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EVALUATING A METHODICAL APPROACH FOR DEVELOPING MODULAR PRODUCT FAMILIES IN INDUSTRIAL PROJECTS

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1. Introduction

To offer individualised products at globally marketable prices, developing modular product families aims to generate the external product variety needed using the lowest possible internal variety. A methodical approach that supports the development of modular product families was developed by the Institute for Product Development and Mechanical Engineering Design (PKT) at Hamburg University of Technology [Krause 2011]. This Integrated PKT-Approach for Developing Modular Product Families consists of several methodical units (Figure 1). The units Design for Variety and Life Phases Modularization are the basis of the Integrated PKT-Approach being developed and published in further research projects [Blees 2010]. This contribution evaluates these methodical units through industrial application. The current state of research into reducing internal variety is given, with a focus on the references, which the approach builds upon to provide an understanding of how it relates to existing research. The Integrated PKT-Approach steps and tools are presented through an industrial case study of gas inlet valves. Based on this, evaluation of the Integrated PKT-Approach in industrial practice is explained through 10 case studies in an attempt to show its applicability, usefulness and usability, as well as its limitations. The contribution closes with respective conclusions for further research projects as well as with reflection on the described experiences in evaluation of methodical support by industrial case studies.

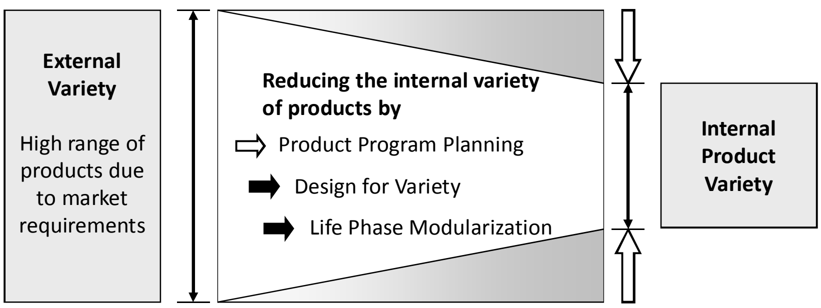


Figure 1. The Integrated PKT-Approach for developing modular product families

2. Scientific background

Several fields of research focus on reducing internal variety, namely *complexity management,* the development of *product families*, *product modularization* and *product platforms*.
The term *complexity* is used differently in product design methodology. Abdelkafi interpreted it in several ways [Abdelkafi 2008], e.g. complexity is the system size, in terms of the number and

diversity of elements. Here, complexity is seen as a characteristic of a product structure that is determined by the number of elements, their variety and relations. Structural Complexity Management is an example of complexity-oriented product design methods based on a matrix approach [Lindemann 2009].

Variety-oriented design methods concentrate on the reduction of internal product variety necessary for a certain external variety. Based on the literature, the ideal of a variety-oriented product structure is defined by the four main attributes [Blees 2010]:

- Clear differentiation between standard components and variant components
- Reduction of the variant components to the carrier of a differentiating attribute
- One-to-one mapping between differentiating attributes and variant components
- Minimal degree of coupling of variant components to other components.

An example of a methodical approach to variety-oriented product development that partly incorporates these attributes is given by Franke and Firchau [Franke 2002].

Product *modularization* has many benefits that can be exploited. A module is a group of components within a product that exhibit stronger internal functional and strategic couplings than external ones. Salvador describes the modularity of a product as a property given by a set of five gradual attributes: commonality, combinability, function binding, interface standardisation and loose coupling of components [Salvador 2007]. Because of the gradual character of these attributes, the modularity of a product can be interpreted as a gradual characteristic as well. The task of modularization is to derive the degree of modularity suitable for adaptation to the corporate strategy [Krause 2011]. In [Jiao 2007] modularization methods are classified by the factors taken into account when defining the modules, which can be technical functional relations or strategic aspects. An example of the strategic aspects gives the Modular Function Deployment [Erixon 1998] where the module drivers of the Integrated PKT-Approach base upon.

A *product platform* can be seen as a common base of a product family that can contain components, processes, knowledge, people and relations, as summarized from literature in [Jiao 2007]. From this base, product variants can be efficiently derived. Production cost reduction and faster market entry are the main benefits of this strategy. The central task of the design of product platforms is to balance the contradictory demands of individual customer solutions and production cost savings by commonality when defining the optimal range of the platform. Simpson proposes an approach focusing on scalable product platforms [Simpson 2006]. Configurational approaches focus on product platforms that allow the derivation of variants by adding optional or individual configuration modules. A brief survey of established product platform design methods is given in [Jiao 2007].

3. The Integrated PKT-Approach for developing modular product families

Based on the existing research presented above, the Integrated PKT-Approach was developed [Blees 2010, Krause 2011] with the following aims:

- to provide continuous methodical support for all steps of developing modular product families
- to derive concrete design solutions, including the redesign of components
- to provide simple graphical views to assist discussions and decision-making.

This section gives a detailed outline of the Integrated PKT-Approach and its procedures using a case study on gas inlet valves at INFICON AG in Balzers, Liechtenstein. The main aim in this project was to meet the existing customer needs with one new product family while reducing the internal variety currently covered by five families.

The steps of the units *Design for Variety* (step 1-6) and *Life Phases Modularization* (step 7-8) are:

1. Analysis of external variety using the tree of variety
2. Analysis of variant functions generating a product family function structure
3. Analysis of variant components drawing the Module Interface Graph (MIG)
4. Analysis of variant working principles
5. Allocation of variant elements (1-4) and derivation of variety-optimized component concepts using the Variety Allocation Model (VAM)
6. Evaluation and choice of new product family concept

7. Identification of life phases-specific module drivers
8. Modularization over all life phases using the Module Process Chart (MPC)

Design for Variety aims to reduce internal variety by redesigning the product family and converging the product towards the theoretical optimal product structure for variety, as mentioned above (Section 2). First, the external variety is visualised using the tree of variety, which shows the customer-perceived differentiating attributes and all product variants, as shown in Figure 2.

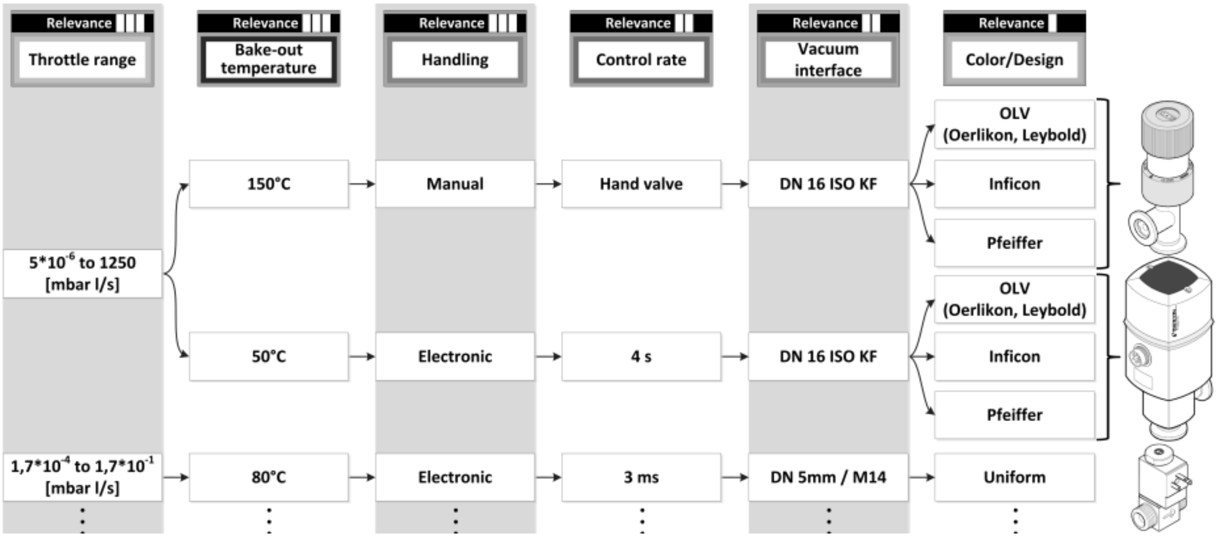


Figure 2. Tree of variety of the existing product families

Internal variety is analysed at three levels of functions, working principles and components. The level of functions is derived using a product family function structure that shows the variety of each function (Figure 3). For each function the corresponding working principles and their variety is allocated. The variety of components is visualised using a Module Interface Graph (Figure 4, left), which shows the variety for each component and their connecting flows.

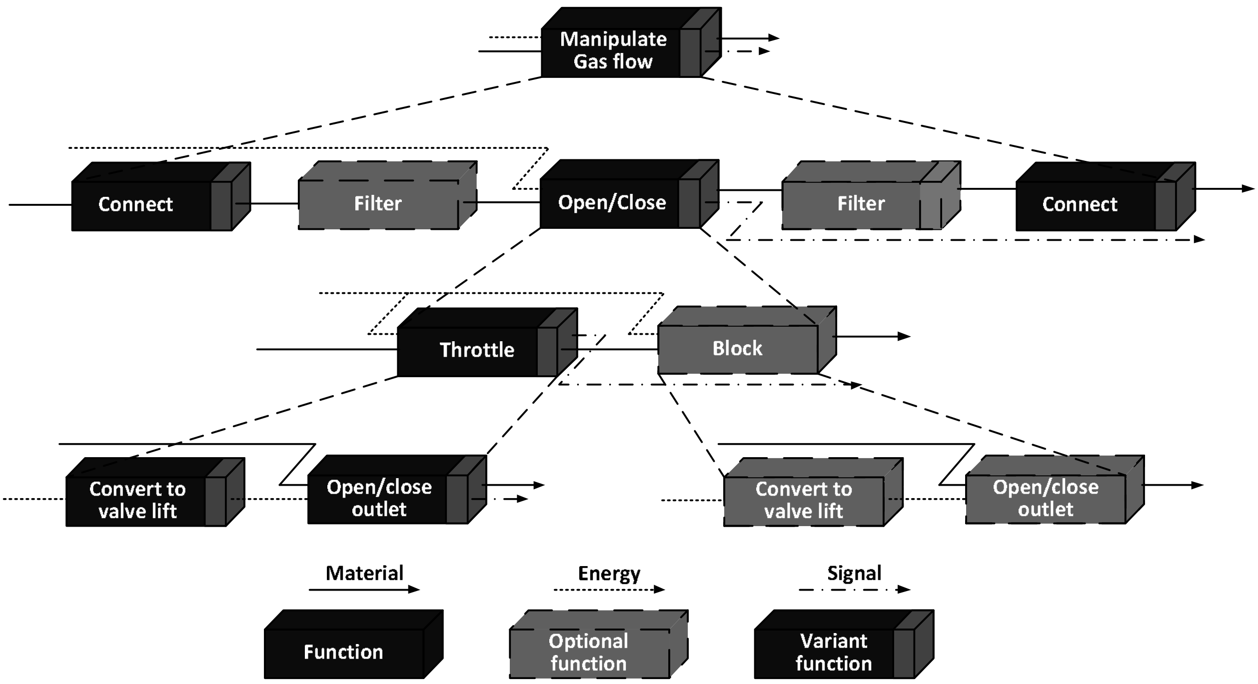


Figure 3. Hierarchical function structure of the existing product families

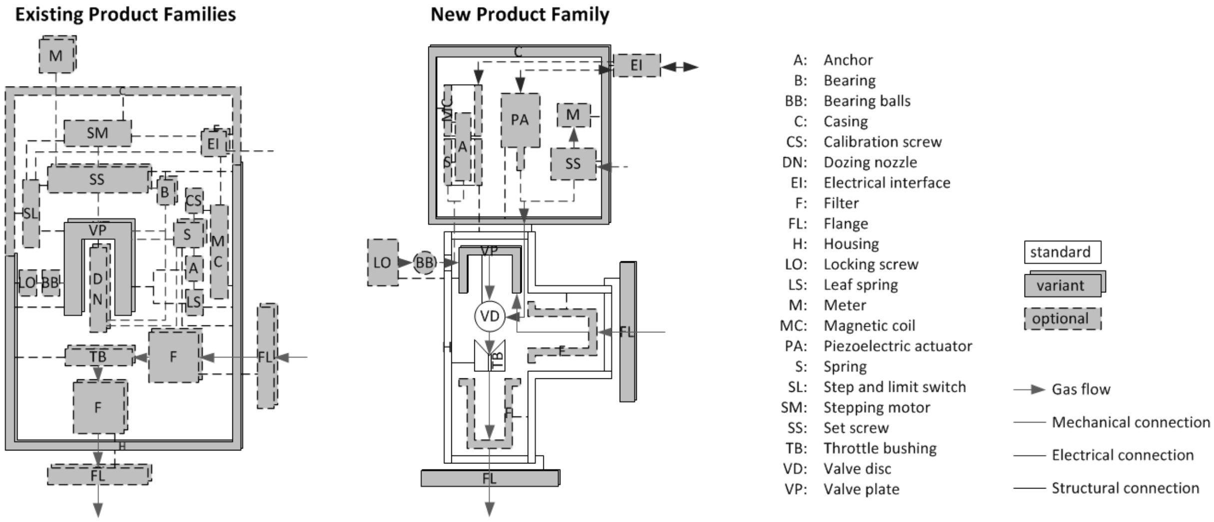


Figure 4. MIGs of the existing valves (left) and the new product family (right)

After this, all variant elements, in terms of differentiating attributes, functions, working principles and components, are inherited into the VAM (Figure 5, left). Mapping one level to the next, causal connections between external and internal variety can be shown and compliance with the optimal variety-oriented product structure theory can be analysed. Weak points can be improved by following a methodical, solution-finding process that covers redesign, modification or new design of components. In the case study, solution-finding using the VAM leads to a variety-oriented concept of a product family. For example, variance of working principles was optimized using a valve disc and a piezo actuator for throttling for all variants. By this, interdependencies caused by differentiating attributes branching over functions, working principles and components could be reduced to comply with the optimal variety oriented product structure (Figure 5, right).

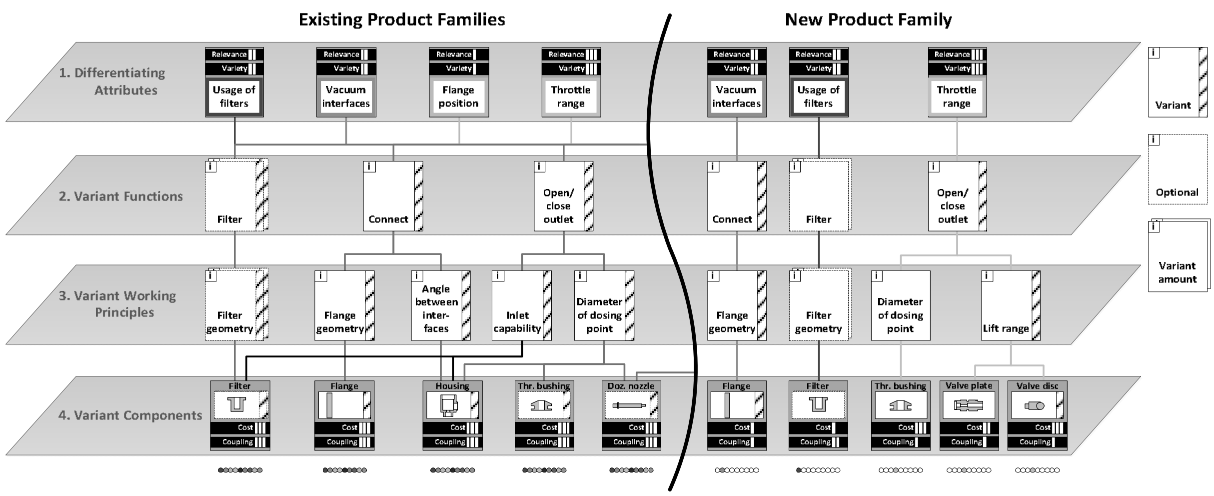


Figure 5. VAM detail of the existing product families (left) and the new product family (right)

The second unit of the Integrated PKT-Approach, *Life Phase Modularization*, sets up a module strategy for the product family, based on the improved design after *Design for Variety*. The central idea is to develop the ideal modularization concepts for each relevant life phase independently, in compliance with the life phase-specific targets of the enterprise. The modularization concepts of a product family are allowed to differ from one life phase to the other. This way, the individual needs of the different phases can be satisfied and benefits are exploited.

First, a technical functional modularization and strategic modularizations from the perspective of all relevant product life phases are developed using network diagrams. These concepts are visualised using the MIG of the product. The Module Process Chart shows the designated modular concepts of all life phases (MPC, Figure 6). During the integration of the modularization concepts conflicts can occur. The MPC supports decision-making and finding an adequate modularization that integrates the needs of all life phases [Blees 2010]. A detail of the modular structure of the product family of gas inlet valves that is now optimised for variety and life phases can be seen in Figure 6.

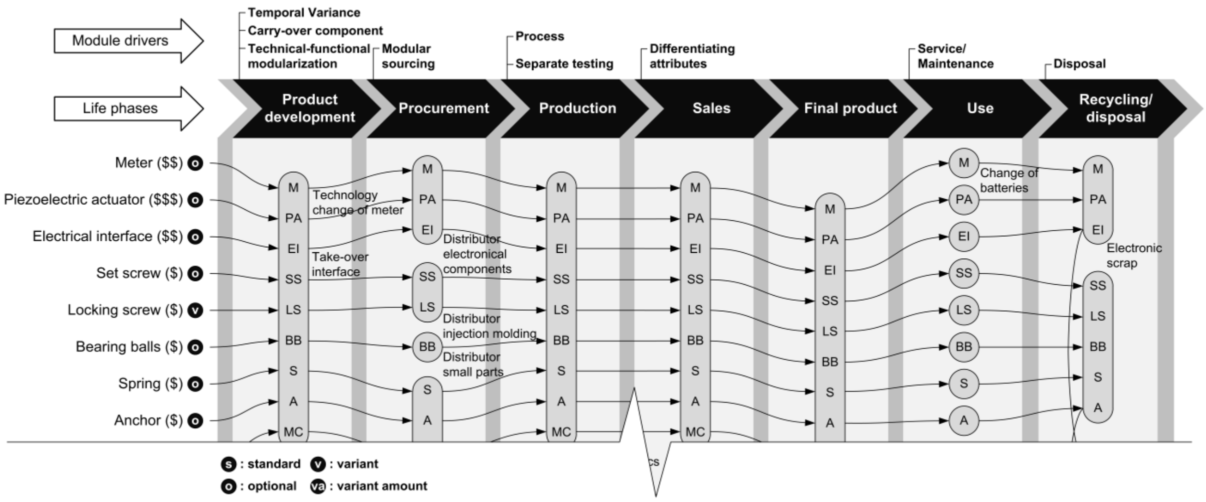


Figure 6. MPC detail of the optimised product family

Again, the MIG is used as a visualisation tool to illustrate the results of the project (Figure 4). Explicit changes can be observed in standard, variant and optional components, as well as connections. Completing the project, the product family of gas inlet valves was designed while considering the restrictions and needs resulting from the MPC (Figure 6). A particular focus was put on the module structure of the "Use" phase. In this phase, interfaces have to be dismountable to perform maintenance operations. Figure 7 shows the final concept for configuring the product variants by adding modules to a product platform. The benefit to components needed is a reduction from 53 to 22, counting the components the company has to hold available to build any possible variant of the family. Components in common are increased from 6 to 13 while the variant components are minimized from 47 to 9. Creating a platform, product variants can be configured by adding the variant and optional modules to the platform.

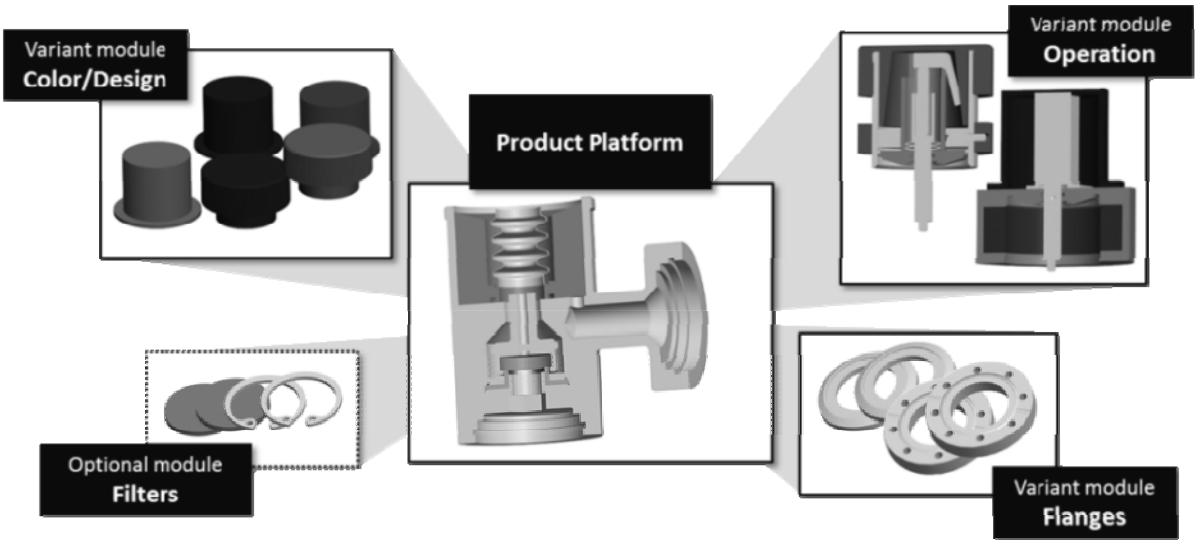


Figure 7. Resulting product family

4. Evaluation using industrial case studies

Case studies in industry were chosen to evaluate the Integrated PKT-Approach as the approach aims to support the development of modular product families in corporate engineering practice. The benefit of the industrial case studies is that the evaluation is very close to the intended application area. A disadvantage is that a detailed evaluation plan could not be prepared at the beginning, as it was not known which industrial projects would go ahead and whether they would be suitable for evaluation.
A method for evaluating methodical support is given by Blessing and Chakrabarti [Blessing 2009]. In this approach, Application Evaluation aims to assess applicability and usability of methodical support. Success Evaluation analyses the usefulness of methodical support.
As in the evaluation of the Integrated PKT-Approach the number and focus of projects to be used as case studies was not known at the beginning, it was not possible to plan an Application Evaluation and a Success Evaluation one after another. However, these evaluation types served as basis in order to allocate which case study serves to evaluate what focus and to conduct the case study respectively. The following aspects were covered:

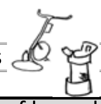
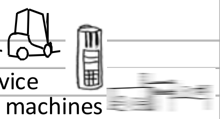
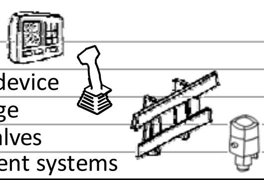
- applicability: constraints in the approach's application area
- usefulness: success in reducing internal variety
- usability: user-friendliness to foster the use of the approach in industrial practice.

4.1 Allocation of case studies to evaluation focuses

The evaluation can be allocated to three phases with different focuses (Table 1). Evaluation Phase 1 is the initial evaluation of applicability, usability and usefulness of the individual methodical units Design for Variety and Life Phases Modularization. The integration of these two units into the PKT-Approach is evaluated. This evaluation was conducted within two research projects of Kipp and Blees [Blees 2010] on product families of herbicide spraying systems and immersion pumps. It successfully showed basic applicability, usability and usefulness of the methodical units and the Integrated PKT-Approach as a basis for further evaluation. This initial evaluation was applied to the original scope of the method, which is the redesign of existing product families.
The focus of Evaluation Phase 2 was to gain an understanding of the boundary conditions required for the applicability of the Integrated PKT-Approach. The main question was whether there are specific methodical needs for further development of the Integrated PKT-Approach to apply it with an expanded scope. This expansion of scope was considered in three directions:

- products with a higher degree of product novelty
- products with higher product complexity in terms of numbers of elements and relations
- a broader product range, i.e. several product families or a whole product program.

Table 1. Evaluation plan

Evaluation Phase 1 (initial evaluation of applicability, usability and usefulness)				
Projects 		Focus on initial evaluation of		
		Single methodical units	Integrated PKT-approach	
1	Herbicide spraying systems	●		
2	Immersion pumps	●	●	
Evaluation Phase 2 (evaluation of boundary conditions for the applicability)				
Projects 		Focus on boundary conditions for		
		Product complexity	Variant range	Degree of novelty
3	Ground conveyor	●	●	
4	Gas detection device			●
5	Paper converting machines	●	●	●
Evaluation Phase 3 (evaluation of usefulness and usability)				
Projects 		Focus on boundary conditions for		
		Single modules	A product family	Several product families
6	Displays	●		●
7	Operating device	●		●
8	Fork carriage	●	●	
9	Gas inlet valves			●
10	Measurement systems		●	

Evaluation Phase 3 focuses on usability and usefulness of the Integrated PKT-Approach. During this phase, industrial partners needed to apply the Integrated PKT-Approach to single modules being used, as several variants within several product families. Taking this into account, the research questions of Evaluation Phase 3 were:

- Does the Integrated PKT-Approach lead to less internal variety of products, maintaining the needed external variety (usefulness)?
- What is the need for improvement in usability?
- Are usefulness and usability for application on single modules being used in a product of higher complexity or over several product families?

4.2 Choice of data collection methods

The choice of data collection methods was influenced by the type of case study performed. The first case studies were conducted by researchers experienced in methods for developing modular product families. In these cases, data on usefulness and applicability was collected by analysing the results of product family optimization, e.g. number of reduced variant components. Usability was assessed by experiencing the problems in performing the method and using the tools oneself. In addition, workshops with the industrial partners involved in using the tools were observed by a second researcher.

The second type of case study involved operators who were inexperienced in the use of methods for developing modular product families. This type of case study was performed on 6 projects in Evaluation Phases 2 and 3. The aim of choosing inexperienced operators was to evaluate whether the Integrated PKT-Approach is usable by engineers not specialised in methodology or the development of product families. A regular group meeting of operators, involving exchange and coaching on the use of the Integrated PKT-Approach was conducted. Questions and problems that arose provide one source for evaluating applicability and usability of the Integrated PKT-Approach. The specific questions and problems of each operator are documented within the project reports written by each operator. Key figures of the new product family concepts being derived by applying the Integrated PKT-Approach were documented in the reports to capture the 'usefulness' results.

Another way of evaluating usability was a questionnaire filled out by the operators and industrial partners involved in the project. The questionnaire was developed based on the experience in Evaluation Phase 2 and applied in Evaluation Phase 3 in all case studies, independent of case study type (experienced or inexperienced operators).

5. Case study results

Results of the single evaluation focuses are presented and summarised below. Topics for further research are derived to enhance applicability, usefulness and usability of the Integrated PKT-Approach.

5.1 Results of boundary conditions for applicability

During Evaluation Phase 2, two of the three applications of the Integrated PKT-Approach were redesigns with a high degree of novelty. For the family of paper cutting machines and the family of gas detection devices, the levels of external variety and functions were analysed successfully by using the tree of variety and function structures. Analysing working principles and components, the methods did not give the operators a way to distinguish between technical solutions being already well-defined and the solutions being still in development. These two projects demonstrate the further need for research on the following questions:

- To which degree of novelty in a product family is the Integrated PKT-Approach applicable?
- In which phase of product development should this modified Integrated PKT-Approach be applied?
- How can uncertainties of still undefined solutions be integrated into the PKT-Approach?

Another field of interest was the question of how to apply the Integrated PKT-Approach to products with higher product complexity in elements and relations. This problem occurred in projects where the product consisted of more than 40 components. In projects where a product could be decomposed into 20-40 components, seen from the first assembly level above the parts level, problems with decomposition were not reported. Projects with more components at this assembly level were the family of ground conveyors and the family of paper cutting machines. They are called products with higher complexity in this contribution as their number of elements requires extra effort in conducting the method (refer to section 2). Working on families of products with higher complexity the operators were confronted with the question of the right level of detail for the use of tools like tree of variety, MIG or VAM.

- How can an operator be supported in choice of level detail when decomposing a product with higher complexity for analysis of internal variety?

The question of whether analysis of a broad product range, e.g. products from different product families or whole product programs, is supported by the Integrated PKT-Approach was covered by the project on ground conveyors. When developing a whole modular product program, the relevant question is whether potential for commonalities can be identified and exploited beyond the scope of single product families. Two aspects were identified:

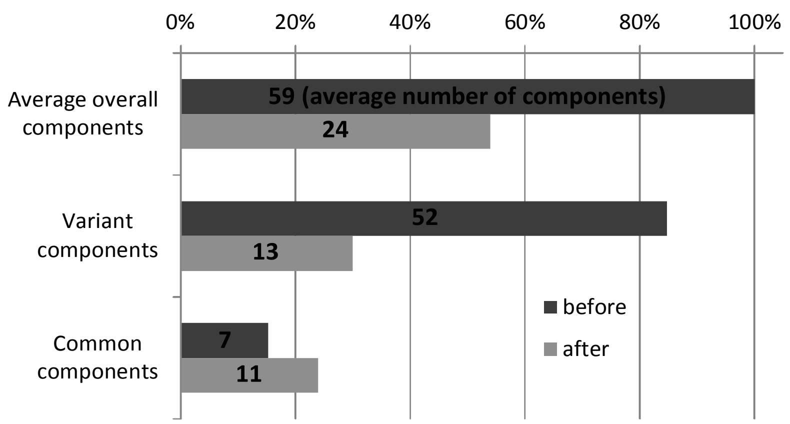
- How can product structures be aligned over several product families?
- How can single modules be prepared for reuse in several product families?

Concerning the preparation of single modules for reuse, initial projects were conducted in Evaluation Phase 3 as well as in projects on several product families.

5.2 Results on usefulness

With regard to usefulness of the reviewed method all projects were analysed with respect to the achieved component numbers. The experience in Evaluation Phases 1 and 2 led to a final set of comparable key figures that was recorded in each project of Evaluation Phase 3. An important measure for internal variance and a clue to variance-induced internal expenses is the amount of variant and common components. This is why the product components are separated into these two groups. The group of variant components consists of components that are either variant or variant and optional while the common components consist of those that are either optional, but not variant, or standard. Reducing the number of components in a whole reduces internal variety by reducing the expenses in component production and handling.

Two major benefits can be observed in the summarised results of the projects in Phase 3 (Figure 4). Compared to the existing products, the overall number of components is significantly reduced. The percentage of variant components is decreased while the percentage of common parts is increased. This shows that the Integrated PKT-Approach was useful in reducing internal variety by reducing the number of components in a whole as well as reducing the variance in the single components.



Project	Overall components		Variant components		Common components	
	before	after	before	after	before	after
6	83	17	82	12	1	5
7	73	28	71	13	2	15
8	49	28	43	19	6	9
9	53	22	47	9	6	13
10	37	27	19	14	18	13

Figure 4. Results of component numbers in phase 3

5.3 Results on usability

The Integrated PKT-Approach's usability is evaluated in two ways. The first way was to conduct evaluation not only by experienced operators but even by inexperienced operators with an engineering background (Section 3.2). For this second type of case study, skills for applying the Integrated PKT-Approach were taught during group meetings and in individual coaching. Over the course of the projects (from 3-6 months), each operator received approximately 6 hours of coaching per month. During this time, the operators achieved the results described in 4.2.2, which shows that they generally succeeded in using the approach. Through feedback during the group meetings and in project documentation, further need for research was identified. In Design for Variety, feedback was given on the effort required in deriving the VAM, which is described in more detail below. In Life Phases Modularization, the need to support conflict resolution between the life phases better was identified. Conflicts may be that the ideal modularization of different life phases may be hard to align to each other or that the module drivers within a life phase lead to conclusions contrary to the ideal modularization within a life phase. In particular, aligning the technical functional module drivers to the strategic module drivers within product development phase was difficult for several operators.
A second evaluation method was a questionnaire for the operators and the industrial partners involved in the projects. The main questions about usability in terms of user-friendliness were to analyse which tools and steps were helpful to the user and which were less helpful. Through this, further development of the Integrated PKT-Approach will lead to further concentration on the elements that support the operator and a reduction in effort put into steps and tools that do not in fact support the operator. Analysing, for example, usability of the VAM, large efforts in generating the VAM of a product family were invested by the operators. However, the 6 questionnaires (methodical inexperienced operators and some of the industrial partners) showed that the level of working principles was perceived as less helpful than the other levels of properties, functions and components (Figure 5). In optimising the VAM, a possible step would be to concentrate effort on generating the level of working principles to the minimum necessary for gaining support from that level.

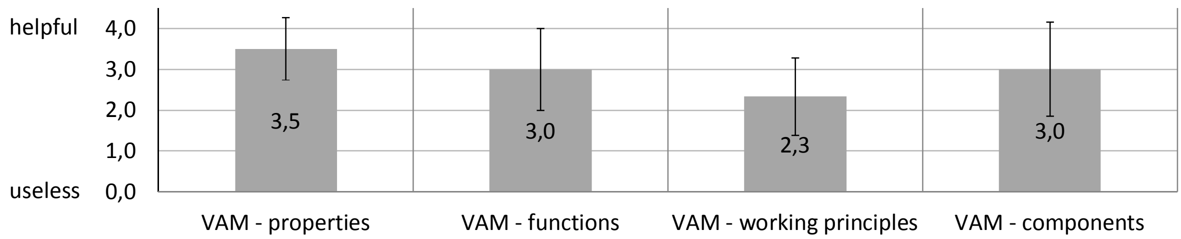


Figure 1. Case study results on usability of the Variety Allocation Model (VAM)

The main improvement needs deducted during this evaluation to raise the usability and by this, acceptance of the operators, are:

- improvement of methodical support in conflict resolution within the Life Phases Modularization
- optimisation of the proportion between effort and benefit in generating the VAM and its comprehensibility.

Conducting the analysis of usability it was very helpful to have questionnaires and to coach the operators. Through this, the perceptions being shared in the questionnaire answers could be related to the actual work of the operators.

6. Conclusions

To evaluate the Integrated PKT-Approach for Developing Modular Product Families, evaluation of 10 industrial projects was carried out. The results show general applicability for the redesign of existing product families. The usefulness of the Integrated PKT-Approach is proven by the project results. For all projects a medial component reduction by 59% and a medial reduction of variant components by 74% could be achieved. These results were achieved by experienced as well as by methodically inexperienced operators applying the Integrated PKT-Approach within several companies demonstrated general usability.

The need for further research is defined and summarised into three research fields: The research project “Development of modular product programs” deals with the question of how the Integrated PKT-Approach can be used over a broad range of variants, e.g. several product families or whole product programs. This includes the definition of the product program aligned product structures, as well as the development of modules for use within the whole product program. The need for consolidation of product models and tools, comprehensive visualisations and improved usability of methodical steps leads to the research project “Product models for visualisation of modular product structures”. Discussions with the industrial partners involved in this evaluation of how to establish modular structures continuously in a company exploiting its benefits in all life phases has inspired a project on “Knowledge Transfer Support for Developing Modular Product Families”.

While working on finding practicable evaluation procedures, the experience during this evaluation of the work with inexperienced operators provided significant insights into the use of the method, enabled by exchange among operators and coaching them in use of the method.

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