ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

AN ASSESSMENT OF METHODICAL APPROACHES TO SUPPORT THE DEVELOPMENT OF MODULAR PRODUCT FAMILIES

Dieter KRAUSE, Sebastian RIPPERDA
Hamburg University of Technology, Germany

ABSTRACT

Global competition and the trend to individualized products force companies to lower their internal variety, which can be achieved through modular product structures. The literature comprises a wide range of approaches to support the development of modular product families. A selection of significant methods are investigated and evaluated. The method Integrated PKT-Approach for Developing Modular Product Families developed at the Institute of Product Development and Mechanical Engineering Design (PKT) is also characterized. This approach was developed based on the existing literature and approaches and further experience from industrial practice. It integrates aspects of design for variety with technical-functional and product-strategic modularization methods. The methodical approach, as well as its relevance and development, is explained in addition to the literature review.

Keywords: design for X, integrated product development, product architecture, product families, product structuring

Contact:
Sebastian Ripperda
Hamburg University of Technology
Institute of Product Development and Mechanical Engineering Design
Hamburg
21073
Germany
sebastian.ripperda@tuhh.de

1 INTRODUCTION

In product development modular product structures can address the challenges of global competition and support the development of individualized products (Krause et al., 2011). They enable companies to offer customized products at reasonable prices.

The literature provides a number of approaches for supporting the development of modular product structures in order to achieve high variety for the customer with small internal variety for the company and to cope, reduce or avoid complexity related to the development of highly modular products. Thus, higher volumes are produced in standard modules, which in turn achieve a cost reduction through economies of scale, particularly for purchase, manufacturing and assembly. Another effect of modular products is that processes can be parallelized, such as separate testing or parallel production.

This paper characterizes a selection of significant methods for supporting the development of modular product families, using relevant criteria, and outlines them. Firstly, the relevant criteria are deduced from literature and project experience. Based on these criteria, significant approaches that resulted from work in this field of research are characterized. The method *Integrated PKT-Approach* for Developing Modular Product Families developed at the *Institute of Product Development and Mechanical Engineering Design (PKT)* is also characterized. This approach was developed based on existing literature and approaches and has improved and expanded them. The aim of this methodical approach, its relevance and the main influences of other approaches are explained.

2 RELEVANT CRITERIA FOR METHODOLOGIES DEVELOPING MODULAR PRODUCT FAMILIES

During assessment of methodologies for supporting the development of modular product families and research on this topic, a number of criteria were identified from the literature which every approach should consider to reach an optimal product family. Based on this, these criteria could be confirmed by experiences from ten modularization projects and completed by further criteria. Among the criteria from the literature are the considerations of *product variety*, *technical-functional modularization*, *product-strategic modularization*, *product program view* and *concept evaluation*. Projects resulted in the need for the criteria *product-related visualization*, *redesign for modularization*, *integration of interdisciplinary expertise*, *guideline*, *tailored to corporate situation*, *usability in corporate context*, consideration of *process and company structures* and *costs*.

The first criterion, consideration of *product variety*, describes that a method applies not only to a single product, but also takes into account variants of the product or a whole product family. The next two criteria ask whether there is a *technical-functional modularization* (e.g. Stone, 1997) or a *product-strategic modularization* (e.g. Erixon, 1998). The following criterion, *product-related visualization* qualifies whether the approach works with an illustration of the product (e.g. sketched geometry, cad drawing, etc.) and the existing flows in the product (energy, materials, etc.). *Redesign for modularization* addresses the redesign of the product for modularization. Specification of improvement activities must be named. A grouping of components into modules without design changes does not count as redesign. The applicability of the method in a workshop is summarized under the criterion *integration of interdisciplinary expertise*. The criterion *guideline* requires specification of the methodical work to be performed in the individual steps of the method and an accurate description of every single step. The adjustment of the approach to the company situation is represented in the criterion *tailored to corporate situation*. This criterion is also measured in the range of the industries/products and the number of successful applications in the described case studies. Another criterion is *usability in corporate context*, which estimates the daily usability/applicability of the method in the company by employees in the context of average qualifications. *Product program view* intends to include the entire product program in the method. The consideration of *process and company structures* treats the organizational structure and supply chain management, and *costs* focuses on complexity costs caused by product/process complexity. A qualitative and/or quantitative *concept evaluation* of the optimized product in comparison with the starting product should be conducted (e.g. key figures).

3 CHARACTERIZATION OF DESIGN METHODOLOGIES

The purpose of this characterization is to give a complete overview of relevant approaches supporting the development of modular product families.

Table 1 shows the overview of relevant methodical approaches for supporting the development of modular product families ordered by the year they were published.

Table 1. Comparison of the characterized sources

	methodologies															
	Caesar	Pimmler/Eppinger	Ulrich/Eppinger	Kusiak/Huang	Stone	Göpfert	Erixon	Jiao	Martin/Ishii	Schuh	Simpson	Hölttä-Otto	Harlou/Mortensen	Pahl/Beitz	Lindemann	Krause
year	1991	1994	1995	1996	1997	1998	1998	1999	2002	2005	2005	2005	2006	2007	2009	2011
criteria																
product variety	●	○	◑	◑	●	○	◑	●	●	●	●	○	●	◑	○	●
technical-functional modularization	○	●	●	●	●	●	○	●	●	○	●	●	●	●	●	●
product strategic modularization	◑	◑	◑	○	○	◑	●	●	◑	◑	○	○	●	○	◑	●
product-related visualization	○	○	○	●	◑	●	◑	◑	○	○	○	◑	◑	●	◑	●
redesign for modularization	●	○	○	○	◑	○	◑	○	●	●	◑	○	●	◑	◑	●
integration of interdisciplinary expertise	●	◑	●	○	◑	●	●	◑	○	●	◑	○	●	◑	◑	●
guideline	●	●	◑	◑	●	●	●	○	●	◑	●	●	◑	◑	●	●
tailored to corporate situation	●	●	◑	○	●	●	●	○	◑	●	●	○	●	●	●	◑
usability in corporate context	●	●	●	●	●	●	●	○	◑	●	◑	◑	◑	●	●	●
product program view	○	○	◑	○	○	◑	◑	●	○	◑	○	◑	◑	○	○	○
process and company structures	◑	●	●	○	○	●	●	●	○	◑	○	○	●	○	●	○
costs	●	○	●	◑	◑	○	●	●	○	●	○	○	●	◑	○	○
concept evaluation	●	○	●	○	●	●	●	●	○	●	●	●	●	●	○	◑

○ not/weakly considered
◑ partially considered
● mainly considered

The columns list the selected methodologies which contribute to the development of modular product families. The lines list the criteria described in Section 2. Each criterion of the methodologies is classified into three categories: not/weakly considered, partially considered and mainly considered.

Variant Mode and Effect Analysis – Caesar

Variant Mode and Effect Analysis (VMEA) provides a cost-oriented design methodology for variant series products that supports an appropriate definition of diversity and an optimal design of individual parts and assemblies diversity (Caesar, 1991). The VMEA uses the variant tree according to Schuh (Schuh, 1989) within an iterative approach that involves the four steps market-oriented identification and design of product functions, deriving the design alternatives, evaluating the alternatives and lean distribution of complex products. The variant tree is used as an analytical instrument and for visualization of the diversity. It represents the diversity on the horizontal and the assembly sequence on the vertical. The tree provides a forecast of the variety of parts, assemblies and product level independent of the construction progress of the product. The VMEA provides ten measures for assistance to structure and design the components particularly for an optimized assembly process. However, the method does not offer extensive support of variant-design at all stages of product development.

Design Structure Matrix – Pimmler/Eppinger

The Design Structure Matrix (DSM) can accommodate couplings between the various elements of a system with the aim of deriving reasonable modules based on these interactions. Pimmler/Eppinger (Pimmler et al., 1994; Eppinger et al., 2012) proposes to use the DSM to design the product architecture by the interfaces of the components. An organizational structure is derived by analysis of the interactions related to the communication of the considered departments, teams and individuals, for example. For the derivation of a process structure, for example, activities can be analysed. In the MDM (Lindemann et al., 2009), different matrices can be merged. The DSM is a well-established tool for modularizing according technical-functional correlations. With the addition of organizations and processes it also partially covers product strategic module drivers. However, the DSM does not focus on handling variety nor derives direct measures for the direct design of the product.

Product development – Ulrich/Eppinger
Ulrich/Eppinger (Ulrich et al., 1995) describes an overall approach for product design and development, although no complex products are addressed in the examples. It addresses and defines a high variety of product development issues, such as processes/organization, product planning, customer requirements and specifications, ideation and evaluation, basics of product architecture, industrial design and business fundamentals. Basics of modularization such as bus and slot modularity are defined; however, a broad discussion for a modularization procedure is not given.

Development of Modular Products – Kusiak/Huang
Kusiak/Huang describes a mathematical approach for the development of modular products (Kusiak et al., 1996). Two matrices - the functional requirements and the design parameters of the products - are composed, which are connected via an interaction graph. Via permutation algorithms and simultaneous exchange a compatibility matrix is formed, from which modules can be derived. In addition to the mathematical procedure for technical and functional modularization, a suitable product-related visualization called the interaction graph is provided.

Towards a Theory of Modular Design – Stone
Stone provides an approach to modularization at the functional level (Stone, 1997). It uses a further development of the sales-oriented functional structure (Pahl et al., 2007) and constitutes functional modules based on these. The approach gives a list of designations for functions and flows, allowing division into different levels. The flows are divided between the functions in the categories material, signal and energy flow. The hierarchical arrangement of the functions can thus be shown. In the sales-oriented function structure, the flow of energy, material and information is drawn between the functions and then sorted. Central to the modularization approach are three heuristics by which modules are identified in the functional structures. The heuristics are based on the dominant flow, branching flow and the conversion transmission functions. Each of these heuristics provides one functional module concept per functional structure. The generated function module concepts are then combined by each heuristic and functional structure to form a comprehensive functional module concept. In the next step, customer requirements are involved by priority ranking to the functions and flows and by a prediction about the usefulness of the resulting functional modules. Finally, the identified functional modules will be compared with the existing functional modules.

METUS – Göpfert
METUS describes a method of common modular design of the product and the organization (Göpfert, 1998). The aim of METUS is to harmonize the modular design of the products and the organizational structure of the company. For the products, alternative product architectures are developed, technically evaluated and improved. Subsequently, alternative forms of project organization are created and evaluated using an overall technical-organizational evaluation. A Key tool for performing the modularization is a route-like visualization. On the left side of this route, the product idea is hierarchically fragmented in functions (function structure in tree form). On the right side of the route, sub-functions are assigned to components, which in turn are merged to modules and to the product itself (building structure in tree form). An organizational unit is responsible for each of the modules, so that the linkages between product architecture and project organization can be illustrated. Göpfert provides no tools or guideline for module formation for products and focuses mainly on the adjustment of product structure and organization structure. For this purpose a software application is available.

Modular Function Deployment – Erixon
The method Modular Function Deployment (MDF) (Erixon, 1998) describes a continuous method for developing new modular products that considers product strategic aspects. MDF begins with clarification of customer requirements using a custom Quality Function Deployment. Subsequently, the features of the product are defined (functional structure), and, based on this, technical solutions are chosen. Central to the method is the Module Indication Matrix (MIM). In this matrix, the partial

functions, including the chosen technical solutions, are evaluated for certain criteria and modularization modules are then derived. Erixon defines these criteria as Module Driver (e.g. separate testing of functions), which he allocates to the categories product development and design, variety, production, quality, purchasing and after-sales. To assist the module driver evaluated components, components can be identified that should form a single module, or the base for a module. Then similar evaluated components can be integrated to form one module. In the final step, the individual modules are designed where a reference is made to the existing methods. Using the module drivers and the Modules Indication Matrix, Erixon provides a method that allows a reasonable product modularization based on strategic reasons. Technical and functional couplings are not considered specifically.

Developing Product Family Architecture – Jiao

The approach of Jiao (Jiao et al., 1999) for developing a Product Family Architecture (PFA) generates three similar views on product family design. The development starts with functional modelling based on a customer requirement analysis. This is followed by a collection and analysis of demanded data, during which a customer grouping, functional classification for each customer group and a determination of target functional requirement values are carried out. The first phase is completed with the representation of the functional view of a product family in the form of a combined decomposition/classification tree. In the second phase, the technical modelling is based on modularizing technological solutions. For this purpose, the design parameters are first formulated. Then a design matrix is used which maps the functional requirements to design parameters. The blocks in the matrix, formed by an algorithm, represent the design modules. In the third and final phase, a physical modelling through economic evaluation of physical modules is carried out. Therefore the performance of physical module candidates will be measured. Firstly, the utility of a product attribute which describes the functional performance of the physical module is estimated. Secondly, the cost of physical modules is gauged. Both factors, utility and cost, result in the economic evaluation of building blocks. After a characterization of the economic value, the configuration structure for each product family is established, leading to the derivation of the bill of material.

Design for Variety – Martin/Ishii

The Design for Variety by Martin/Ishii (Martin et al., 2002) is a comprehensible approach to assessing the technical coupling strength of components as well as planned future changes and to finally derive long-term stable platforms. To do this, the structure and design of the product is considered. In the first step, the Generational Variety Index (GVI) is determined, which expresses the likely effort of necessary adjustments in the event of changes in components. In the second step, the coupling strengths of all components are determined using the Coupling Index (CI), which expresses the sensitivities of the components to changes in the connecting flow (energy, materials, etc.). Using GVI and CI, the components are assigned to concrete guidance for standardization and modularization. These are the changes in the allocation structure between functions and components, freezing a specification, reducing internal couplings and oversizing of components.

Produktkomplexität managen - Schuh

The approach *Produktkomplexität managen* (Schuh, 2005) - pursued in the management of complexity - the basic ideas:

1. Complexity should be understood holistically. To do this, all relationships between the strategy of the company, the product structure and the measures of complexity management should be recognizable.
2. The product complexity is the cause of corporate complexity and has priority.
3. Complexity management should be approached using a proven method toolbox. Here, a support consultant is more important than the scientific discourse or a theoretical derivation.

Schuh used the method VMEA for the design of diverse product families. So he mainly considers a product strategic modularization by assembly order with a focus on evaluation of costs.

Approach to Product Family Design – Simpson

Simpson provides an approach (Simpson et al., 2012) with the aim of allowing an optimal degree of commonality in product family development. For this purpose he used the Platform Planning Process presented by Robertson and Ulrich (Robertson et al., 1998) as a methodological framework in which

he embeds the methods of other authors, such as the Design Structure Matrix DSM (Browning, 2001; Eppinger et al. 2012), the Generational Variety Index GVI (Martin et al., 2002), multi-objective optimization and multi-dimensional data visualization. Depending on demand, other alternative methods can be embedded.
The focus of this integrated approach is the mathematical determination of optimum parameters of the variant components (e.g. battery storage, dimension and potential). The fundamental functional and component structure is not questioned here. The results of the mathematical optimization are evaluated by Product Family Penalty Function (PFPF) so that an optimal set of parameters can be selected. The integrated approach to product family design provides no cost-based evaluation. Methodological building blocks for cost-based evaluation were published separately (Park et al., 2006).

Modularizing Product Architectures Using Dendograms – Hölttä-Otto
Hölttä-Otto and Otto developed a performance measurement system to derive and evaluate product platforms already in the design phase (Hölttä-Otto et al., 2003; Hölttä-Otto, 2005; Hölttä-Otto, 2006). This is mainly based on the assessment of similarities of input and output values of individual functions and the similarities of the technical components. Additionally, Hölttä-Otto defined 19 key figures and assigned them to the fields of customer satisfaction, diversity of products, after-sales, organization, flexibility, change and development complexity. Similar to the evaluation process of Erixon (Erixon, 1998), the approach of Hölttä-Otto et al. is to apply a variety of aspects in the assessment and therefore large effort is required to capture the individual figures.

Product Family Masterplan – Harlou/Mortensen
Harlou described the development of product families based on modular product architectures (Harlou, 2006). The architecture, beside the building principle, depicts the structure of product families over time. Thus an architecture prescribes how components are to be reused in different products. A platform is the physical implementation and the reusable realization of an architecture. There is a distinction between reused elements, the standard designs, and non-reused elements, the design units. It is shown how processes and systems can be simplified by reusing the way products are developed and the use of standard designs. The work is based on the theories of artefact, the theory of technical systems and the theory of domains. In addition to the theoretical considerations, two tools are presented: the generic body diagram and the Product Family Master Plan (PFMP). The Generic Diagram organ supports the development of the structure and interfaces of an architecture. The PFMP is used to support the development of product families and variety in product families in particular. The industrial benefits of the two tools and theoretical contributions have been evaluated by several applications in industry.

Structural Complexity Management – Lindemann
The modularization in Structural Complexity Management by Lindemann et al. is based on the Multiple-Domain Matrix (MDM), consisting of multiple DSMs and domain mapping matrices (DMM) (Lindemann et al., 2009). The procedure is divided into five main steps. The starting point is a system definition of complex product structures. For this purpose, the domains components, functions, features and production constraints and their dependencies are determined. The second step provides information on the relationship between the elements and is carried out in workshops. In the third step, indirect relationships are determined. In addition to the matrix of the direct coupling of the geometric components, matrices are placed that represent the secondary, indirect coupling of components. In the subsequent structure analysis the module formation is done by a cluster analysis. Depending on the pre-established matrices, the functional coupling of the various components is taken into account, as well as the cluster analysis for direct geometric coupling and coupling via features. Finally, the results of the feasibility analysis (product design application) are examined with the help of experts. The procedure according to Lindemann et al. has the advantage of a very broad applicability and extensibility of the approach to additional domains. However, an explicit consideration of variety is not addressed. In addition, for the application of MDM, the computer-aided analysis for the user is difficult to trace, which may weaken the acceptance of the results.

Size Ranges and Modular Products – Pahl/Beitz
Pahl/Beitz considers modular systems in relation to the development of modular product families (Pahl and Beitz, 2007). The method is fundamentally based on the VDI 2221. In this method the criterion for the selection of modules is the estimation of which costs affect the individual modules of the entire product families. Detailed procedure steps within the step of selecting and evaluating are non-existent. The other points in the procedure are the same in VDI 2221, but this method is not limited to the creation of modular products. Pahl/Beitz conveys the basics of VDI 2221 for modular product development.

Integrated PKT-Approach – Krause
The *Integrated PKT-Approach* for Developing Modular Product Families (Krause et al., 2011) consists of the two major methods *Design for Variety* and *Life Phases Modularization*. It pursues the objective of reducing internal variety for the company and offering optimized external variety for the customer. A description of the approach, its relevance and progress follows in the next section.

4 INTEGRATED PKT-APPROACH FOR DEVELOPING MODULAR PRODUCT FAMILIES

The *Integrated PKT-Approach* for Developing Modular Product Families (Krause et al., 2011) was developed at the Institute PKT at Hamburg University of Technology by learning the strength and weaknesses of the introduced approaches combined with industry project experience. Five aims evolved for reducing the internal variety:
• Combining the product-oriented view with the process-oriented view of product variety
• Integrating technical-functional and product-strategic module drivers along the product life phases
• Redesign of components to enable a variety-optimized product structure
• Fostering team discussion and integration of experts by specific product family related visualizations
• Support for reducing variety tailored to corporate needs.
The *Integrated PKT-Approach* consists of several method units (Figure 1).

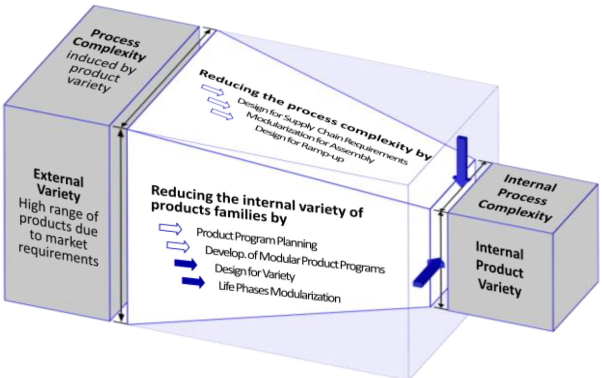

Figure 1. Research motivation and goals of the Integrated PKT-Approach (Brosch et al., 2012)

The fundamental method units *Design for Variety* and *Life Phases Modularization* are described below. Other method units are currently under development. *Product Program Planning* and the *Development of Modular Product Programs* expand the approach to a program-wide consideration. The method units *Design for Supply Chain Requirements*, *Modularization for Assembly* and *Design for Ramp-up* address process complexity.

4.1 Design for Variety

Design for Variety (Blees et al., 2010; Kipp et al., 2010) formulated four aims to converge product families to an ideal of a variety-oriented product structure derived from the literature:
• Clear differentiation between standard components and variant components
• Reduction of the variant components to the carrier of differentiating properties
• One-to-one mapping between differentiating properties and variant components
• Minimal degree of coupling of variant components to other components.

In the first step of the method, the external market-based and internal company varieties of the product family are analysed. For this purpose a Tree of External Variety (TEV) (Figure 2) is used to visualize the selection process of the customer by linking variant product properties relevant to customers and the offered product variants.

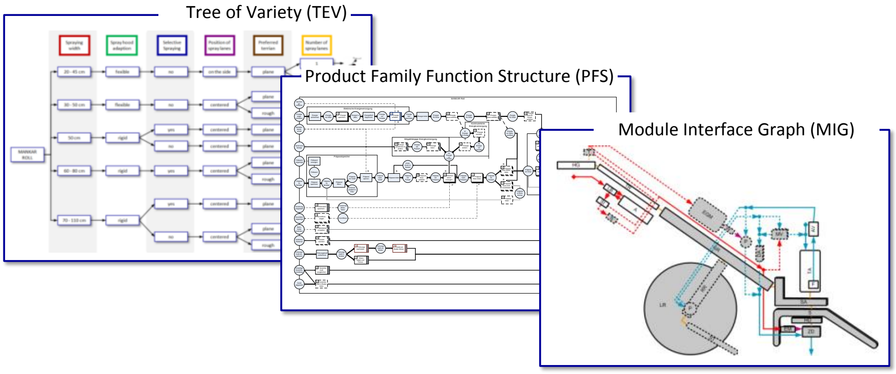

Figure 2. Tools for the analysis of product variety (Brosch et al., 2012)

Internal variety is analysed at the levels of functions, working principles and components. The Product Family Functional structure (PFS) (Figure 2) shows the variety of functions and also has the option to represent variant and optional functions. The variety of components and connecting flows can be visualized and analysed with the Module Interface Graph (MIG) (Figure 2). The information from these graphs is used in distinct ways in the methodical units of the *Integrated PKT-Approach*. In Design for Variety the three graphs are merged into the Variety Allocation Model (VAM). The allocations between differentiating properties, functions, working principles and components are visualized by connections between the four levels of the VAM. The degree of fulfilment of the ideal of a variety-oriented product structure described previously can be examined. Any weak points in the design can be identified for variant conformity at all levels of abstraction. This shows that the VAM can be used as the basis for solution finding.

4.2 Life Phases Modularization

Life Phases Modularization (Blees et al., 2010; Blees, 2011) generates a continual module structure by transferring the results of *Design for Variety* for each relevant product life phase, checking consistency and conflicts between different life phases. In considering different product family structures for each individual phase, conflicts between phases can be identified and addressed by new design concepts. The method is divided into the following steps:

1. Development of a technical-functional modularization
2. Development of modularizations for all stakeholders and product life phases
3. Combination of modularizations
4. Derivation of the modular product family structure.

The product strategic modularization continues with the results of the technical-functional modularization. The development of modularization perspectives for all relevant product life phases is performed by module drivers associated with individual life phases. Modules are developed by specifications of the module drivers, e.g. separate testing is specified by hydraulic and electrical test. These specifications are linked to the components of the product in network diagrams. In these diagrams, module candidates can be identified by grouping components that relate to a common module driver specification. Possible conflicts are revealed by visualizing the different life phase modularizations in the MIG (Figure 2) and solved. The Module Process Chart (MPC) transparently combines the elaborated perspectives of chosen life phases and supports the coordination process.

4.3 Strength/Potential and Influences

According to Table 1, the *Integrated PKT-Approach* has its strength in the product-related visualization, its integration of interdisciplinary expertise, its guided application and usability in corporate context. These criteria all evolved from demands in industrial project experience. Further criteria, like consideration of the whole product program, the consideration of process and company structures or the consideration of costs are not included but are currently under development.

The main influences on the development of the approach are shown in Table 2, a detail from Table 1 with influence criteria indicated.

Table 2. Influence on the Integrated PKT-Approach

		methodologies					
		Caesar	Kusiak/Huang	Stone	Göpfert	Erixon	Krause
	year	1991	1996	1997	1998	1998	2011
criteria	technical-functional modularization	○	●	● ▨	● ▨	○	●
	product strategic modularization	◑	○	○	◑ ▨	● ▨	●
	product-related visualization	○	● ▨	◑	●	◑	●
	redesign for modularization	● ▨	○	◑	○	◑	●

○ not/weakly considered
◑ partially considered
● mainly considered
▨ influence on *Integrated PKT-Approach*

The visualisation tool MIG is inspired by Kusiak/Huang (Kusiak et al., 1996). The redesign aims of the methodical unit *Design for Variety* are influenced by the design guidelines of Caesar (Caesar, 1991). The technical-functional modularization of the methodical unit *Life Phase Modularization* is carried out by the modularization approach of Stone (Stone, 1997) and Göpfert (Göpfert, 1998). The module drivers are a concept known from Modular Function Deployment (Erixon, 1998) that has been enhanced with concrete specifications to develop modules. The used network diagrams are related to Göpfert (Göpfert, 1998).

5 CONCLUSION

Supporting the development of modular product families is shown in many approaches in the literature. To give an overview of which approach can be used under which circumstances, characterization and comparison of the relevant approaches was performed. The characterization criteria were deduced from literature and project experience. The *Integrated PKT-Approach* developed at the *Institute of Product Development and Mechanical Engineering Design (PKT)* was described, characterized and compared to the other approaches. The approach focuses on a combination of technical-functional modularization and product-strategic modularization. It uses a product-related visualization and gives measures for redesign for modularization. This paper describes the strength and potential of the *Integrated PKT-Approach* and how other approaches influenced the development of this approach. The applicability, usefulness and usability, as well as the limitations of the *Integrated PKT-Approach* were shown before by an evaluation of ten case studies (Eilmus et al., 2012).

However, the development of the approach is not yet complete and further method units are under development. The approach is going to be expanded to include *Product Program Planning* and the *Development of Modular Product Programs* for a program-wide consideration. Process complexity will be addressed by the method units *Design for Supply Chain Requirements*, *Modularization for Assembly* and *Design for Ramp-up*. Further method units will follow.

ACKNOWLEDGMENTS

We gratefully thank Tammo Bahns, Gregor Beckmann, Max Brosch, Sandra Eilmus, Steffen Elstner, Nicolas Gebhardt, Jennifer Hackl, Niklas Halfmann and Henry Jonas for assistance in the literature review process.

REFERENCES

Blees, C. (2011) *Eine Methode zur Entwicklung modularer Produktfamilien*, Vol. 3, Dissertation. Hamburg: TuTech-Verlag.

Blees, C., Kipp, T., Beckmann, G. and Krause, D. (2010) Development of modular product families: Integration of design for variety and modularization. *Proceedings of Norddesign2010*, pp. 159-168. Gothenburg.

Brosch, M., Beckmann, G., Griesbach, M., Dalhöfer, J. and Krause, D. (2012) Design for value chain – An integration of value chain requirements into the product development process. *Proceedings of Norddesign 2012*. Aalborg.

Browning, T. (2001) Applying the design structure matrix to system decomposition and integration problems: A review and new directions. *IEEE Transactions on Engineering Management*, Vol. 48, pp. 292-306.
Caesar, C. (1991) *Kostenorientierte Gestaltungsmethodik für variantenreiche Serienprodukte*, Dissertation. Düsseldorf: Technische Hochschule.
Eilmus, S., Gebhardt, N., Rettberg, R. and Krause, D. (2012) Evaluating a methodical approach for developing modular product families in industrial case studies. *12th International Design Conference - Design 2012*, pp. 837-846. Dubrovnik.
Erens, F. (1996) *The Synthesis of Variety – Developing Product Families*, Dissertation. Eindhoven.
Eppinger, S. and Browning, T (2012) *Design structure matrix methods and applications*. Cambridge: MITPress.
Erixon, G. (1998) *Modular Function Deployment – A Method for Product Modularisation*, Dissertation. Stockholm: Royal Institute of Technology.
Göpfert, J. (1998) *Modulare Produktentwicklung – Zur gemeinsamen Gestaltung von Technik und Organisation*, Dissertation. Wiesbaden: Gabler.
Harlou, U. (2006) *Developing product families based on architectures*. Copenhagen: Technical University of Denmark.
Hölttä, K., Tang, V., and Seering, W. (2003) Modularizing product architectures using dendograms. *International Conference on Engineering Design*. Stockholm.
Hölttä-Otto, K. (2005) *Modular Product Platform Design*, Dissertation. Helsinki.
Hölttä-Otto, K. and Otto, K. (2006) Platform concept evaluation. In Simpson, T., Siddique, Z. and Jiao, J. (eds) *Product Platform and Product Family Design*, pp. 49-72. New York: Springer.
Jiao, J. and Tseng, M. (1999) A methodology of developing product architecture for mass customization. *Journal of Intelligent Manufacturing*, Vol. 10, pp. 3-20.
Jiao, J. and Tseng, M. (2000) Fundamentals of product family architecture. *Integrated Manufacturing Systems*, Vol. 11, No. 7, pp. 469-483.
Jiao, J., Zhang, L. and Pokharel, S. (2006) Process platform and production configuration for product families. In Simpson, T., Siddique, Z. and Jiao, J. (eds) *Product Platform and Product Family Design*, pp. 377-402. New York: Springer.
Kipp, T., Blees, C. and Krause, D. (2010) Anwendung einer integrierten Methode zur Entwicklung modularer Produktfamilien. *Design for X. Beiträge zum 21. DfX-Symposium*, pp. 157-168. Hamburg: TuTech-Verlag.
Krause, D. and Eilmus, S. (2011) A methodical approach for developing modular product families. *International Conference on Engineering Design*, Vol. 4, pp. 299-308. Copenhagen.
Kusiak, A. and Huang, C. (1996) Development of modular products. *IEEE Transaction on Components, Packaging, and Manufacturing Technology*, Vol. 19, No. 4, pp. 523-538.
Lindemann, U., Maurer, M. and Braun, T. (2009) *Structural Complexity Management: an approach for the field of product design*. Berlin: Springer.
Martin, M. and Ishii, K. (2002) Design for variety: developing standardized and modularized product platform architectures. *Research in Engineering Design*, Vol. 13, pp. 213-235.
Pahl, G. and Beitz, W. (2007) *Engineering Design*. Berlin: Springer.
Park, J. and Simpson, T. (2006) An activity-based costing method to support product family design. In Simpson, T., Siddique, Z. and Jiao, J. (eds) *Product Platform and Product Family Design*, pp. 336-358. New York: Springer.
Pimmler, T. and Eppinger, S. (1994) Integration analysis of product decompositions. *Proceedings of the 6th Design Theory and Methodology Conference*, pp. 343-351. New York.
Robertson, D. and Ulrich, K. (1998) Planning for product platforms. *Sloan Management Review*.
Schuh, G. (1989) *Gestaltung und Bewertung von Produktvarianten*, Dissertation. Aachen: Technische Hochschule.
Schuh, G. (2005) *Produktkomplexität managen*, Vol. 2. München: Carl Hanser.
Simpson, T., Bobuk, A., Slingerland, L., Brennan, S., Logan, D. and Reichard, K. (2012) From user requirements to commonality specifications: An integrated approach to product family design. *Research in Engineering Design*, Vol. 23, pp. 141-153.
Stone, R. (1997) *Towards a Theory of Modular Design*, Dissertation. Austin: University of Texas.
Ulrich, K. and Eppinger, S. (2004) *Product Design and Development*, Vol. 3. New York: McGraw Hill.