A CLASSIFICATION FRAMEWORK FOR PRODUCT MODULARIZATION METHODS

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ABSTRACT

The modularization of product architectures and the standardization of components and modules across a product family or product portfolio constitute approaches to reduce the internal variety in an enterprise while keeping the range of the external variety. Thus costs and development time can be reduced through scale effects and further transparency within the product portfolio can be enhanced as well. In this context a plethora of methods and approaches to identify modules in product architectures has been introduced. These methods differ in the application area and the procedure and show different benefits and weaknesses. This paper introduces a classification framework for modularization methods and approaches that provides a systematic overview on past and current developments. Therefore an extensive literature survey on modularization was carried out to identify the major methodologies introduced in the last years.

Keywords: Product modularity, product architecture, modularization methods, classification framework.

1 INTRODUCTION

During the last decades the change from a sellers' to a buyer's market has led to an increase of variant products in order to meet individualized customer requirements. Furthermore, a large number of product families has immerged and the product life cycle has been considerably reduced to meet constantly changing and expanding customer needs. On the one hand this has led to more complex products, which incorporate several different functionalities and on the other hand the plethora of different products and variants has led to larger, unclear and complex product portfolios. In this way the internal complexity and variety in an enterprise has increased to satisfy the external variety, which is required in order to operate the market. [1]

Therefore, main objective of a large number of research activities and publications in the last years has been to reduce the internal complexity and variety and at the same time to preserve the variety and the range of a product portfolio, as illustrated in Figure 1. [2]

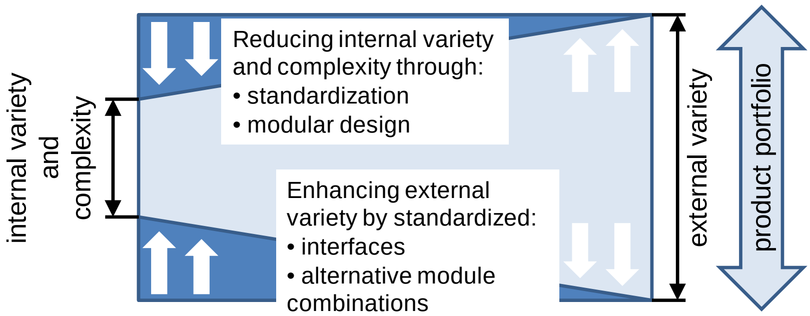

Figure 1. Motivation and scope of research activities.

An approach to achieve the reduction of internal variety and therefore internal complexity is to modularize product architectures and define standardized modules. Whereby, modularization is the process of decomposing product architecture into modules. These modules, as Gershenson et al. [3] defines, can be seen as units, which provide a unique basic function necessary for the product to operate as desired. Further, product architecture is defined by Ulrich [4] as the arrangement of functional elements, the mapping from functional elements to physical components and the specification of the interfaces among interacting physical components.Thereby, modularization of products leads to reduction of design lead time and costs, improves design quality and facilitates redesign and change processes. Furthermore, modularization enables the standardization of components and the definition of standardized physical interfaces and therefore facilitates the development of product variants [3, 5].

Another approach in order to reduce internal complexity is the identification and definition of product platform elements that can be used across the variants and products of a product family. In the literature is mentioned that a product platform can be seen as a common set of subsystems, components, processes, technologies shared by all variants in a product family [6, 7]. Thus can be standardized in order to reach scale effects and reduce design lead time. Furthermore, the identification of modules or platform elements can be carried out at various levels of product aggregation and abstraction, i.e., between systems, subsystems, components or functions [6].

In this work we concentrate on modularization methods and approaches but it is important to note that many of these methodologies can be also used to identify and define platform elements in product architectures.

Although in the last twenty years a lot of research has been done in this field and a plethora of different approaches to modularize single products or whole product families have been published and can be found in the literature (s. Chapter 4) there is a lack of a systematic overview on the existing methodologies. Scope of this work is to provide an efficient synopsis of the major modularization approaches introduced in the last years through the introduction of a classification framework. Thereby, diverse methodologies are categorized according to consistent characteristics, such as the application area of the methodology.

In the next chapter past research works on systematizing and assessing diverse modularization methodologies are presented that are relevant to this paper. In chapter 3, at first a brief introduction to the scope and benefits of modularization is given and then a systematic overview on the major modularization methods and approaches is presented. Subsequent in chapter 4, the classification framework is introduced by elaborating its dimensions and an overview on the methods by means of the framework is presented. Finally, in chapter 5 some critical conclusions and areas of future work are given.

2 RELATED RESEARCH

In the past years several categorization and assessment works for modularization and platform-based design methodologies have been introduced and can be found in the literature [8-11].

Holtta et al. [8] carry out in their work an analysis of three major modularization methods. The Design Structure Matrix [12, 13], the Function Structure Heuristic Method [14] and the Modular Function Deployment Method [15] are being deployed to modularize three different end-user products and a product family. Thereby, Holtta et al. [8] discovered that all three methods, given identical inputs, produce different results. Reason for this is that each method was developed from a different viewpoint and for different application areas.

Fixson [9] provides in his work an extensive literature survey over 15 years on modularization and commonality research and analyzes the included references according to their subject, their effect and the introduced research method.

Jiao et al. [10] provide in their work a comprehensive review of strategies for product family design and platform-based product development. Thereby, they introduce a decision framework, which provides a holistic view on product family design and takes design aspects from the customer to the functional, physical and process perspective into consideration. Modularization of a product’s architecture as well as the communalization of physical components constitutes thereby only an aspect of the physical and functional perspective of the framework. In the same sense Gershenson et al. [11] present a review of existing measures of product modularity and methods to modularize product architectures. Each method is briefly described and discussed according to its benefits and boundaries. Finally, Gershenson et al. [11] discuss on which abstraction levels there is consensus and commonalities in modularization methods and measures.

Similarly to Gershenson et al. [11], scope of this work is to provide a systematic overview on existing modularization methods, which facilitates the decision making about which method or approach is more suitable for a specific application area. This includes a clearly visualized classification framework for the different methodologies to modularize product architectures. Whereby, the categorization is carried out according to the application area and the potential of the method.

3 REVIEW ON MODULARIZATION METHODS

As companies strive to rationalize engineering design, manufacturing and support processes in order to reduce and manage internal complexity they are focusing on modularity. Thereby, modularity refers not only to product architectures but also to processes and resources that fulfill various functions and can be considered as distinct building blocks [3, 16].

In this context main scope of modularization is the reduction of product complexity and internal variety in an enterprise. Thereby, standardization of modules or components is enhanced in order to achieve scale effects and to reduce cost and development time. Furthermore, modular designs and the deployment of standardized components improve the reliability and quality of the product and allow an easier product diagnosis, maintenance, repair and disposal [16].

Nevertheless, a large number of influencing factors and constraints has to be considered in order to achieve positive effects by modular design. Thereby, the application area of modularization has to be clearly defined at the beginning of the design or redesign process and must incorporate the product life-cycle, technology and quality issues in order to realize its potential [16]. Furthermore, in accordance to the application area, the abstraction level – physical or functional – to carry out the modularization has to be defined.

Over the past years a plethora of different approaches and methods to achieve modularity in New Product Development and Product Redesign has been introduced. Yet there is a lack of a systematic review on the different methodologies. Figure 2 shows an overview and systematization of important publications and methods on modularization of product architectures and product families. The review begins in the early 90's with the book of Pahl and Beitz [17]. For clarity the initial publications for a modularization method or approach are shown and a small number of subsequent publications of the same research group. Furthermore, the relations between different methodologies are documented.

Design Structure Matrix (DSM) [13], Function Heuristics [14], Modular Function Deployment (MFD) [15] and Design for Variety (DfV) [5, 18] can be seen as the major modularization methods. Whereby, DSM, Function Heuristics and MFD concentrate on modularization, Design for Variety constitutes a more extended approach, which includes the modularization aspect.

In order to reveal and explore alternative product architectures and to improve thereby the quality of the resulting product design Pimmler and Eppinger [13] proposed a component-based Design Structure Matrix to model and analyze a product's architecture. Furthermore, by using the DSM method design coordination demands can be supported, that are required when subsystems interact [19]. Because of the component-based analysis of product architecture the modularization cannot be carried out in the early phases of New Product Development, as in these phases little is known about the exact component structure of a product. In addition, the simultaneous consideration of more than one product or a product family in order to reveal modules applicable across the product family is not possible.

Stone et al. [14] introduced a systematic approach to identify modules of a product on a functional basis. Thereby, modules are identified according to the major flows in the function structure. Stone et al. [14] provide in their work a number of rules (heuristics) to identify modules and a large number of publications can be found which introduce further heuristics to identify modules depending on the specific application. Because of the more abstract analysis and the standardized approach to set product function models this method can be easily optimized to consider a larger variety of products. [20]. Nevertheless, the poor repeatability and the varying results constitute the major disadvantage of the approach [8].

Modular Function Deployment (MFD) [15] considers more strategic and abstract management parameters to develop a modular product structure. MFD is also based on function structures, but modularity drivers other than functionality are considered. Furthermore, MFD is designed to modularize single products and Ericsson et al. [15] provide in their work an amount of twelve modularity drivers to achieve that considering diversity, assembly, life-cycle and re-usability parameters. As by the Function Heuristic approach, the MFD's major disadvantage is the poor repeatability of the method's results [8].

Finally, Design for Variety (DfV) is an approach, which considers customer demands in a product line in order to identify the optimal design for a product while minimizing the life-cycle cost of providing the variety [18]. DfV uses product structure graphs and ratings as model for the product architecture in order to identify the optimal design and is developed for the redesign process of existing products. On this basis a large number of further developments can be found in the literature, which apply not only for single products but also for product family design [21]. Thereby, modularity is an aspect of the redesign process. The initial and the optimized product architecture can be described using metrics in order to assess the result [5].

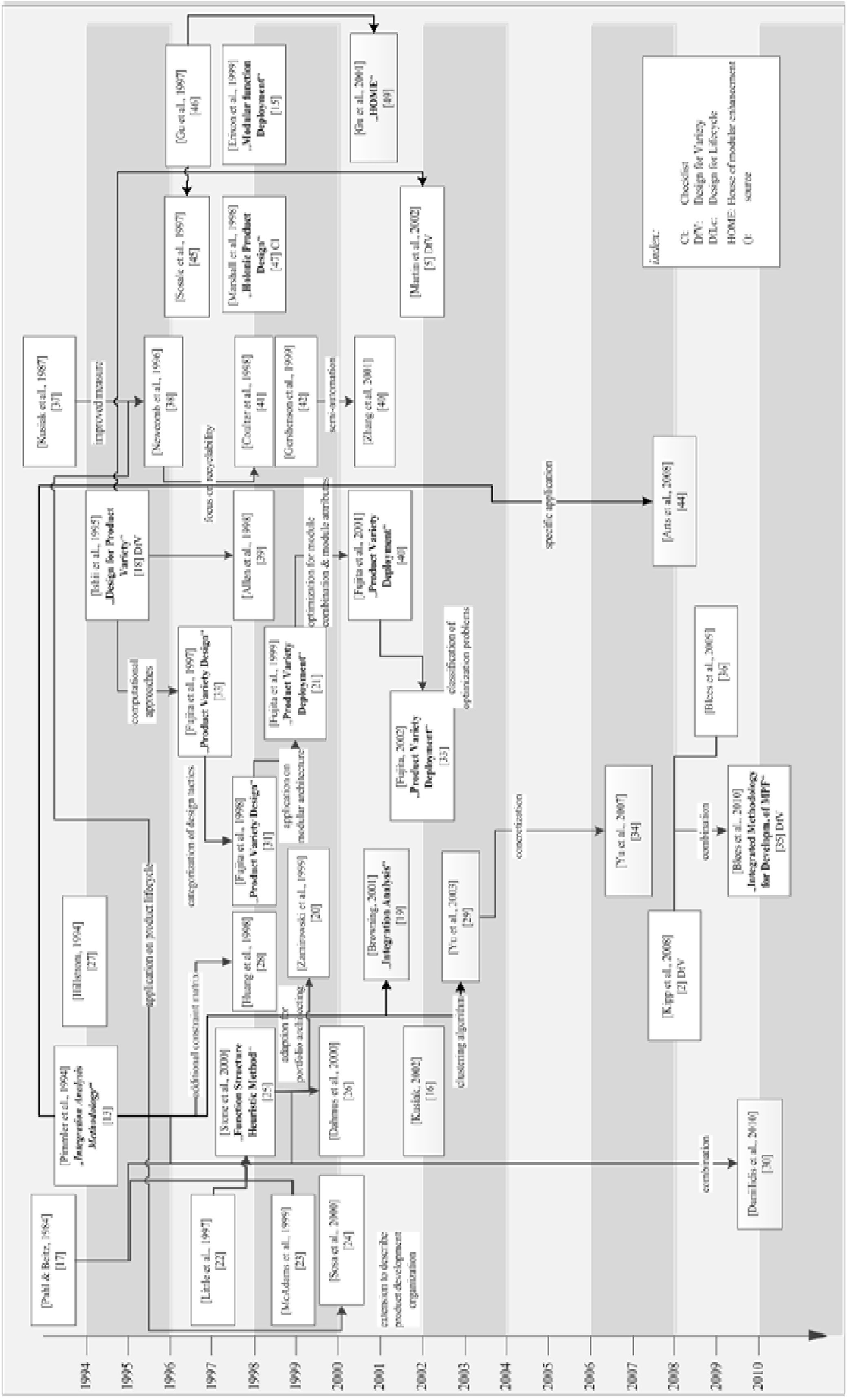

Figure 2. Overview of some important modularization approaches.

Figure 2 shows an overview on the major modularization methods and their further developments and combinations found in the literature. Important to note is that in the years between 2004 and 2006 no major developments could be found.

4 CLASSIFICATION FRAMEWORK

In order to systematize this plethora of methodologies and provide a clear overview this paper introduces a classification framework. Thereby different methodologies to achieve modularity are classified according to parameters that describe the application area and the capabilities of each approach. In the following sub-chapters the dimensions of the framework are elaborated and some examples of classified methods are given to demonstrate the application of the framework.

4.1 Application area of modularization methods

After a thorough literature-survey it was concluded that the parameters, which definitely characterize the application area of each modularization approach are the *product variety*, the *product generation* and the *product life-cycle*. As shown in Figure 3 these parameters are used by means of the classification framework as categorization criteria.

Product variety

Variety is one of the most often mentioned driving factors for modularity (e.g. in [49], [50] and [35]). Due to general market saturation it becomes more and more important to fulfill specific customers' needs. Globalization and therefore globalized competition enhances this impact even further, so that offering specialized products on a wide range is a key factor to success [1]. Providing this variety of products is possible, but only in combination with minimal company-internal variety (s. Chapter 1). This difficulty of offering high external variety on the one hand while minimizing internal-variety on the other hand can be resolved by modularization. Furthermore, product variety can be used to characterize the application area of a modularization approach. Thus we can identify three categories of modularization approaches according to their capability in identifying modules in one or more product architectures. Hence, these categories are as follows:

1. Single product
2. Product family
3. Product portfolio

The difference between product family and product portfolio is that a product family consists of a group of related products derived from a common product platform [51]. Whereas, a product portfolio is defined as the sum of all products offered by a company [1] and usually consists of several product families. Variety within a portfolio therefore stands for creating a set of product families, which serve the customer's demands in the best way [20].

Product generation

The development of a new product or product family is time-, effort-intensive and fraught with risk. Thus it is efficient to take future product generations into consideration when developing a new product. By this way changing market requirements can be easier adapted to the products' specification.
Some methods strive to support New Product Development (NPD), whereas a larger number of methods have been introduced to support product reengineering and redesign. Therefore, product generation constitutes a further characteristic to describe the application area of a modularization method. In this research we distinguish between *product reengineering* and *New Product Development.*

Product life-cycle

A challenging yet very important aspect of creating successful products is the product's life-cycle. The consideration of the product life-cycle during the design phase can have a major impact on manufacturing and assembly cost and a major influence on the customers' satisfaction with the product and the product's image. Thereby, the customer's increasing awareness of the environment brings matters of recycling and reusability more and more into focus [38]. Ishii et al. [52] state that modularity in product design impacts every stage of the product life-cycle and modular design can create benefits for many aspects of a product life-cycle such as design, assembly, services and recycling [53]. Therefore, in the context of the classification framework for modularization methods a standardized product life-cycle [54] constitutes the third parameter to characterize the application area of a method. As three parameters are utilized in order to carry out the classification, the framework can be graphically visualized, as shown in Figure 3. Furthermore, Figure 3 provides an overview of the parameters scaling.

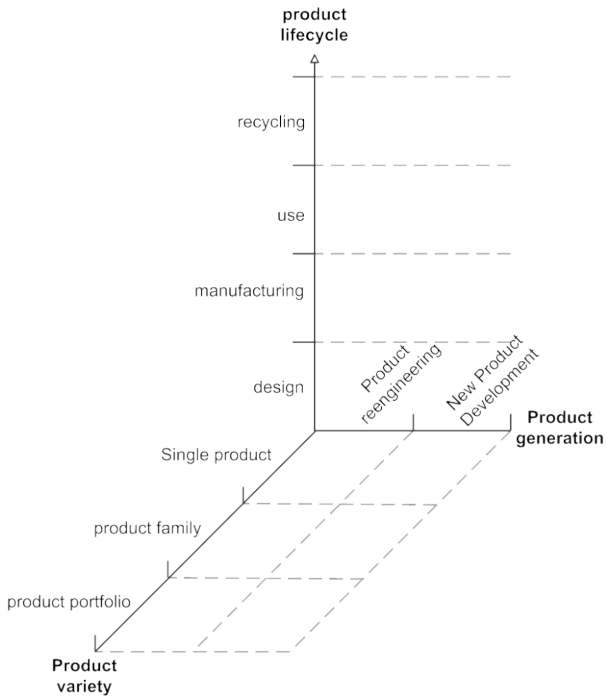

Figure 3. Classification framework for modularization methods.

Finally, further categorization criteria can be used in order to classify modularization methods. For example, the product type – e.g. technical or design product, individual or customized product – might also have an effect on the selection and utilization of a method to modularize a product's architecture. Furthermore, the customer type – e.g. OEM-product or supplier product – can be utilized to classify products and therefore modularization methods. In this research we concentrate on three basic parameters that describe the application area and the goals of a modularization approach. An examination and implementation of further criteria would go beyond the scope of this paper to provide a simple overview. Nevertheless, it would provide a further perspective on the classification and consists an essential future task.

4.2 Categorization of modularization methods

In order to demonstrate the deployment and effectiveness of the classification framework a few modularization methods and approaches are categorized as an example. Important to note is that the information for the classification of the methodologies is acquired from the case studies of the relevant publications. Figure 4 shows the classification of four major modularization methodologies (see Chapter 3) and of a few further developments.

In Figure 4 (a) the application area of *Design for Variety* (DfV) is illustrated. Thereby, Ishii et al. [18] proposed a methodology to capture the broadest customer demands during the development of a product. This methodology is described as *Design for Product Variation* [18]. *Product Variety Deployment* constitutes a further development designed to tackle the simultaneous optimization problem of a product family [21]. In addition, Blees et al. [35] introduce in their work an approach for the utilization of DfV to capture modularization demands from all life-cycle phases of a product.

The *Function Heuristic Method* of Stone et al. [14, 25] is shown in Figure 4 (b) in relation to the dimensions of the classification framework. Furthermore, a development of this methodology is shown that introduces an approach to deploy *Function Heuristics* for portfolio architecture design [20].

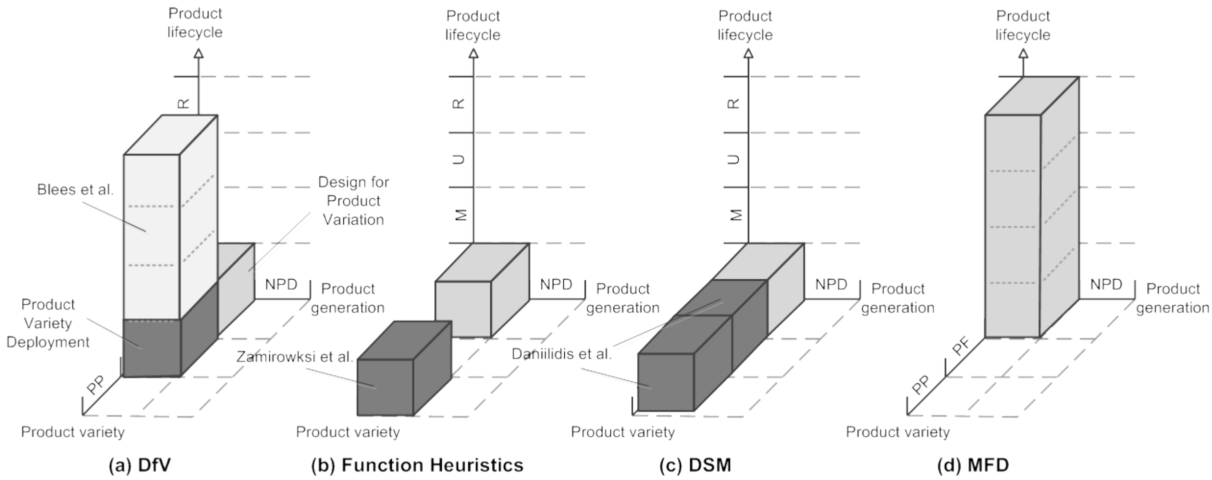

Figure 4. Exemplary categorization of some modularization methods.

Figure 4 (c) illustrates the application area of *Design Structure Matrix* (DSM) as it was introduced by Pimmler et al. [13] to identify modules in a product architecture. Additionally, an approach is shown to utilize DSM for the modularization of product families or for the identification of common modules across a product portfolio [30].

Finally, in Figure 4 (d) *Modular Function Deployment* (MFD) [15] is shown in accordance to the classification framework. Thereby, MFD provides designers and product managers with a holistic modularization potential from a more managerial perspective.

5 CONCLUSION AND FUTURE WORK

This work provides a systematic overview on modularization methods and approaches and on current developments in the field of modularization. A classification framework is introduced in order to enhance transparency and facilitate decision making when a modularization approach is to be deployed for a certain application. Therefore, the application area is utilized as categorization criterion for the classification of different methodologies. Thereby, the application area is explicitly described by three parameters, the *product life-cycle*, the *product generation* and the *product variety,* which constitute the dimensions of the framework. For the purpose of this research an extensive literature survey was carried out in order to identify the major trends on modularization. During this task it became apparent that the three parameters mentioned above constitute consistent characteristics for a homogeneous description of the application area. Each modularization method or approach can be explicitly categorized according these criteria. Thereby, the abstraction level – functional- or component-based methods – on which a modularization method is deployed, is excluded as classification criterion. The reason is that the abstraction level of the method deployment significantly affects the product variety on which a method can be deployed. Hence, one can conclude that functional-based modularization methods possess a wider application area according to the *product variety* dimension of the framework than component-based methods that can be deployed for the optimization of single products. In conclusion the classification of several methods and approaches according to the framework revealed that the three defined dimensions of the framework are adequate to provide a transparent and systematic overview on modularization methods.

Nevertheless, as stated in Chapter 4.2 the information for the classification of the modularization methods was acquired from relevant publications and not from the application of these methods on own product examples. In order to review the current positions of the methods in the framework, the methods must be deployed and utilized using own examples. Thereby, the effectiveness of the methods in relation to the application area needs to be verified. Furthermore, in order to carry out an examination as accurate as possible both end-user and technical products have to be considered and utilized as case studies. Thereby, it is important to note that in most case studies found in the literature only end-user product are used as examples to demonstrate the deployment of a method. In addition, a structured procedure has to be set up in order to facilitate decision making on which method is more adequate for a specific application situation. At this point the examination and realization of further perspectives to the classification using criteria as the product or customer type may be beneficial.

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