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TOOLS SUPPORTING THE DEVELOPMENT OF MODULAR SYSTEMS

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Abstract

Because of the benefits modular systems provide, industrial enterprises are increasingly interested in using them for their products. This paper focuses on the support of the development process of modular systems. The objective is to find out, if the various design phases are sufficiently supported by methods and tools. Thus an overview of methods and tools described in literature is presented relating to the various design phases. In order to reveal which tools are currently used in industrial practice and to discover further needs, a survey was carried out. Because of the insufficient support revealed in the synthesis phase, this phase is considered more detailed. Finally an idea for an approach for the synthesis of modular systems is presented, which takes into account that modular systems are often based on already existing products, completed by newly added functions. One central characteristic of the approach is the interconnected parallel view on structures and modules on different abstraction levels.

Keywords: modularization – product families, complexity, product structure, engineering process, configuration management

1. Introduction

During the last years industrial enterprises have become more and more interested in modular systems, due to the difficulty to bring higher customer orientation and standardized products together. Main benefits from the use of modular systems are lower product costs, less required development time and higher product quality [1]. Besides, the management of product and process complexity has become an important aspect when utilizing modular systems [2]. Although the use of modular systems in product development leads to a remarkable saving of time and effort, the development of a modular system itself is still extremely time consuming and complex.

The objective of this paper is to reveal whether the development support of modular systems is sufficient over the whole development process. In order to answer this question, two steps are made. At first an overview of existing design tools that support the development of modular systems is given. Secondly, the design of modular systems in industrial practice is regarded. Design engineers were asked which tools they used for designing modular systems, where support deficiencies existed and which problems arose during the development process.

In literature, the terms of "modular system" and "product platform" are not used in an unique manner [3]. Furthermore, in practice it is often difficult to classify the product architectures clearly to one of these terms. Due to this problem, this survey does not distinguish between modular systems and product platforms, because the differences are of no importance here.

2. Related work

Modular systems have been considered from several viewpoints and perspectives. Basic classifications of modular systems and modularity are described in [4], [5] and [6]. A comprehensive view of platforms and modularization from the perspective of industrial enterprises is presented in [7]. [8] gives an overview of configuration management. Issues from engineering configuration systems and sales configurators up to knowledge systematization and configuration management principles are considered.

Results of a survey about modularity in use are published in [9]. There, interviews were carried out to collect experiences that five companies made with modularity. The study describes issues associated with modularity. In particular the relation between organization and product structure has been marked as an important subject.

General approaches for designing modular systems are discussed in [2] and [10]. In [5] and [11] steps for the development of modular systems are formulated more detailed. [2] focuses on complexity management. Here, development approaches have been studied considering the aspects of economics and customer requirements as well as visualization and evaluation of the product structure.

Summarizing the related work, literature does not give information about the tools currently applied in industrial practice for the development of modular systems. Besides, none of the approaches in literature takes into consideration explicitly the characteristics of past products for the development of modular systems.

3. Methods

For this research, existing literature was examined as applied method, which was supplemented by questionnaires. Based on the examination of literature, existing design tools and methods supporting the development of modular systems are analyzed. As a main criterion, the tools and methods are classified according to the different design phases they support:

- *Planning*, *Conceptualization and Modularization*, *Synthesis*, *Evaluation and Optimization* as well as *Configuration*.

A second criterion is the type of support. Here, a differentiation between strategies, methods and computer tools is carried out. The used design phase model is based on a serial development approach and does not take simultaneous actions into account. Nevertheless, several of the defined phases may be undertaken simultaneously. For example, the evaluation and optimization phase does not necessarily follow after the synthesis phase. Already in the conceptualization and modularization phase structure-optimizing aspects can be of interest. Additionally, for the synthesis phase concurrent evaluation may be integrated to shorten and reduce needed iteration loops. In order to keep the model clear and easy, the serial approach might be accepted, while keeping the assumption in mind, which does not exclude the possibility of using the parallel or integrated approach.

In order to achieve information about the tools that are currently used in industry for the development of modular systems, questionnaires were utilized. The questionnaires were designed on the basis of open answers. Questions of the questionnaires included, for example:

- "In your opinion, what is the most time consuming activity while developing modular systems?"

- “Which problems have you noticed during the interface design?”

The reason for choosing this type of questionnaires is that a large field of possible answers can be examined more easily in an easier way and non-predictable answers could be obtained. The questionnaires were distributed via e-mail to design engineers, who had been contacted by telephone in advance. The enterprises that took part in the survey are five German small and medium size enterprises as well as globally acting automotive suppliers. The products they supply as modular systems are in some kind related to driving systems. Because of the small number of participating enterprises, reasoning with statistical value is not possible.

4. Results

The results are structured into for parts. First, an overview on existing tools and methods for the development of modular products is given. The second part summarizes the results of a survey about the designing of modular systems. Then the synthesis phase is discussed in detail. Finally, an idea for an approach for the synthesis of modular products is presented.

4.1 Tools and methods for designing modular systems

For the design process of modular systems a lot of different tools and methods are developed. The central question of this contribution is, whether all design phases are sufficiently supported. Therefore, existing design tools are considered. Due to this, tools and methods are categorized in relation to the already named design phase model (Figure 1). As a second criterion the type of support is used. The support types are differentiated between strategies and methods as well as tools that may have the status of computer programs. It should be mentioned, that the given overview does not contain all existing tools and methods. Listed are those, which are regarded to be the most established, completed with some exemplary results of current research. Within the categories of the support type the tools and methods are listed alphabetically and without any hierarchical meaning. On the basis of the two main criteria the following picture can be drawn:

Some of the most established methods for the early phases are MFD™ (Modular Function Development) [12] and VMEA (Variant Mode and Effects Analysis) [13]. While the MFD™ method mainly supports the modularization phase including the clarification of customer requirements, VMEA is more strategically oriented. The VMEA method gives guidance for early variety recognition and avoidance. The software tool MODMAN™ is based on the MFD™ method and contains all major steps of the procedure [12]. To some extend, the Complexity Manager® [13] can be seen as software tool utilizing the VMEA method. It consists of four modules focusing on variety management by graphical representation of the product characteristics and specifications as well as representation through variant trees. Moreover, process management and process cost management are modules of the software system.

Furthermore, two examples of recent and more specific methods for the conceptualization and modularization phase are shown in Figure 1. In [14] an approach to develop a product architecture based on quantitative functional models is described. A series of structured methodologies are summarized under the title of DFV (Design For Variety) [15]. Therein central used indices for measuring the product architecture are the generational variety index measuring the amount of redesign effort and the coupling index as a measure of the amount of coupling among the product components.

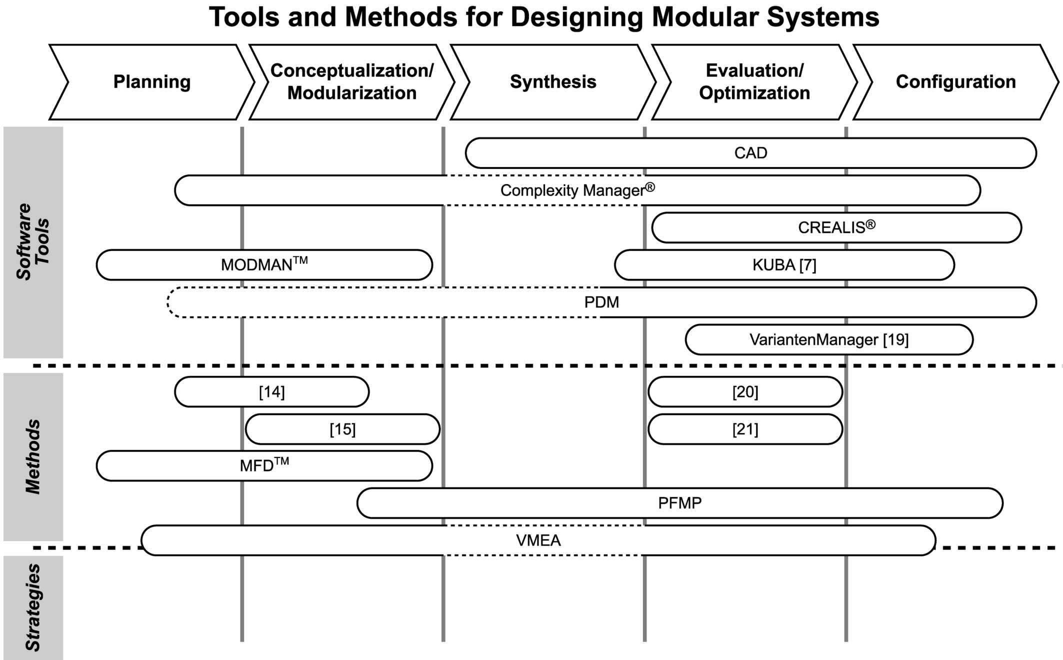

Figure 1. Tools and methods categorized in relation to design phases.

Looking on the late phases, CAD and PDM systems are established tools. The CAD systems [16] already support the creation of modules up to the configuration of products on the basis of the designed modules, whereas PDM systems [17] are restricted mainly to supply with information that becomes more and more detailed during the development phases. For evaluation and optimization the majority of the tools (CREALIS® [18], KUBA [7] and the VariantenManager [19]) use cost based approaches. Besides, the three latter tools support design engineers with representations of variant trees. A method that allows quantifying the value of each single identified design alternative is formulated in [20]. In order to reduce the number of modules for improving the design modularity, an approach is presented in [21], that basically uses compatibility and connection matrices.

A linkage of early and late design phases can be attributed to the PFMP (Product Family Master Plan) [22], a method that helps to represent the structures of modular systems. The PFMP modeling procedure contains five phases with a number of tools. At the beginning the identification of the configuration task and the product family master plan is regarded. An important component of these phases is the function means tree supporting the early phases of modular system development. During the next two phases the conceptual and detailed modeling of the product family master plan is performed. Finally, IT experts realize the model as a configuration system.

Summarizing the results drawn, it can be pointed out that a sufficient support exists for the early phases of planning and conceptualization/modularization as well as for the late phases of evaluation/optimization. However, this does not mean that no more improvements can be made. For the synthesis phase the situation looks different. Even if CAD systems are powerful tools, no specialized methods or tools are known, which help detailing the interfaces and modules design.

4.2 Survey on applied design tools

Aiming to find out which supporting tools and methods currently are used for the design of modular systems, a survey has been carried out. Besides an inquiry about the tools that are applied for designing modular systems, problems that occur during the process as well as time consuming activities and proposed improvements were considered.

The tools used are categorized in relation to the design phases in an analogue way like above-mentioned for existing tools (Figure 2). However, in this case, it is not distinguished between different types of support. The widest applied tools are CAD systems. They are particularly used in the synthesis and evaluation/optimization phase. Besides modules' modeling, geometric checking and tolerance analysis are done with CAD systems. In the configuration phase CAD systems play a dominant role for modeling and visualizing configured design variants.

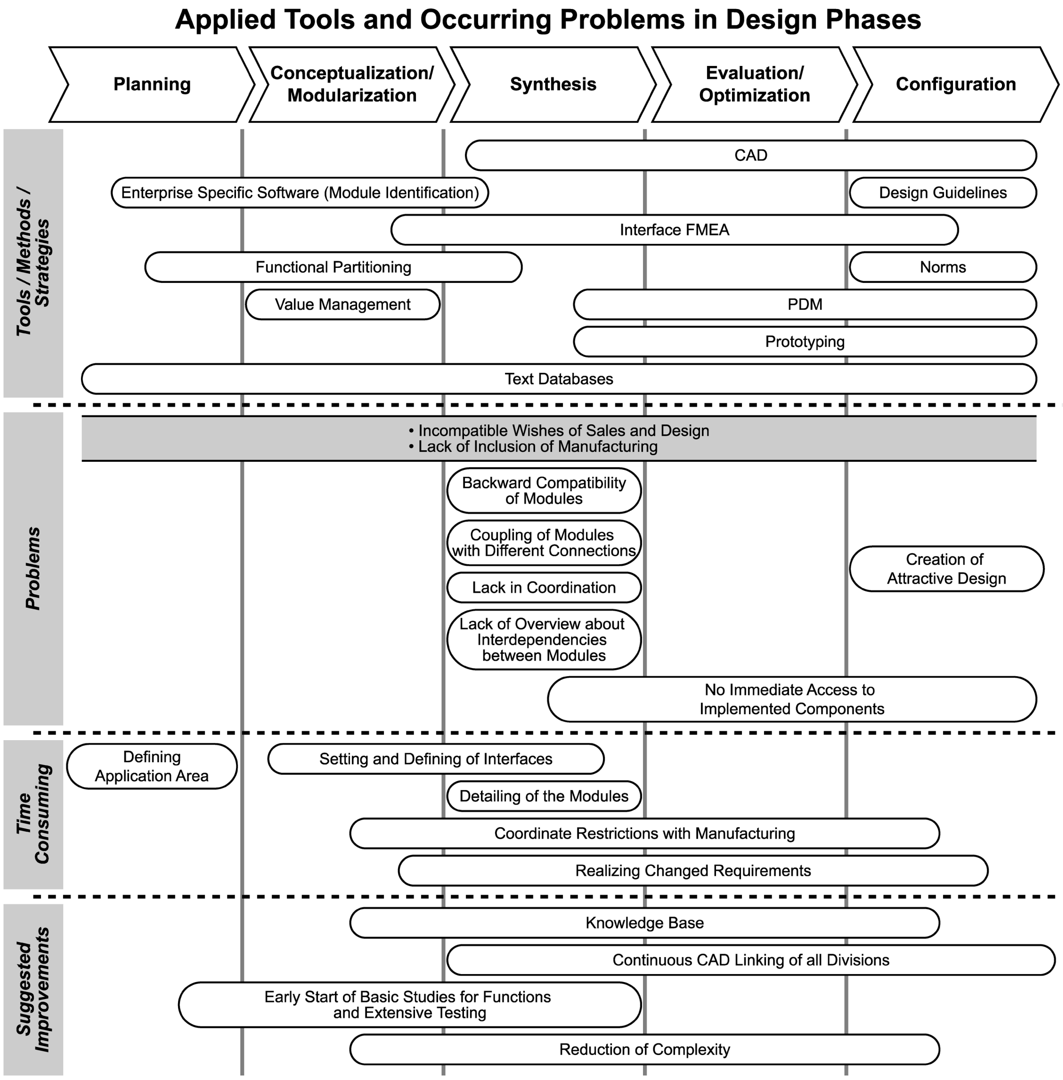

Figure 2. Survey results.

Related to the early phases, enterprise specific software tools as well as functional partitioning and value managing methods are named in the survey. To some extend, text databases are used to store and share design information. From the synthesis phase interface FMEA and prototyping are applied to improve the interface design quality and to validate the designed modules and their compatibility. For managing and coordinating the data of modular systems in the late design phases, PDM systems are common. Regarding the configuration phase, bills of material derivable from PDM systems become important. In order to configurate products based on the created modules, norms and design guidelines are used.

Concerning problems occurring during the development phases, two types of problems arise. The first problem type comprises questions not be clearly associated with the design phases. These are incompatible esthetic design problems or other requirements from the sales department. Furthermore, the lack of inclusion of manufacturing into the design process often causes problems. The second problem type is connected to certain design phases. According to the synthesis phase, backward compatibility of modules with older generations and coupling of modules with different connections causes product related problems. Lack in coordination and overview of the interdependencies between modules hinder the development process and an easy solution finding. A special problem of the configuration phase is that an attractive design has to be created with standardized modules. Furthermore, no immediate access to already implemented modules leads to problems in the development process.

As most time consuming actions in the early development phases, the definition of the application area as well as the setting and defining of the interfaces are named by design engineers. Additionally, the detailing of the modules is considered as one of the most time consuming tasks. Two more or less phase independent aspects are the coordination of restrictions with manufacturing as well as the handling and realization of changed design requirements in established modular systems.

Suggested improvements are the use of a comprehensive knowledge base for several design phases and continuous CAD linking of all relevant divisions. Moreover, an early start of basic studies about used functions and extensive testing as well as complexity reduction were proposed to improve the development process of modular systems.

Finally, some additional aspects, observed through the survey, will be mentioned. Enterprises dealing with modular systems that have grown over a long term (several years or decades) do not see problems with the synthesis phase of modular products. In contrast, enterprises acting in markets with short product cycles and short predefined development time, as e.g. in the automotive sector, want to get more control on the design process. Particularly the synthesis phase containing the interface and module design is regarded as not well supported.

4.3 Synthesis phase of modular systems

Due to the results of the overview on existing tools and the presented survey this part focuses more detailed on the synthesis phase. A central task of the synthesis phase is the transformation of modularized structures as results from the conceptualization phase into modules, which ideally should fulfill all requirements. The synthesis phase of modular systems can be considered to have two aspects; on the one hand the design of suitable interfaces and on the other hand the design of the modules inside.

In [23] the interfaces are regarded to be a core issue when designing modular products. Many benefits of modular products like the ability of parallel development or the ability to create variants by changing modules cannot be utilized, if the interfaces are poorly designed.

For the synthesizing phase no specialized tools or methods were found that take all the specific demands into account, due to the module details. In general, classical design methodology like described in [5] can be applied to some degree for this phase, particularly for designing the interior of the modules. However, problems occur, where the inside of the modules are coupled through the interfaces with other modules. Even if modularity is used to reduce the complexity and the dependencies within the products, the constraints related to the interfaces of the various modules can lead quickly to unclear interrelations. Therefore, the mostly used method for interface designing is "trial and error", which needs many iterations [24], since almost only small changes are appropriate to avoid uncontrollable consequences to other linked modules.

In order to support design engineers to keep the overview, several approaches seem to be useful. As a more extensive method the PFMP [22] can be applied. Through the functions means tree and the product family master plan itself, structures and relations within modular systems can be made obvious. An alternative approach is suggested by [25] that includes interactions between functions, mapping from functions to physical chunks and physical attachment of the chunks. The use of the functional level and flows to represent interrelations is described in [26]. A generic approach for the representation of interface relations is published by [27].

A dilemma of modular systems that was also referred to the survey is their comparative "static" feature. It is often quite difficult or impossible to make changes. This requires a wide redesign of the modular system. In order to reduce the number of necessary redesigns, interface design that is stable over time and robust to variation is a crucial part of modularization projects [28]. The interfaces should be designed with potential for future needs [29]. Another possibility could be the use of strategies that support the design of "dynamic" modular systems. Such strategies should help to minimize the efforts for redesigning that are necessary to fulfill the changed or extended requirements. Design modifications have to be found, which allow achieving the desired changes, without simultaneously destroying the systematic of the modular system.

4.4 Approach for a framework

The outcome of the study shows the need to support the synthesis phase of modular systems. Due to this fact, the following approach has been formulated by the authors. It has to be mentioned that this approach is not yet completed, but presented as a basis for discussion. Figure 3 offers a simplified image of the suggested design approach.

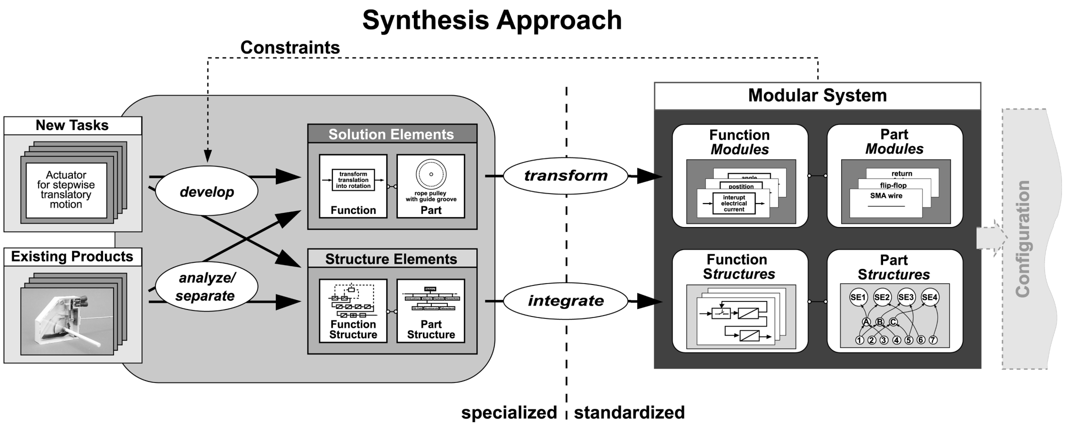

Figure 3. Synthesis of modular systems using solution and structure elements.

The approach is characterized by an intermediate step with a simultaneous view on solution and structure elements. According to [30], where the utilization of different abstraction levels linked to each other has been considered for product modeling, the solution and structure elements are described on a functional and part level.

As an input to the development process, new tasks as well as existing solutions can be used. In case of new tasks it is necessary to develop solution and structure elements. If a modular system or fractions of it already exist, its modules and structures should be considered. The solution elements are described on functional and part level. In an analogous way, the structure elements consist of functional and part structures. If existing products shall also be included into the development of the modular system, these get analyzed on functional and part level. As a next step, the resulted functional and constructional interrelationship is separated into the solution and structure elements.

In order to achieve the use of the solution and structure elements within a modular system, they are processed from their specialized characteristic into a standardized design for a modular system. The solution elements will be transformed into standardized function and part modules with unified interfaces. Furthermore, the structure elements are combined or integrated into the structure variants of the modular system as function structures and part structures. In a subsequent step the modular system can be used for the configuration of products.

5. Conclusions

For the development of modular systems several tools and methods are available which support the process of the planning and conceptualization phase as tools that help to evaluate and manage the configuration of modular products. The support during the synthesis phase is still insufficient. Here modules, defined on functional level, have to be transferred into parts with modular properties. Although some methods that improve the transparency already exist, it is still difficult to design the interfaces without losing the perspective for the depending module interrelations. A systematic approach for designing the module interfaces that may also contain design rules and guidelines, is needed. Moreover, one should mention that today the connections between the influencing factors of module interfaces are not clearly understood.

Due to the fact that the presented survey is only based on five participating enterprises, the universality of the results is not ensured. Nevertheless, some general tendencies could be revealed. A problem that has been named repeatedly is the difficulty of creating attractive esthetic design using standardized modules. Additionally, the static characteristic of modular systems that often needs big efforts to realize changes in established systems seems to be an important issue. Even if commercial tools for supporting communication in design processes are available, the lack in information distribution and coordination is obvious.

This approach can be seen as a framework for a tool for the synthesis of modular systems. The separated view on structures and modules can help to increase the transparency. Furthermore the design of module interfaces is supported through information available on different abstraction levels. Due to the benefits of design reuse [31] the inclusion of existing design, as an input for the design of modular systems seems to be an important aspect. One essential question related to this approach is if a sufficient linking between modules and structures can be ensured. Before a final evaluation with a prediction of its ability can be done, the approach has to be detailed further. The support of processing new tasks into modular systems should be improved. Additionally, next steps could comprise the integration of powerful methods which already exist, especially from relation representation and complexity managing. Further benefits could be achieved by integrating evaluation and optimization tools.

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References

[1] Meyer, M.H. and Lehnerd, A.P., "The Power of Product Platforms: Building Value and Cost Leadership", The Free Press, New York, 1997.

[2] Blackenfelt, M., "Managing Complexity by Product Modularisation: Balancing the Aspects of Technology and Business During Design Process", Doctoral Thesis, Royal Institute of Technology (KTH), Stockholm, 2001.

[3] Tichem, M., Andreasen, M.M and Riitahuhta, A., "Design of Product Families", Proceedings of ICED '99, Munich, 1999, pp.1039-1042.

[4] Koller, R., "Konstruktionslehre für den Maschinenbau: Grundlagen zur Neu- und Weiterentwicklung technischer Produkte mit Beispielen", Springer, Berlin, 1998.

[5] Pahl, G. and Beitz, W., "Engineering Design – A Systematic Approach", Springer, London, 1996.

[6] Ulrich, K., "The role of product architecture in the manufacturing firm", Research Policy, Vol. 24, 1995, pp. 419-440.

[7] Andreasen, M.M., McAloone, T. and Mortensen, N.H., "Multi-Product Development – Platforms and Modularisation", Working Report, Department of Mechanical Engineering (MEK), Technical University of Denmark, 2001.

[8] Riitahuhta A., "View and Experiences of Configuration Management", Proc. 5th WDK Workshop of Product Structuring, Tampere, 2000, pp.1-21.

[9] Stake, R.B. and Blackenfelt, M., "Modularity in Use – Experiences from Five Companies", Proceedings of 4th WDK Workshop on Product Structuring, Delft, 1998, pp.11-25.

[10] Kohlhase, N. and Birkhofer, H., "Development of Modular Structures; The Prerequisite for Successful Modular Products", Journal of Engineering Design, Vol. 4, No. 3, 1996, pp.279-291.

[11] Ehrlenspiel, K., "Integrierte Produktentwicklung: Methoden für die Prozessorganisation, Produkterstellung und Konstruktion", Hanser, München, 1995.

[12] Erixon, G., "Modular Function Deployment – A Method for Product Modularization", Doctoral Thesis, Royal Institute of Technology (KTH), Stockholm, 1998.

[13] Schuh, G. and Schwenk, U., "Produktkomplexität Managen: Strategien, Methoden, Tools", Hanser, München, 2001.

[14] Stone, R.B., Wood, K.L. and Crawford, R.H., "Using Quantitative Functional Models to Develop Product Architectures", Design Studies, 21, 1999, pp.239-269.

[15] Martin, M.V. and Ishii, K., "Design for Variety: Developing Standardized and Modularized Product Platform Architectures", Research in Engineering Design, 13, 2002, pp.213-235.

[16] Lashin, G., "Baukastensystem für Modulare Straßenbahnfahrzeuge", Konstruktion, No. 1/2, 2000, pp.61-66.

[17] Vainio-Mattila, M., "Report on Using Product Data Management Software in Managing Modular Products", Proceedings of 5th WDK Workshop of Product Structuring, Tampere, 2000, pp.63-78.

[18] Elsner, G., Krüger, M.M. and Uhl, H., "Management variantenreicher Systemprodukte mit CREALIS - Baukästen, Konfiguration, LifeCycle Costs", VDI-Berichte, No.1645, 2001, pp.139-150.

[19] Hauck, C., Puri, W., Ehinger, G. et al., "Komplexitätsmanagement", in: Krause, F.-L.T., Tang, T. and Ahle, U., (Eds), Leitprojekt: integrierte Virtuelle Produktentstehung, Fraunhofer IRB, Stuttgart, 2002.

[20] Gonzales-Zugasti, J.P., Otto, K.N. and Baker, J.D., "Assessing Value in Platformed Product Family Design", Research in Engineering Design, Vol. 13, 2001, pp.30-41.

[21] Stewart, L.C., McIntosh, M.W., Bras, B. and Rosen, D.W., "Identification of Limiting Factors for Improving Design Modularity", Proceedings of ASME DETC98, Atlanta, 1998, DETC98/DTM-5659.

[22] Mortensen, N.H., Andreasen, M.M. and Harlou, U., "Conceptual Modeling of Product Families in Configuration Projects", Proceedings of 11th Symposium "Design For X", Schneitach, 2000.

[23] Stake R., "On Conceptual Development of Modular Products: Development of Supporting Tools for the Modularisation Process", Doctoral Thesis, Royal Institute of Technology (KTH), Stockholm, 2000.

[24] Smith, J.S., Robb, M.D., Duffy, A.H.B., Thomson, A. and Nisbet, C., "An Experience of Modularity Through Design", Proceedings of ICED '01, Glasgow, 2001, pp.467-474.

[25] Oosterman, B.J., Gaalman, G.J.C. and Kuijpers, F.P.J., "Visualizing Interdependencies in Technical Design", Proceedings of 5th WDK Workshop of Product Structuring, Tampere, 2000, pp.63-78.

[26] Stone, R., "Towards a Theory of Modular Design", Doctoral Thesis, University of Texas at Austin, Austin, 1997.

[27] Stake R., "A Generic Information Platform for Product Families", Doctoral Thesis, Royal Institute of Technology (KTH), Stockholm, 2000.

[28] Blackenfelt, M., "On the Development of Modular Mechatronic Products", Licentiate Thesis, Royal Institute of Technology (KTH), Stockholm, 1999.

[29] Blackenfelt, M. and. Sellgren, U., "Design of Robust Interfaces in Modular Products", Proceedings of ASME DETC00, Baltimore, 2000, DETC00/DAC-14486.

[30] Lippold, C., "Eine domänenübergreifende Konzeptionsumgebung für die Entwicklung mechatronischer Systeme", Doctoral Thesis, Institute of Engineering Design, Ruhr-University Bochum, Bochum, 2001.

[31] Duffy, A.H.B. and Ferens, A.F., "An Analysis of Design Reuse Benefits", Proc. ICED '99, Munich, 1999, pp.799-804.

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