *improve maintenance* have been chosen.

Pimmler & Eppinger describe the *energy-type interaction* as the necessity of energy transfer in between two components and as a valid measure for decreasing development time. Within the development of a product different design teams may be assigned to the development of individual components. Components sharing high energy flows are interdependent and their respective design teams need to interact frequently, which enhances coordination effort and increases development time [24]. The *energy-type interaction* was therefore chosen as a dependency measure for the modularization of the Garrett GT2860R. *Disassembly time* is described by Qian and Zhang as a dependency measure for improving the end-of-life treatment of a product as well as service and maintenance [28].

For every measure selected by the design team, a similarity /dependency matrix is created in Step 4. Dependency and similarity matrices line the different functional elements or physical elements, which have been identified through the creation of the product scheme on both axes. For every modularity measure which has been identified, the similarity/dependency of each element to every other functional element or component has to be evaluated by the design team. Measures can be either quantitative or semi-quantitative. All measures have to be normalized into a common scale. In every cell of a dependency matrix the value states the dependency of an element to another element according to a dependency measure. In similarity matrices the value states the similarity of an element to an element according to a similarity measure.

The dependency matrices for the measures *energy-type interaction* and *disassembly time* can be seen in table 2 and 3. In order to make the two measures comparable, a common scale of 1-4 has been chosen. The scores for *energy-type interaction* have been determined by evaluating the respective flow of energy in between the components. The Garrett GT2860R has been disassembled and the time for disassembly has been measured in order to identify the scores for *disassembly time*.

Table 2: Dependency matrix for *energy-type interaction*

	Turbine Housing	Turbine	Crank	Compressor	Compressor Housing	Pressure Can
Turbine Housing	-	2	0	0	0	0
Turbine	2	-	2	0	0	0
Crank	0	2	-	2	0	0
Compressor	0	0	2	-	0	0
Compressor Housing	0	0	0	0	-	0
Pressure Can	0	0	0	0	0	-

Table 3: Dependency matrix for *disassembly time*

	Turbine Housing	Turbine	Crank	Compressor	Compressor Housing	Pressure Can
Turbine Housing	-	0	0	0	2	1
Turbine	0	-	4	0	0	0
Crank	0	4	-	4	0	0
Compressor	0	0	4	-	0	0
Compressor Housing	0	0	0	0	-	1
Pressure Can	0	0	0	0	1	-

In Step 5 rows and columns of individual dependency and similarity matrices are reordered in order to find a suitable cluster of the functional elements and components. Once rows and columns are reordered, different modules can be chosen and combined into a proposal for a product architecture for every dependency and similarity matrix. In the clustered matrices, elements which should be arranged in the same module are located next to each other. This way, an efficient product architecture according to the measure can easily be identified. Table 4 shows the reordered dependency matrix for *disassembly time* and the reordered dependency matrix for *energy-type interaction*. It can be seen that the matrix for *disassembly time* recommends the clustering of the turbine housing, compressor housing and pressure can into one module and compressor, turbine and crank into another. The matrix for *energy-type interaction factor* on the other hand shows strong dependencies between turbine housing, turbine, crank and compressor, which indicates clustering them into one module.

Table 4: Reordered dependency matrix for *energy-type interaction*

	Turbine Housing	Turbine	Crank	Compressor	Compressor Housing	Pressure Can
Turbine Housing	-	2	0	0	0	0
Turbine	2	-	2	0	0	0
Crank	0	2	-	2	0	0
Compressor	0	0	2	-	0	0
Compressor Housing	0	0	0	0	-	0
Pressure Can	0	0	0	0	0	-

Table 5: Reordered dependency matrix for *disassembly time*

	Turbine Housing	Compressor Housing	Pressure Can	Turbine	Crank	Compressor
Turbine Housing	-	2	1	0	0	0
Compressor Housing	2	-	1	0	0	0
Pressure Can	1	1	-	0	0	0
Turbine	0	0	0	-	4	0
Crank	0	0	0	4	-	4
Compressor	0	0	0	0	4	-

In the final Step 6 of TOMM the design team critically reviews the different product architectures created in Step 5. Based on the judgment of the design team, a final product architecture is selected. In the case of the redesign of a Garrett GT2860R, the design team has several different options based on the information the two reordered matrices provide. One efficient choice would be to cluster turbine housing, compressor housing and pressure can into one module and turbine crank and compressor into another one. In the further redesign process, changes in the construction of the elements clustered in one module can be conducted much easier. This will result in a shorter developing time and an improved end-of-life treatment of the product.

For the future development of the method, a weighting of criteria will be made possible and supported through an integrated clustering algorithm in order to enable an objective decision for the preferred solution.

6. Conclusion

In this article, existing methods for product modularization have been analyzed and it has been claimed that the field of product modularization methods still lacks of flexibility and standardization. In reaction to this, the concept of a Target-oriented Modularization Method (TOMM) has been introduced. The method assists product design teams in defining modular product architecture according to criteria fitting their design goals. It helps generating alternative proposals for product architectures based on similarity and dependency analysis and modularization measures. This new generic method allows for the consideration of design goals addressing all dimensions of sustainability. It has been demonstrated on the example of a Garrett GT2860R turbocharger and considering the design goals *decrease development time*, *improve end-of-life treatment* and *improve maintenance*.

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