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BALANCING INTERNAL AND EXTERNAL PRODUCT VARIETY IN PRODUCT DEVELOPMENT

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ABSTRACT

Applicability of “Mass Customization” to mechatronic systems is proven by various product examples in automobile industry. For example, chassis performance is adjusted to the driver’s specific wishes or to present driving circumstances, such as road condition. As a basic principle, hardware forms functional framework while software defines specific functional contents and characteristics.

Balancing internal with external product variety emerges as critical success factor in this context. From external point of view, as much variety shall be provided as end customers are willing to pay for. From internal point of view, each product variant induces consequential costs and thus lessens profitability. In this contribution, a methodology of designing a construction kit for customer specific solutions based on classic German design theories is proposed. A modular product architecture forms the logical context of the construction kit for customer specific solutions. Deduced products are individualized by selection and connection of standardized, discretely and continuously varying components. Thus economic variation becomes feasible also on a high technical level.

Keywords: Product Variety, Complexity, Mass Customization, Design Methodology, Construction Kit for Customer Specific Solutions

1 INTRODUCTION

As mechanics, electrics, electronics and software follow a synthesis trend to mechatronics, customer specific variation can increasingly be offered at competitive prices. The basis of this approach is formed by the competition strategy of Mass Customization. Mechatronic systems make up one of the most promising application area within the branch of industrial goods.

1.1 Mass Customization

The term “Mass Customization” combines the two contrasting approaches of Mass Production and Customization. Mass Production implies cost reduction due to scale effects and gained production experience. Customization focuses on exact fulfillment of customer’s requirements and results in an unique competitive position. Mass Customization therefore aims at producing products to meet individual customer’s needs with mass production efficiency [1]. Thus customized products are offered at prices comparable to standard products and continuous individual relationships are established between each customer and the manufacturer [2-5]. The combination of cost leadership and differentiation results in a simultaneous, hybrid competition strategy (figure 1).

For producing companies, the focus of Mass Customization lies on individualizing material core products. Often, tailored services related to the core products are offered in addition. Prerequisites of economic success of Mass Customization are mature markets and flexible technologies. Mature markets are characterized by heterogeneous, rapidly changing customer requirements, which can hardly be predicted. Flexible product technologies, such as adaptable materials or mechatronic systems, allow easy adaptation to the individual customer’s preferences. Furthermore, generative or Laser driven production technologies make economic production possible in spite of varying characteristics and low lot sizes.

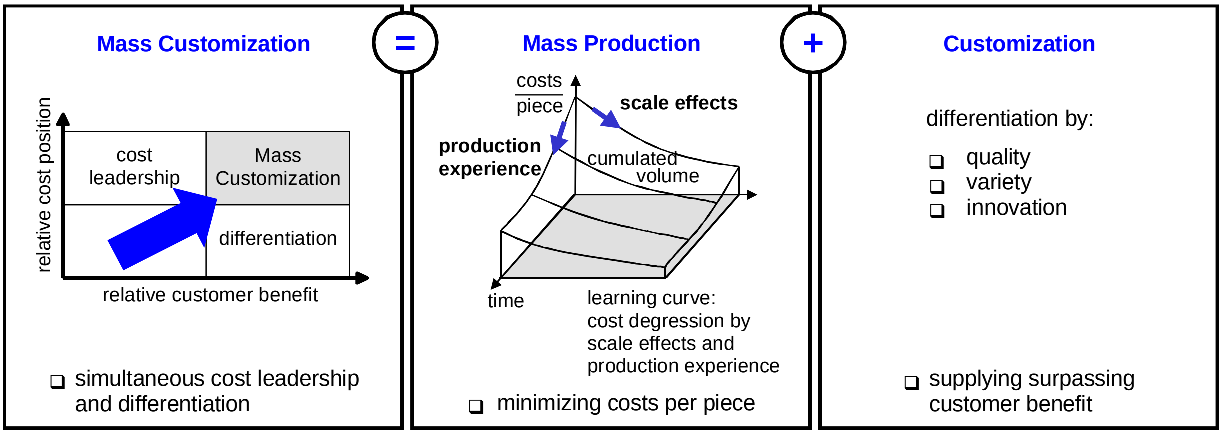


Figure 1. Definition of Mass Customization (based upon [6, 7])

1.2. Mechatronic Systems

Mechatronic systems emerge from functional shift and extension of mechanics to electrics, electronics and software. As a result of closely interacting disciplines, adaptive and intelligent systems are formed (figure 2). Due to functional integration of mechanics, electrics, electronics and software, the borderline between standard and variable system functions can be moved into areas of low efforts. Software thus advances to a variety driver within mechatronics and increasingly depends on application specific knowledge. Therefore, mechatronic systems are one of the most promising application field of Mass Customization for producing companies.

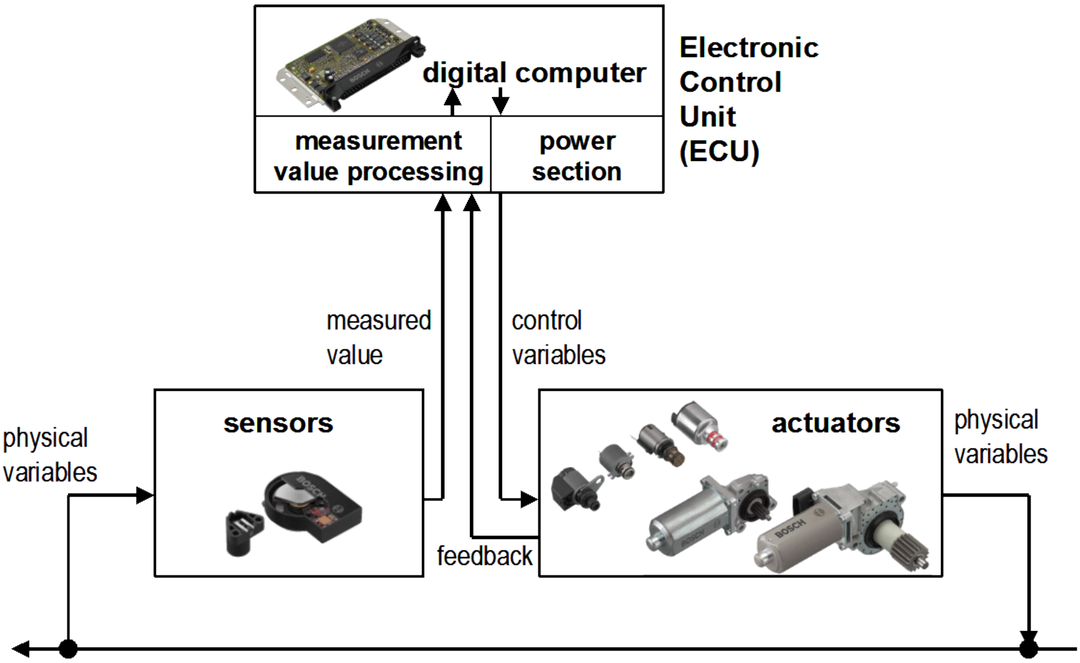


Figure 2. Principle of a mechatronic system

2 CUSTOMER SPECIFIC CONSTRUCTION KIT

In order to economically realize a wide range of variation, development must focus on order neutral creation of construction kits for customer specific solutions. With the term “customer specific construction kit” a construction kit is described, from which a defined range of customized products can be deduced. Deducing a customer specific variant implies reusing requirements, specifications, functions, principles, components up to product documentation and operation plans following a modular product architecture (figure 3). A detailed overview of modularization practices can be found in [8]. The extent of reuse ranges from taking standards to selecting discretely varying options and adapting continuously varying options.

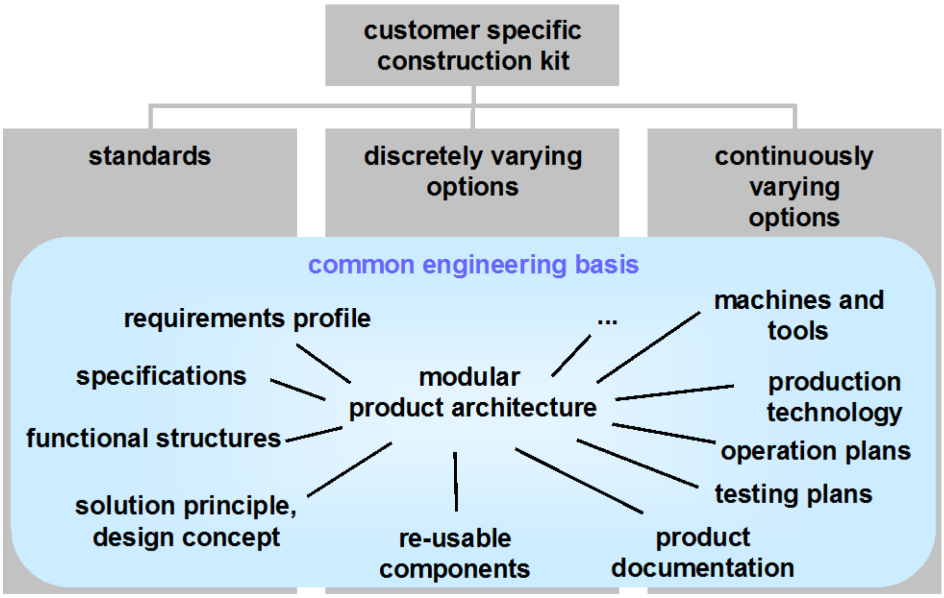


Figure 3. Costumer specific construction kit

In contrast to conventional construction kits, the customer specific construction kit is based on a prospective and revolutionary development approach. In industrial series production, construction kits are typically derived from already processed orders. The affiliated development approach can be subsumed as “retrospective” because sales volumes and specification ranges are already well known and serve as valuable basis of analysis. “Prospective” however means that the construction kit is developed in order to meet future requirements of new products. Synergies between different variants shall be opened up from the first deduced product on. Potential sales volumes are not yet known and have to be pre-estimated using market surveys. “Revolutionary” adds the challenge of developing such a foresighted design frame all at once instead of a step by step implementation.

A common product architecture of all products to be deduced serves as logical backbone of the customer specific construction kit. Deduced variants and applications are individualized by selection of standardized, discretely and continuously varying components and cross-disciplinary variation mechanisms.

Defining validity limits of the customer specific construction kit forms the basis of effecting a compromise between cost degression and individualization. Besides aspired lot size, the following four dimensions of validity have to be fixed (figure 4). The range of individualization (1st dimension) characterizes built-in variety. It reflects the spectrum of selection alternatives as well as limiting combination rules and exclusions. The defined range of individualization decisively influences how many application development projects can be served by the same construction kit. As counterpole to individualization, the 2nd dimension “level of product hierarchy” stands for standardization. As pointed out by [9] modularization in new product development can take place at many different levels. Therefore the product hierarchy level of standardization indicates, whether standardized components can be found on level of parts, subassemblies or entire platforms. From production point of view, the number of preferred production technologies and the flexibility of production method are represented by the 3rd dimension “range of production”. With the 4th dimension “temporal stability” intended economic life-time, questions of generation planning, upward- and downward compatibility are addressed.

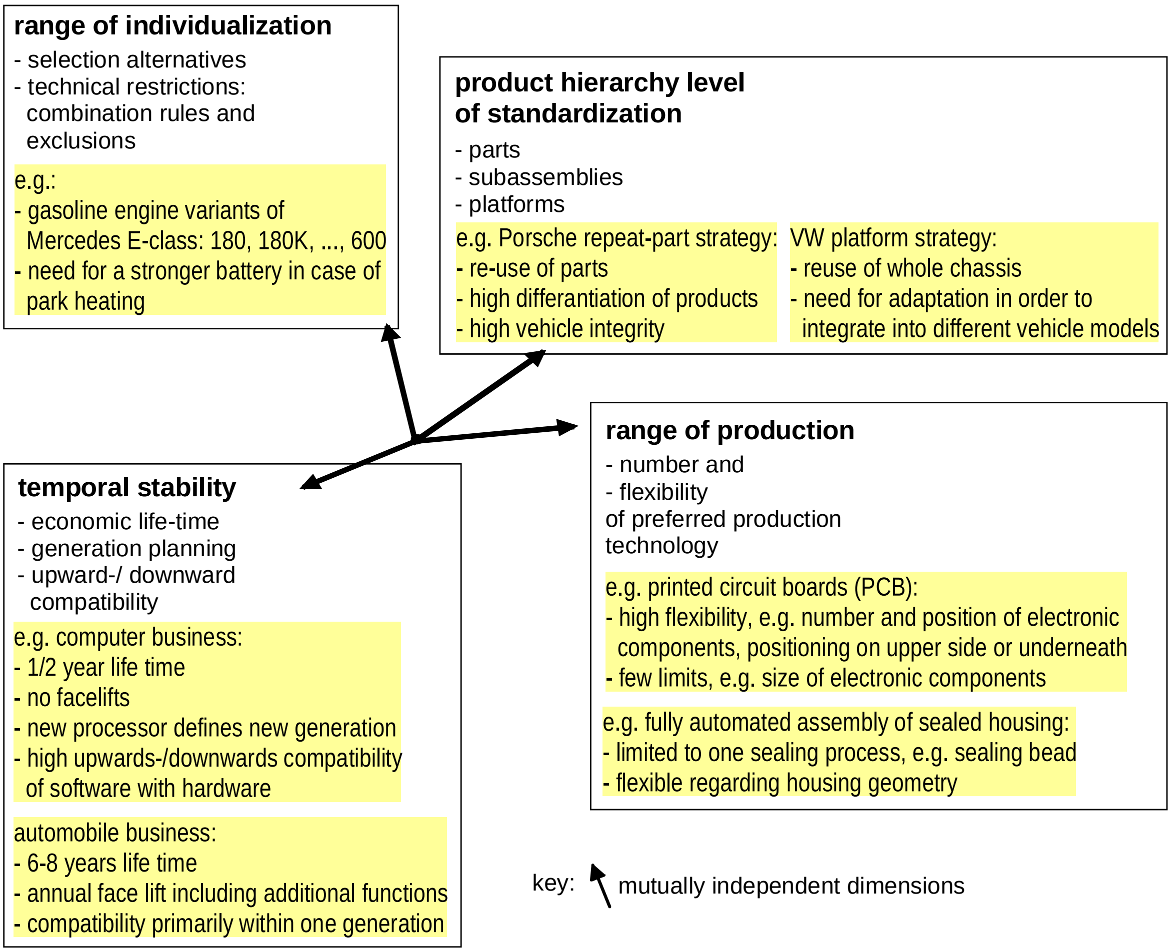


Figure 4. Defining validity of customer specific construction kit

3. DESIGN METHODOLOGY

In order to put such a customer specific construction kit into industrial practice, a corresponding design methodology has been developed [10]. The subsequently presented design methodology supports a systematic, methodical procedure of order neutral creation of construction kits for customer specific solutions with regard to specifics of mechatronic systems. The methodology meets the following three demands. First, classic German design theories are integrated. Thus, the methodology is based on a systematic, methodical procedure. Second, known methods and tools of creating standards and discretely varying components are used and supplemented by new approaches of designing continuously varying components. For each design phase, a selection of appropriate solution approaches is provided in a clear and well structured manner. Third, cross-disciplinary variation mechanisms are created by integrating and coordinating involved disciplines. According to the respective design phase, needs of coordinating partial solutions between involved disciplines are changing. Therefore, focus of design methodology lies on defining appropriate interfaces between partial solutions in order to form a balanced overall solution. In the following, these characteristics are described using examples.

3.1. Phases

Due to underlying prospective and revolutionary development approach, the design task is characterized by a high degree of innovation which results in the need of early design phases, e.g. “establishing function structures” or “finding working principles”. As reference, VDI guideline 2210 E is taken, in which a multitude of German design approaches were unified [11], compare also VDI 2206 [12]. Based on this phase model, the design methodology for customer specific construction kits is structured into six phases (figure 5). During the initial phase “planning customer specific requirements” clear limits between standards and variation are drawn within specification. This separation of product characteristics into “standards”, “discretely varying” and “continuously varying” is kept up during entire subsequent design process. Based on specifications, a functional product architecture is derived (phase 2). Partial functions and functional structures are partitioned according to provided variability and involved disciplines. According to [13], possible product modularity depends on similarity between the physical and functional architecture of the design. In phase 3, appropriate working principles are selected and cross-disciplinarily connected. Special attention is paid on mutual interactions between chosen principles, effects and algorithms.

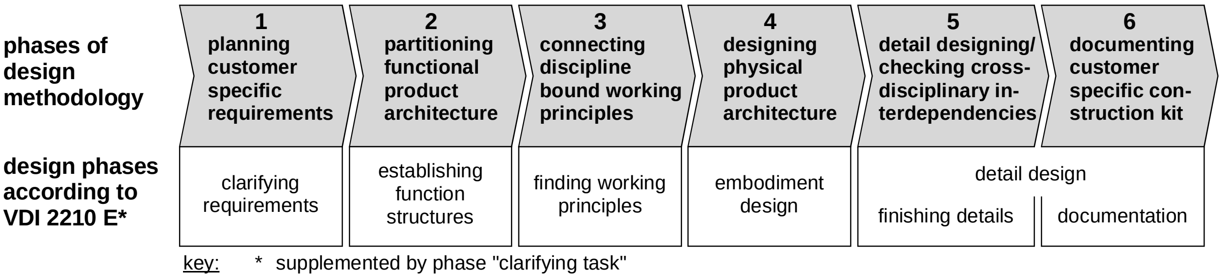


Figure 5. Phases of design methodology

Physical product architecture derived from the principle solution makes up the logical backbone of the customer specific construction kit (phase 4). On condition of this common structure, standardization and individualization are balanced. Standard, discretely varying and continuously varying components are designed to be mainly independent from each other and to be recombined. Due to standardized interfaces, the construction kit can be expanded order neutrally as well as order specifically. In phase 5, modular structures and components are detailed. Functionality and compatibility of connected variation mechanisms are checked. Finally, results worked out in phases 1-5 are comprehensively documented in phase 6. Besides product documentation, procedures and rules of handling the construction kit are defined.

3.2. Methods Use and Results

Adequate methods and tools are assigned to each phase of the design methodology for customer specific construction kits. On the one hand, they are structured applying the view-points “entire mechatronic system”, “mechanics/ electrics/ electronics” and “software”. On the other hand, they are separated according to their application into “standards”, “discretely varying” and “continuously varying”. Examples of methods and tools are Quality Function Deployment, generalized elements of Product Line Approach known from software development, morphological boxes, modularization, up-/downscaling, architecture evaluation and compatibility checks. In figure 6, methods of phase 2 “partitioning functional product architecture” are shown. Functional product architecture is an architecture of system functions, whose partial functions are adapted to individual preferences by variation and adaptation.

In figure 7, the methods “enhanced functional subdividing” and “enhanced functional structuring” are applied to the case study “power window actuator”. The methods are based on functional subdivision and functional structuring introduced by [14, 15]. Using enhanced functional subdividing, the entire function is subdivided into partial functions, until these can be separated into “standard (S)”, “discretely varying (V)” and “continuously varying (I)” partial functions. As a guideline, system variety shall be isolated in distinguished partial solutions. Thus, an embodiment structure is prepared from early on, in which standard components are kept distinct from individual components. In case of the power window actuator, individualization is realized in user interface (switch) and squeeze protection. For example, the switch can be configured in a manner that the window moves downwards

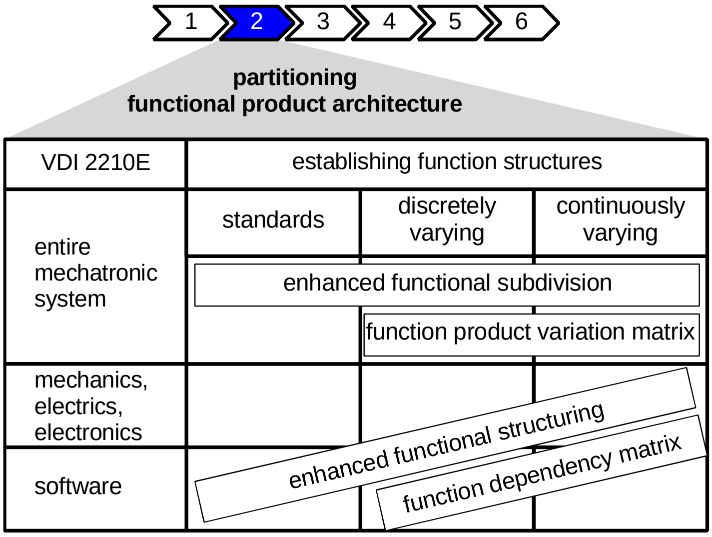


Figure 6. Methods use in phase 2

if the switch is pressed shortly or if pressing is kept up continuously. The configuration of the switch is chosen according to the customer's or end customer's wishes. Set-actual comparison for squeeze protection however has to be adapted to the window lifter's engine power. Also, the roadster's function of inside pressure regulation when closing the doors has to be taken into account. While a squeeze situation requires that the window immediately moves backwards and stays open, inside pressure regulation takes the windows to open shortly and close again instantly when doors are closed.

Partitioning partial functions into standard, discretely varying and continuously varying depends on the disciplines in which the functions shall be realized. Therefore, enhanced functional subdividing and enhanced functional structuring are mutually interacting with each other. Following enhanced functional structuring, partial functions are structured into the corresponding disciplines. In the process the general guideline is applied, that high degrees of individualization are to be implemented in software. Mechanical, electric, electronic subsystems shall primarily be used to realize standards or discretely varying partial functions. Supplementary, individualization options shall be separated in one discipline only. Thus coordination efforts within development and testing are minimized.

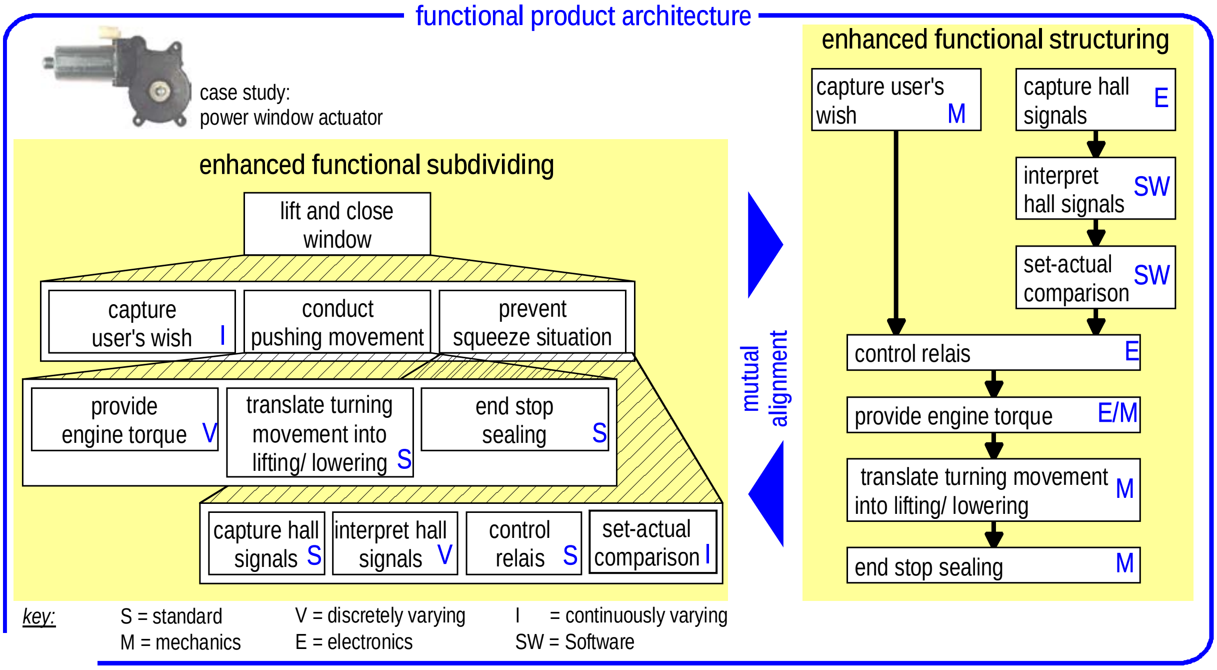
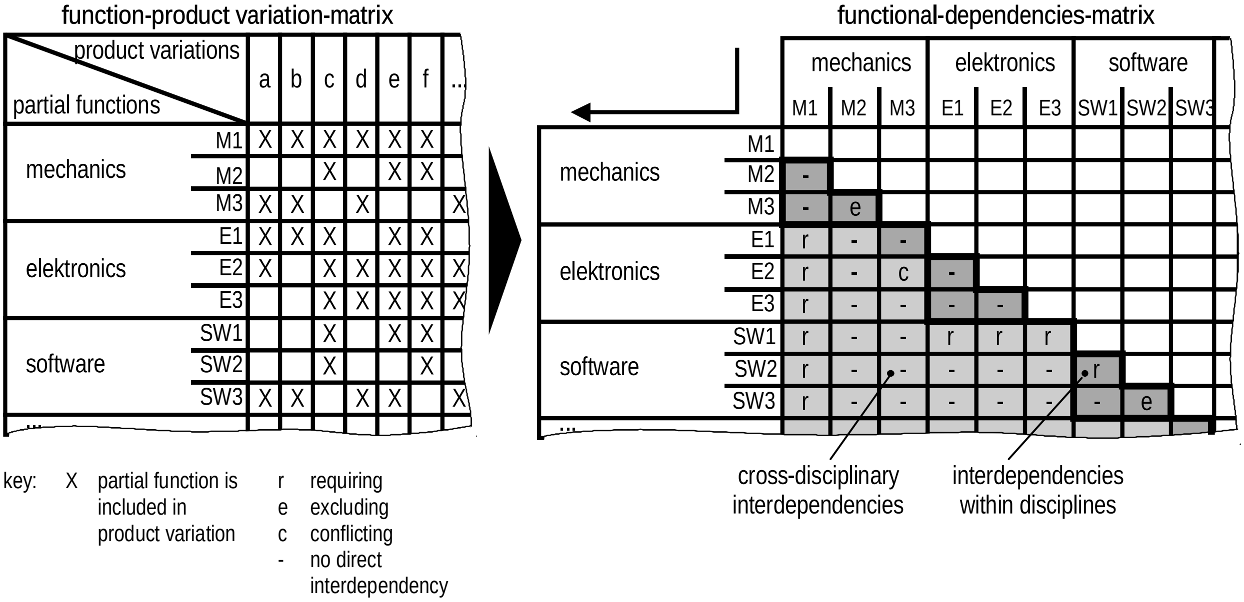


Figure 7. Case Study Power Window Actuator



function-product variation-matrix

partial functions	product variations	a	b	c	d	e	f	...
mechanics	M1	X	X	X	X	X	X	
	M2			X		X	X	
	M3	X	X		X			X
elektronics	E1	X	X	X		X	X	
	E2	X		X	X	X	X	X
	E3			X	X	X	X	X
software	SW1			X		X	X	
	SW2			X			X	
	SW3	X	X		X	X		X
...								

functional-dependencies-matrix

		mechanics			elektronics			software		
		M1	M2	M3	E1	E2	E3	SW1	SW2	SW3
mechanics	M1									
	M2	-								
	M3	-	e							
elektronics	E1	r	-	-						
	E2	r	-	c	-					
	E3	r	-	-	-	-				
software	SW1	r	-	-	r	r	r			
	SW2	r	-	-	-	-	-	r		
	SW3	r	-	-	-	-	-	-	e	
...										

cross-disciplinary interdependencies

interdependencies within disciplines

key: X partial function is included in product variation

r requiring
e excluding
c conflicting
- no direct interdependency

Figure 8. Example of methods use in phase 2

Besides enhanced functional subdividing and structuring, mutual logical dependencies between optional and necessary partial functions have to be determined and checked. In order to fulfill this purpose, matrices are applied. The idea of “function-product variation-matrix” (figure 8) is based on the “product and feature matrix” of software development [16]. In function-product variation matrix alternative choices of functions of the customer specific construction kit are mapped. Due to the pursued prospective design approach predicted product variations are taken instead of selected pilot customers. In addition to the overview of alternative functional ranges, transparency of mutual dependencies is given in a functional-dependencies-matrix (based on feature graphs [16]).

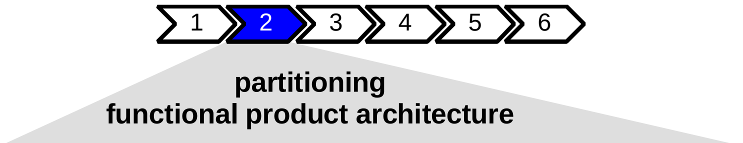
Core result of design methodology’s phase 2 is a functional product architecture to be used by all customized variants. An overview of resulting partial results of phase 2 is given in figure 9.

3.3. Cross Disciplinary Variation Mechanisms

Besides general tolerance of cross disciplinary variation mechanisms, in particular compatibility of interconnected variety ranges has to be ensured. Basis of coordinating partial solutions between involved disciplines is established by breaking down the entire function into partial functions during phase 2 as described above.

Mutual compatibility of discipline bound working principles, effects and algorithms is checked and ensured in phase 3. Only working principles which are compatible among each other, are selected and connected. Due to cross linked disciplines, working principles must not only be compatible within each discipline, but also cross disciplinary. Principle solutions are only valid, if variety ranges of partial working principles complement one another to the functionally required overall variation span. Interactions between alternative states of interconnected working principles are checked, whether they weaken, exclude or intensify each other. Critical constellations must be replaced by alternative working principles.

In the context of physical product architecture (phase 4), logical variation possibilities are embodied in terms of components and coordination is optimized as a whole. In this step, cost effects of assigning variety to disciplines become evident. The strategy of cross disciplinary variation mechanisms is put into action by the following approaches. As already known from conventional construction kits, customers select components out of a collection of alternatives as well as additional components can be mounted. As characteristics of construction kits for customer specific solutions these mechanisms



VDI 2210E	establishing function structures
entire mechatronic system	- enhanced functional subdividing - enhanced functional structuring - functional range of expected product variations - specification of - cross-disciplinary functions - functional interfaces between the disciplines - discipline bound standardization and variation share
mechanics, electrics, electronics	- specified partial functions - partial functions assigned to disciplines to become: - standards - discretely varying - continuously varying - structures of partial functions - specified interfaces between partial functions - specified interfaces between disciplines - dependencies between partial functions
software	- defined software features - software partial functions to become - standards - discretely varying - continuously varying - structures of partial functions - feature graph - specified interfaces within software partial functions - specified interfaces with other disciplines

Figure 9. Partial results of phase 2

are completed by adaptation of discretely varying components and configuration of continuously varying components. Prerequisites are standardized interfaces, independent components and limited interactions between all kinds of components.

In phase 5, connected variation mechanisms are investigated on level of the entire mechatronic system and optimized if necessary. In detail, combination of discrete and continuous variation ranges must correspond to the overall variation span defined in the specification.

Variation mechanisms determined along development are documented using parameter tables (for discretely varying components) and technical restrictions or constraints (for continuously varying components) in phase 6. Besides direct and desired interdependencies, also unwanted interactions of multiple parameter variation are documented.

4. CONTROLLING THE BALANCE OF INTERNAL AND EXTERNAL VARIETY

In order to control consequent realization of product variation, a measurement system consisting of key figures must be put up and integrated into business processes. Within these processes, not only responsibilities, but also reporting and decision structures have to be defined. In figure 10, the resulting process is illustrated. During conceptual design of customer neutral platform development the appropriate degree of re-use is planned. As all platform standards, preferred production processes and preferred components, are stored in a universal techniques catalogue, new proposals for standards are identified. Proposals must be released by a technical committee before they become a part of the techniques catalogue. If open questions are left, proposals are reworked. Key figures of planned re-use are used as milestone criterion of platform concept release.

Once the platform concept is released, derived variant or application projects can use the planned re-use as development guide. First of all, specific product requirements are compared with planned re-use. If deviations from techniques catalogue are detected, they have to be released by the technical committee. As next step, the planned conformity factor of the customer project resulting from comparison has to be released at the milestone “conceptual design”. The conformity factor describes in how far a derived variant or application follows the planned logic of re-use. From this point on, realized conformity factor is continuously reviewed against planned conformity factor. Thus a self controlling system is implemented.

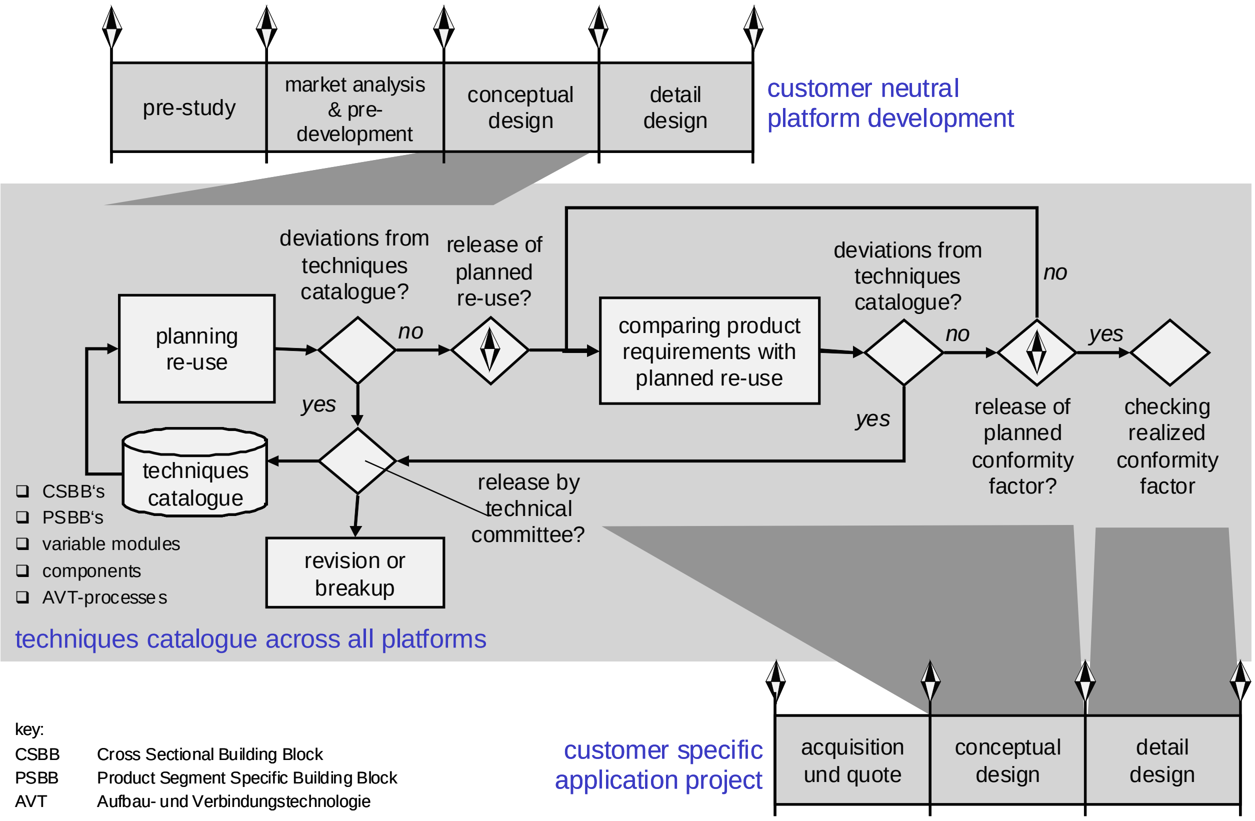


Figure 10. Business process of controlling internal variety

5. CONCLUSIONS AND FUTURE PERSPECTIVES

In this contribution, a design methodology for customer specific construction kits is presented. Applying this design methodology, producing companies are enabled to open up potentials of mass customizing mechatronic systems.

However, successfully initializing, implementing and keeping up a customer specific construction kit, relies on a profound change of values and behaviour in all classical key functions of an enterprise. Therefore, much thought and effort must be spend on change management in order to implement the new design methodology. Special emphasis must be put on sales and marketing, engineering, production and logistics.

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