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Identifying Expedient Variations in PGE – Product Generation Engineering

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Abstract

Product development can be described as PGE – Product Generation Engineering: A new product is developed based on at least one existing reference product. For the development of the new product generation subsystems from reference product are either carried over or used as the starting point for new development in the form of embodiment variation or principle variation. This contribution referrs to development situations where the functional requirements for a new product generation are defined and potential reference products are known. Based on this a method is presented, which supports the choice of the finally used reference products and the identification of the required type of variation a) to fulfill the functional requirements and b) to limit the share of newly developed subsystems as an indiciator for the overall development cost. The method is developed and firstly applied in cooperation with an automotive supplier in the development of a multifunctional solenoid valve for the thermal management for electric vehicle. The basis for the presented approach are design structure matrices to depict on the one hand the relation between functional requirements and subsystems which are in the simplest case components. On the other hand they map the interrelations between the different subsystems. Such matrices can e.g. be derived from existing modeling approaches which link i.a. geometry models in CAD with models of functional structures. The final result of the described method is displayed in an additional matrix which was specifically developed for the presented method. It includes for several potential reference products and all functional requirements of the new product variations of PGE which would be necessary to achieve the intended range of functions and resulting variation shares. The detailed analysis and implementation of the derived variations as well as the choice of one or more specific reference products have conclusively to be done by the developer himself. The method is helping in systematically creating multiple starting points for possible solutions as well as providing a decision support for this process.

Keywords: Reference Product, Share of New Development, DSM, FAS4M

1 Introduction and Motivation

The debate on the 'dieselgate' is ongoing (Bennhold, 2018). Amongst other topics, politicians, managers and engineers discuss, whose task it is to predetermine aims, for example regarding car emissions or to specify the technologies to achieve those aims. Regardless of the result of this debate are the current development state of different technologies and the next development steps which are possible without undergoing a too big technological and economical risk, an essential factor for the way and iterations in which the desired aims are achieved. Thus, methods are required which support, in different aspects, the selection and implementation of technological solutions based on the currently existing systems. In this overall context the following sections present a method which focusses in detail on the design of new generations of technical systems, using as an example a particular subsystem which will be needed for upcoming, electrically powered vehicles.

2 State of the Art

2.1 PGE – Product Generation Engineering, Product Creation and Assessment of Changes

PGE – Product Generation Engineering according to ALBERS is an approach to describe product development based on two main hypotheses (Albers, Nikola, Wintergerst, 2015): First, every development of a new product is based on at least one existing product. Such systems are called "reference products". Reference products can be preceding products of the same company ("internal reference products") (Albers, et al., 2016a), but as well competitor's products or systems from other branches ("external reference products"), for example. Hence, the development of a new product is understood as the development of a new product generation. Starting with reference products the second main hypothesis states that the development of a new product generation can completely described as a combination of three different activities, which are different ways of how subsystems of the new product are developed:

- Carryover variation: Subsystems from reference products are directly reused and only changed at the interfaces to other subsystems, if this is necessary for system integration.
- Embodiment variation: The solution principle of a subsystems is maintained compared to the reference product, but the embodiment of the subsystem and its elements is adjusted.
- Principle variation: A new solution principle is chosen. Going along with that is the design of the embodiment for this new solution principle.

Embodiment variation and principle variation are together the share of new development. In a survey developers from industry confirmed the description of product development projects according to the PGE approach (Albers, et al., 2016a). Product development projects are characterized by the conflict of aims between keeping development risks low on the one hand and generating sufficient differentiating characteristics for market success on the other hand. Challenges and risks in the development process are related to the share of newly developed subsystems, i.e. the share of embodiment variation and principle variation, the organisational origin of the used reference products and the system level that is affected by variations, referring to the extent of change in the system structure compared to the reference product (Albers, Rapp, Heitger, Wattenberg, & Bursac, 2018). Using the development of several product generations of the Dual Mass Flywheel, a powertrain component in cars, as a case study, (Albers, Bursac, & Rapp, 2016b) show, how different variations led to development risks and costs. The example furthermore indicates that the different variations of PGE are related in a characteristic ways to the change of the wirk structure of a product. The wirk structure describes the relation between

the embodiment of technical subsystems and components and their functions (Albers, Sadowski, 2014).
Weber & Husung describe the design of a new product as the iterative combination of existing blocks ("patterns"), each of which including a specific way, how the relation between certain characteristics and properties is implemented (Weber & Husung, 2016). As an essential part of the design process, different of those patterns have to be connected to create a product with a set of certain characteristics leading to a certain set of desired properties. The change of individual subsystems in an already system and the effects on other subsystems in that system can be modelled, i.a. by using DSM (Clarkson, et al., 2004). This can give an overview about the "criticality" of individual subsystems, regarding design changes.

2.2 DSM, MBSE & FAS4M

The Design Structure Matrix (DSM) is able to model and analyse the relationship between all the subsystems in highly complex systems (Eppinger, 2012). A typical example would be to analyse all the dependencies between the components of a technical product. This way it is possible to illustrate, which components are affected by the change of one of them.
In System Engineering (SE) there is the vision to store all artifacts of the development in a model-based way. It is referred to as Model-Based Systems Engineering (MBSE) (Beihoff, et al., 2014) (INCOSE Technical Operations, 2007). By model-based treatment of the engineering information, the three "evils" of the SE can be counteracted according to HOLT: Complexity, lack of understanding and communication problems (Holt & Perry, 2013). In addition to the cross-disciplinary modelling of context and stakeholder analysis, use cases, requirements, first aspects of structure and behavior of the system , there is an increasing desire to link discipline-specific models consistently to the interdisciplinary content (Beihoff, et al., 2014). To do so in the domain of mechnics the FAS4M approach was developed (Moeser, et al., 2016).
It focuses on the development of embodiment design starting from functions. The mechanics modeling language (MechML) offers SysML Stereotypes to model functions, principle solutions, concepts and components along with their interdependencies (see Figure 1).

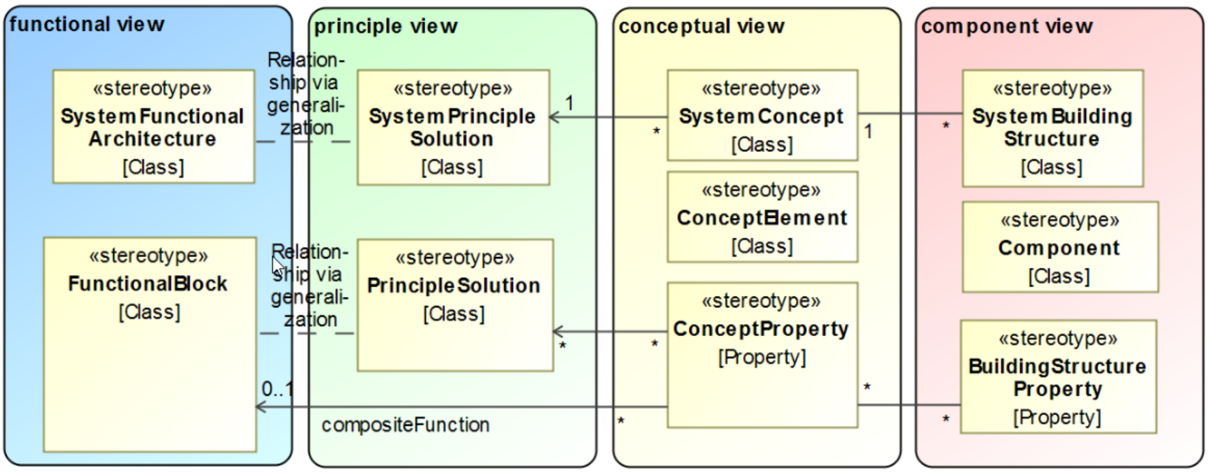


Figure 1. The main stereotypes of MechML for modelling functions, principle solutions, concepts and components (FAS4M-Konsortium, 2016)

The use of such models from previous company-internal products within the PGE opens up potentials for a better effort-benefit balance of modelling. The modelling effort for a new generation can be estimated based on the variation type. (Albers & Moeser ,2016)

3 Need for Research and Research Method

Looking at a development situation, where the desired functional requirments for the next product generation are determined and a set of potential reference products is available, the challenge is to find out of all possibilities those finally used reference products and expedient variations for the individual subsystems. This contribution therefore aims at answering the following research question:

How can expedient variations in PGE be found for the implementation of a known set of functional requirements with a given set of potential reference products?

The research was conducted in an exploratory case study: In an automotive supplier company the development of a multifunctional solenoid valve for the thermal management for electric vehicles was used to develop and firstly apply the presented method. Design structure matrices are used and further own visualisations are developed. Conclusively the method is integrated in a process which illustrates, where and how required basic information is gathered and where the results of the method are used.

4 Finding Expedient Variations

In the next sections the method to find expedient variations for the development of a new product generation is explained at first. After that a possible way of gaining the necessary information based on MBSE is considered and an overall process sketched.

4.1 Identification of Reference Products and Derivation of Expedient Variations

Like shown by Moeser and Albers, a change in the requirements from one product generation to another will result in one out of four different cases (Albers & Moeser, 2016):

- Carry over of the requirements. This means, that the new product generation has to fulfil the same requirements as the previous product generation: → Carry over of the regarding subsystems
- New requirements are fulfilled by the previous product generation. In this case the requirements for the new product generation are adjusted, compared to the previous product generation. However, the subsystem from the previous product generation can fulfil these adjusted requirements without any adaption, for example due to over-dimensioning or "power reserves" → Carry over of the regarding subsystems
- New requirements can be met by using the same principle but the components have to be changed in dimensions → embodiment variation of the regarding subsystems
- New requirements cannot be met by embodiment variation → Principle variation of the regarding subsystems

Therefore it is possible to identify the relation between requirements to fulfil in the next product generation on the one hand and fulfilled requirements provided by a reference product on the other hand as a basis for deciding between carryover variation (CV), embodiment variation (EV) and principle variation (PV).

Based on this the presented method requires deeper knowledge about the used reference products. Especially the correlation between subsystems and functions of a reference product as well as the dependencies between all the subsystems are from interest. The method uses two matrices to illustrate the results of these analysis. The Function-Subsystem-Matrix (FSM) (Figure) is specific for each reference product or new product generation and is used to display the relation between the different subsystems and the functions of the system. The Design Structure Matrix (DSM) (Figure) is also specific and displays the connection between the different subsystems and is used to identify subsystems which are affected by an embodiment variation or a principle variations of another subsystems. Both matrices are used for the execution of embodiment variation and principle variations as well as to identify the percentage of all three variation types

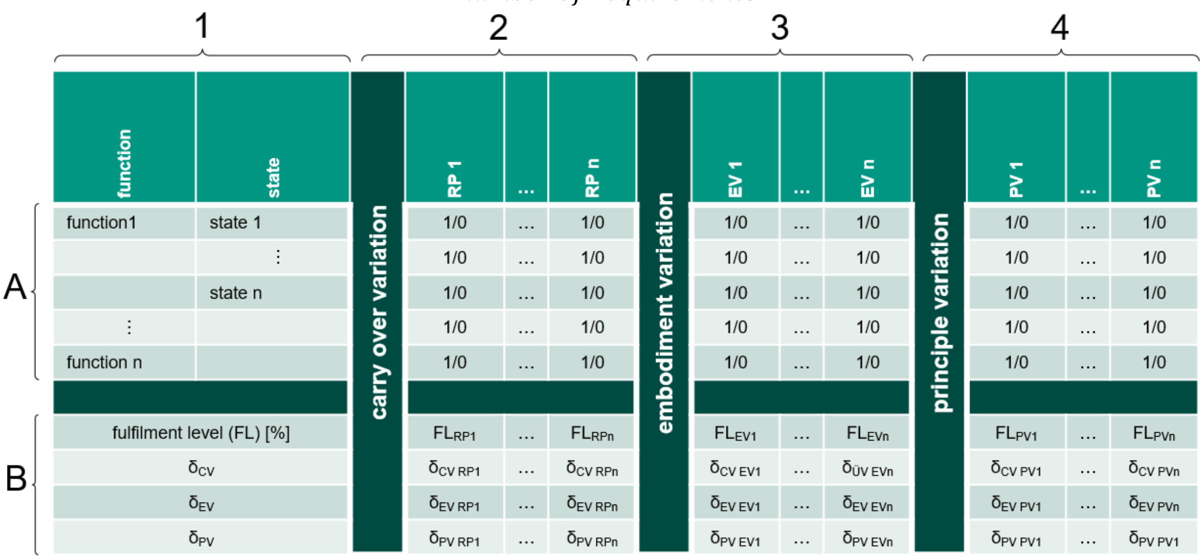
FSM	Subsystem 1	Subsystem 2	...	Subsystem n
Function 1	x			x
Function 2	x	x		
⋮				
Function n		x		x

DSM	Subsystem 1	Subsystem 2	...	Subsystem n
Subsystem 1	-	x		x
Subsystem 2	x	-		x
⋮			-	
Subsystem n	x	x		-

Figure 2. FSM and DSM

A third matrix, the "PGE-Matrix" as shown in Figure 3 is the core item of the presented method. The PGE-Matrix is used to visualize the binary comparison of all required functions and function states for the next product generation with the functions and function states a reference product or its subsystem offers. The PGE-Matrix shows an overview about possible solutions for the complete or partial implementation of an aspired functional framework. This way the PGE-Matrix offers the possibility to choose adequate reference products for a new product generation. By using the fulfilment level (FL) and the percentages of carry over variation, embodiment variation and principle variations the PGE-Matrix can display a base for a very first estimation of the development effort for each concept.

$$FL = \frac{number\ of\ fulfilled\ requirements}{number\ of\ requirements}\ [\%]$$



RP*n*	Reference Product *n*	δ_{CV}	Subsystems developed by carry over variation
EV*n*	Embodiment Variation *n*	δ_{EV}	Subsystems developed by embodiment variation
PV*n*	Principle Variation *n*	δ_{PV}	Subsystems developed by principle variation

Figure 3. PGE-Matrix with its different sectors

The set of required functions for the new product generation (G_n) is listed on the left in the PGE-Matrix as shown in Figure 3, A1. The available potential reference products are listed in the columns 2. Each reference product has to be analysed and compared to the intended requirements for G_n. Does a reference product provide a required function / function state (A1) without any variation it is rated *"1"* in the section A2. Otherwise it is *"0"*.

functions	state	carry over variation	RP 1	
function1	state 1		1	Indicates carry over variation of subsystems
	state 2		1	
function 2	state 1		1	Indicates shape variation of subsystems
	state 2		0	
function 3	state 1		0	Indicates principle variation
	state 2		0	

Figure 2. Explanation of how to apply the indicators to the PGE-Matrix

functions	state	carry over variation	RP 1	RP2	
function1	state 1		1	1	
	state 2		1	0	
function 2	state 1		1	1	
	state 2		0	0	
function 3	state 1		0	1	Indicates principle variation by merging the FSM of two reference products
	state 2		0	1	

Figure 3. Indicator for FSM merging

By analysing different reference products in the context of the presented case study it was possible to identify an indicator whether embodiment variation of a subsystem is adequate to meet the new requirement or if principle variation is inevitable (Figure 2). An embodiment variation is indicated by a subsystem, which is able to fulfil a required function to some extent, but not all required function states. A principle variation is indicated by a subsystem that is not able to fulfil a required function at all.
By using the FSM it is possible to determine the subsystems, which are involved in a certain function. Considering the indicators (Figure 24) it is possible to identify which subsystems would have to be developed by embodiment variation to increase the extent to which the required set of functions for G_n is implemented. The results of these embodiment variations are new solutions and are listed the columns 3 analogous to the reference products in sector 2 (Figure 3). The DSM allows to check which other subsystems will be effected by the change of a subsystem. With this knowledge and the new FSM it is possible to calculate the percentages of carryover variation and embodiment variation for each possible solution. Those percentages are listed in the section B3 and will be one considered aspect in the selection of solutions. Using the same technique it is possible to identify the need for principle variation. Solutions created by principle variation are listed in the columns in sector 4.
It is possible to derive from the PGE-Matrix that in special cases (Figure 3 and Figure 6) it might be reasonable to merge different reference products or solutions to fulfil a given functional framework. Therefore it is possible to merge the corresponding FSM and DSM to create a new solution by principle variation.

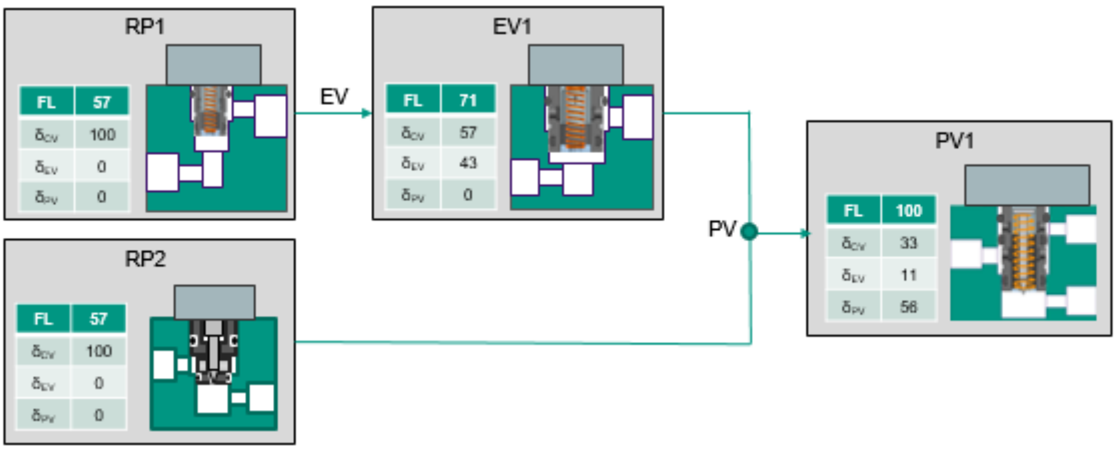


Figure 4. Example of the development process of a solenoid valve

The first application of the method showed that, once all necessary information about the reference products is collected, the developed method is well suited to generate a multitude of possible solutions and concepts which are able to fulfil a given set of functional requirements. At the same time it is possible to determine the percentages of carry over, embodiment variation and principle variations for these solutions on the base of more than one reference product. Using the method, the product developer found new solutions and concepts for the new product generation of solenoid valves.

In the context of this case study it was noticeable that not all created solutions were technically feasible. This leads to the consideration that currently the developer has to check the practicability of each individual potential solution which has been suggested by this method.

After analysing all available reference products the fulfilment level and the knowledge about the identified indicators where a helpful tool to choose the most potential ones for deeper investigations. To identify potential reference products for new product generations it is necessary to have proper knowledge about the products. In case of using internal reference products this can be achieved by appropriate knowledge transfer. Investigations regarding this topic during the case study lead to the result that the common used tools in companies are office solutions. Especially PowerPoint presentations are often used for two purposes – as a communication tool and also for archiving the information. A not in the original development integrated product developer is confronted with much information stored in presentation files if he wants to reuse former product generations. Non-standardized and extensive branching structures additionally aggravate to regain information. Furthermore the saved files do not always contain all the information needed to understand decisions which were made during development processes.

4.2 Support by MBSE

From MechML models according to the FAS4M approach the dependency of components to functions can be retrieved. Thus, the information, which is needed as a basis for FSM and DSM, is known from the models. If a model-based product development is carried out, the matrices can be created based on the models once the products or subsystems of them are used as (potential) reference products in future developments. In the case of company-external reference products, the relevant information must be compiled in other ways and can then be stored in similar models. A comprehensive product model does not have to be created. Only the functions and components with the linking elements have to be mapped.

Thus the effort to prepare the FSM and DSM of the presented method can be reduced by using model-based resources. How this can be done in a continuous process is shown in the next section.

4.3 Overall process

The method presented in this article can be used in combination with MBSE as follows in a continuous process over different product generations. Figure 5 shows a recurring section of a cross-generational process. It focuses on the use of the presented method within the development of generation G_n.

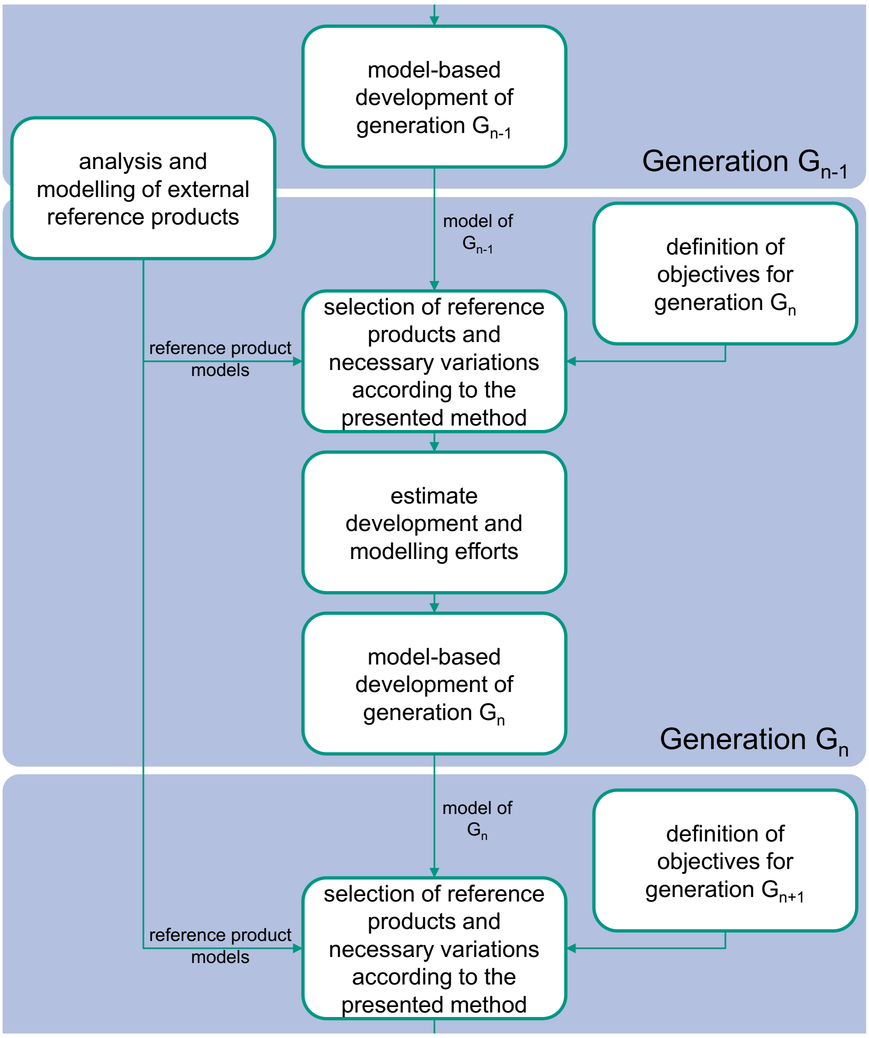


Figure 5. The presented method in a cross-generational process

First, the desired functions of the new generation G_n are needed. They are based on the system of objectives. Secondly, the models of potential reference products are used. From the development of the previous product generation, which was carried model-based, the model of G_{n-1} is available. The models of other (especially external) reference products can be achieved by analysis. In the course of time a database with models will be built up, which can be used over and over again. The models deliver the input for the PGE-Matrix as shown before. Using the method shown in this article, the reference products are selected. Furthermore, the necessary variations are determined. Based on the different cases shown by Albers and Moeser (Albers & Moeser, 2016) the development and modeling efforts are estimated to define the size of the development project. The development of G_n itself is carried out model-based. Thus, the model can be used again for future generations.

5 Conclusions & Discussion

Using the method, promising configurations were found and further assessed in the development process. It shows that systematic PGE by considering the available potential reference products is a key element for product development. However, beyond pointing out possible variations to implement the desired functional requirements, different steps are still left for the developer, including the final decision and its preparation. First, the developer has to analyse in detail, which design activities will be necessary, e.g. in the course of an

embodiment variation. Especially when combining several subsystems from different reference products it is necessary to check consistency, meaning whether this combination is probably possible or not and, if it is, which development efforts are required. The final development of the product will still demand a lot of creative work by the developer.
The limitation of the development risk is tried by choosing configuration with small shares of subsystems, which are developed by embodiment or principle variation. But, as even single variations might cause great development risks in specific cases, this approach gives a first estimation, but needs as well a more detailed assessment in the following development process. This refers as well to the aspect of innovativeness. Building up on already existing systems and models to limit development risks to a great extent might run contrary to reaching a sufficient level of innovativeness. However, for this contribution, a situation in the development process is assumed, where this aspect has already been discussed and transformed into the requirements for the next product generation. Hence, the "innovativeness" – or rather the "newness" – is depicted by requirements for the new product generation which differ to a greater extent from the requirements which were fulfilled by the previous product generation.
The matrices on which the method is based require some effort in their creation, even for systems with a relatively low complexity. It can be argued that those matrices could be available from former development projects, if such models are successively introduced, created and updated within a company, when using internal reference products. In cases where external reference products are used modelling activities might be necessary, at least for subsystems which are taken into account when applying the method. This modelling effort might rise with the complexity of the corresponding systems or subsystems, respectively. The system in the case at hand can be considered to be of modest complexity, compared to a whole car, for example. Looking at more complex systems the level of detail might become an additional influencing factor for the applicability of the method. Looking at the development process of a car one can observe for example that the definition of variations and finally used reference products happens on different levels of detail and with a varying extent to which functions are already defined specific (Albers, Rapp, Heitger, Wattenberg, & Bursac, 2018). Especially in early stages of the development process in some areas only desired properties of the product might be specified, while functions and the technical solution itself are still unclear. The usability of the presented method in such situations is yet not clear.

6 Outlook

Future work is intended to investigate more in detail the consistency of subsystems of a new product generation, when different reference products were used for them and maybe different types of variation. Further support of the developer might enhance the prioritisation and selection of different possible configurations, including in addition to consistency checks a more detailed estimation of development efforts and possible risks. Beyond the analysis of the technical feasibility, support should also be available not only when reusing concepts from reference products, but the product documentation, i.e. all the different models which were created during the development of products. Their at least partial reuse contains efficiency potentials for development processes. It has to be investigated, how the product documentation from reference products has to be provided to the developer to improve the development process.

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