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New Trends in the Design Methodology of Modularization

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Abstract

The paper shows the present status of the design methodology research especially in the topic of the development of modular product architectures preferred from existing product families. After an introduction in the motivation of this topic the state of the art is shown in a compressed way. An introduction is given in the Integrated PKT-Approach of Development of Modular Product Families that was developed at the Institute of Product Development (PKT) at the Hamburg University of Technology (TUHH). After a short overview of the topics of present research work three new trends are introduced, which have a great influence in the future research work of modularization. Future robust product family architecture, modular lightweight design and mass personalization are the important topics, which are explained in more detail.

1 Introduction

Starting from the megatrends globalization, shorter product life cycle and individualization 2.0 (or now 4.0?) there is a lot of pressure in the market to develop and produce a high number of product variants to achieve the customer needs and wishes also in the industry of mechanical engineering which is the focus of this paper. It is state of the art that modularization with the aim to get modular product architectures is a common product strategy to handle a great market variety in a product family design. Otherwise the complexity became greater that means every activity in a company to handle the variety increases the internal variety on the product level as well as on the process level. Therefore you can divide the common strategies in the product based and process based strategies that means modular or platform product strategies and postponement or commonality process strategies.

The main aim of these strategies is to reduce the internal complexity and get a better situation on the market. There are three general possibilities available.

- Reduction of complexity to delete unprofitable product variants from the market
- Increase the benefit of the product for the customer to get more returns
- Reduce the complexity costs to reduce the product costs too

What does complexity cost mean? It contains all cost aspects to handle additional variance of products, components or processes resulting from new customer requirements not covered by the current program. Figure 2 shows a lot of examples, e.g. additional testing, high inventories or long delivery time that increase the complexity and also the complexity costs.

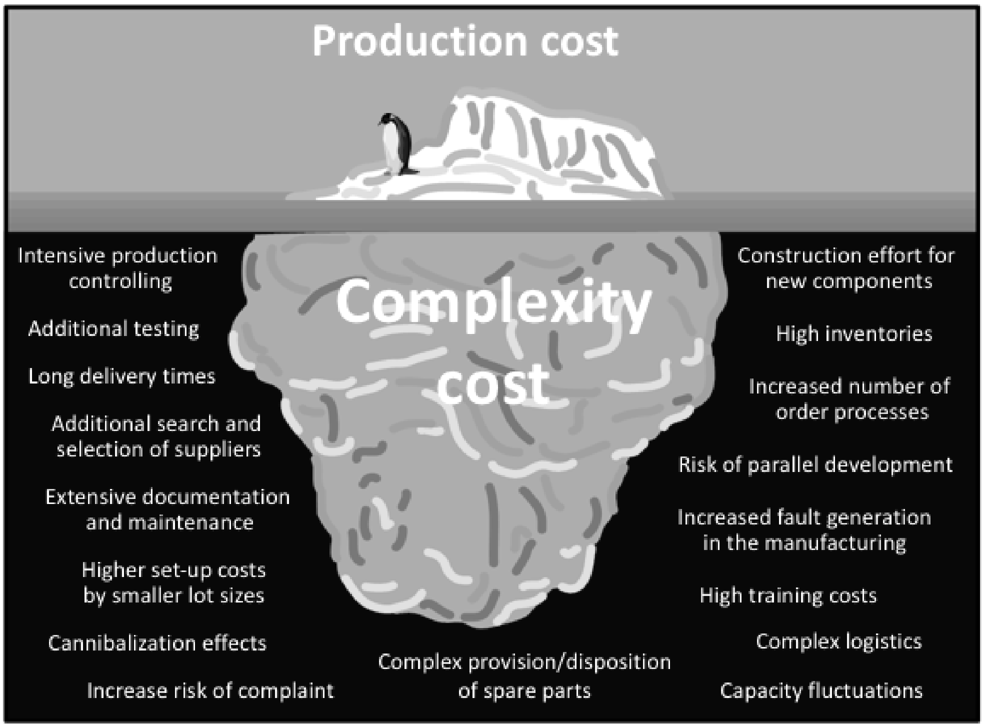

Figure 1: Production costs versus complexity costs

Why does this happen? There are a lot of reasons that complexity induced from the variety (and only this part of the complexity is considered) arises (Figure 3). This complexity has an impact to all product life phases and therefore it is not an isolated item. The complexity costs don't occur immediately if new product variants arise. Some of them start later (temporally) or when the number of variety increases further; and some of them couldn't be reduced later and they are independent from the reduction of variety; e.g. you build a new depot, because you have a lot of different parts. If you reduce the number of parts then you won't get back the investment for the new depot.

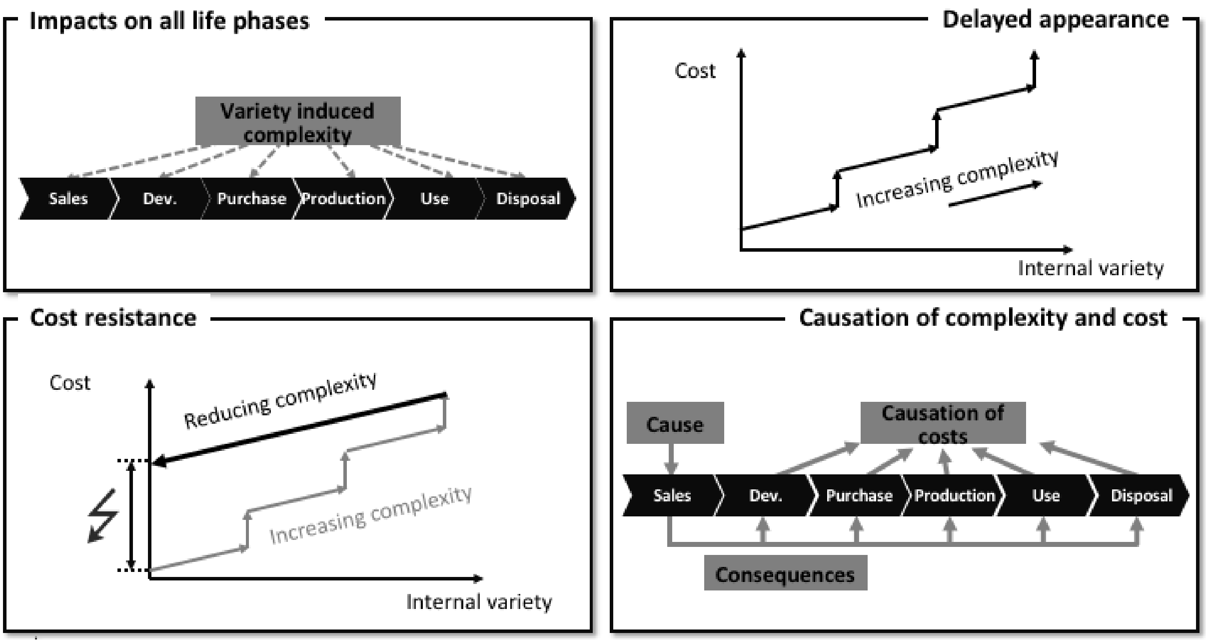

Figure 2: Characteristics of complexity cost [RiKr-2017]

The main reason why you get a high number of variants (and always new variants) is originated in the customer side and the sales department. They want to get a lot of orders to increase the turnover. The consequences of these decisions are received in every stakeholder of the product life phase and cause more complexity costs and sometimes also production costs.

2 State of the Art and PKT-Approach

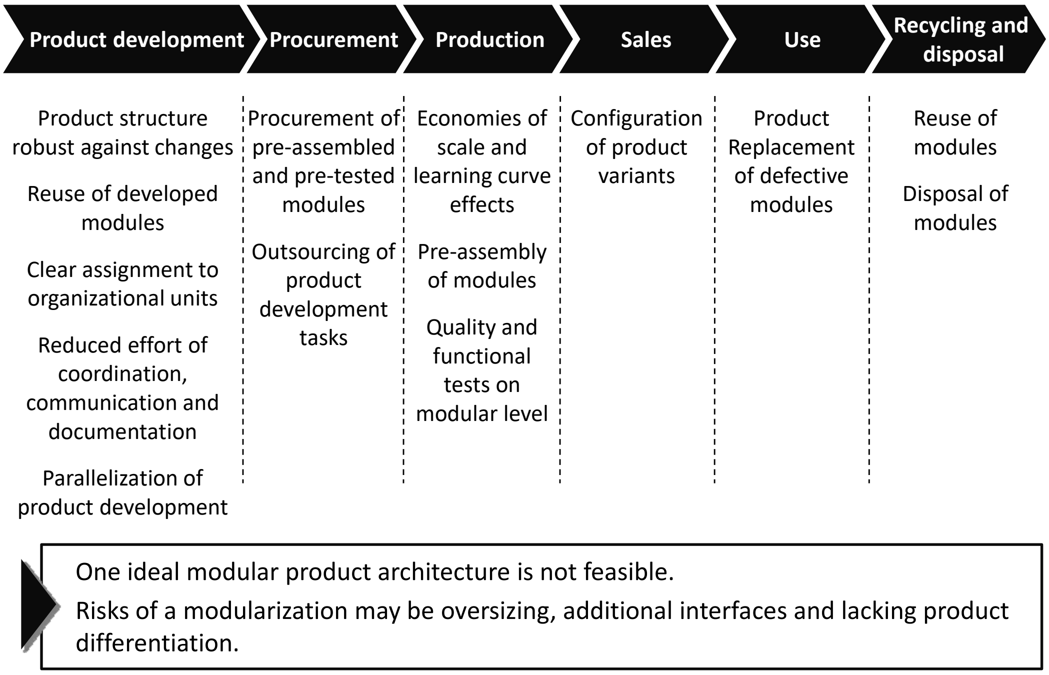

Figure 3: Advantages of modular product architectures

With modular products every stakeholder of a life phase has a lot of advantages, which is shown in Figure 4 and found in a lot of literature and case studies [OHSK-2016]. But the advantages are different from every life phases and therefore optimal product architecture cannot exist, because you can't fulfil all advantages at once. For this reason an integrated approach is developed and called "Integrated PKT-Approach for Developing Modular Product Families" [KBEG-2014]. It integrates technical-functional aspects, like DSM, Modular Design Methodology (MDM) or functional heuristics as well as product strategic elements, like Modular Function Deployment (MFD) or Product Family Maste Plan, in one approach to find the best compromises between the different advantages and the more fuzzy strategic elements which are often in the brains of experts. The modular product architecture is also depending on the useful degree of modularization also called granularity of modularization. Additionally the views of product and process should be integrated in the approach because both views have an influence on the modular product architecture and on the internal processes to develop, produce, assemble and to install the product variants.

A better result of modularization will be available, if you allow to modify the components or to design new components before starting the modularization process. The redesigned components should be more robust against variety (Design for Variety). A very important topic of the approach is the integration of the knowledge of the experts in a company. In workshops team discussions in combination with new or adapted tools fosters the process to find the best compromises in modularization (Figure 6).

In the last ten years a lot of case studies show that the integrated PKT-Approach is suitable and validated and adapted to different scenarios.

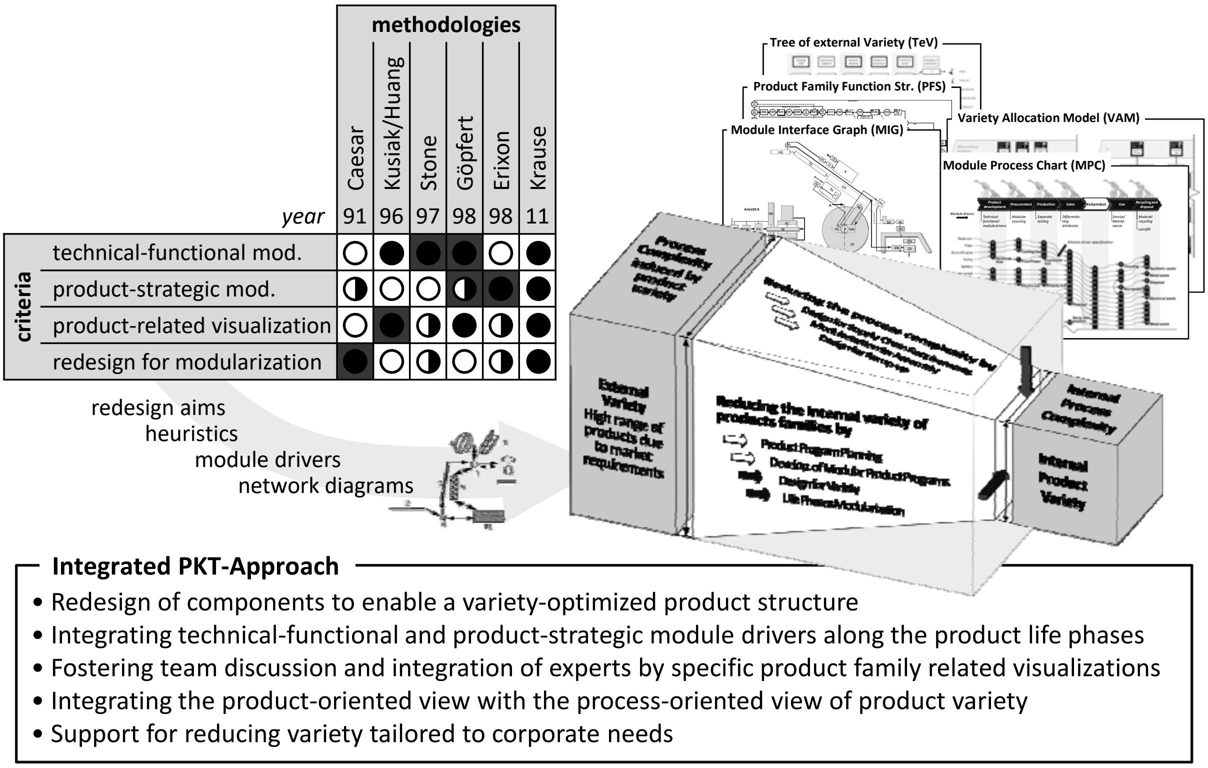

Figure 4: Influence on Integrated PKT-Approach [KrRi 2013]

3 Present Research - New Trends

Starting from the existing methods and tools of the PKT-Approach the present research work is presented and three important trends are showing the first results or the ideas behind this.

3.1 Present Research

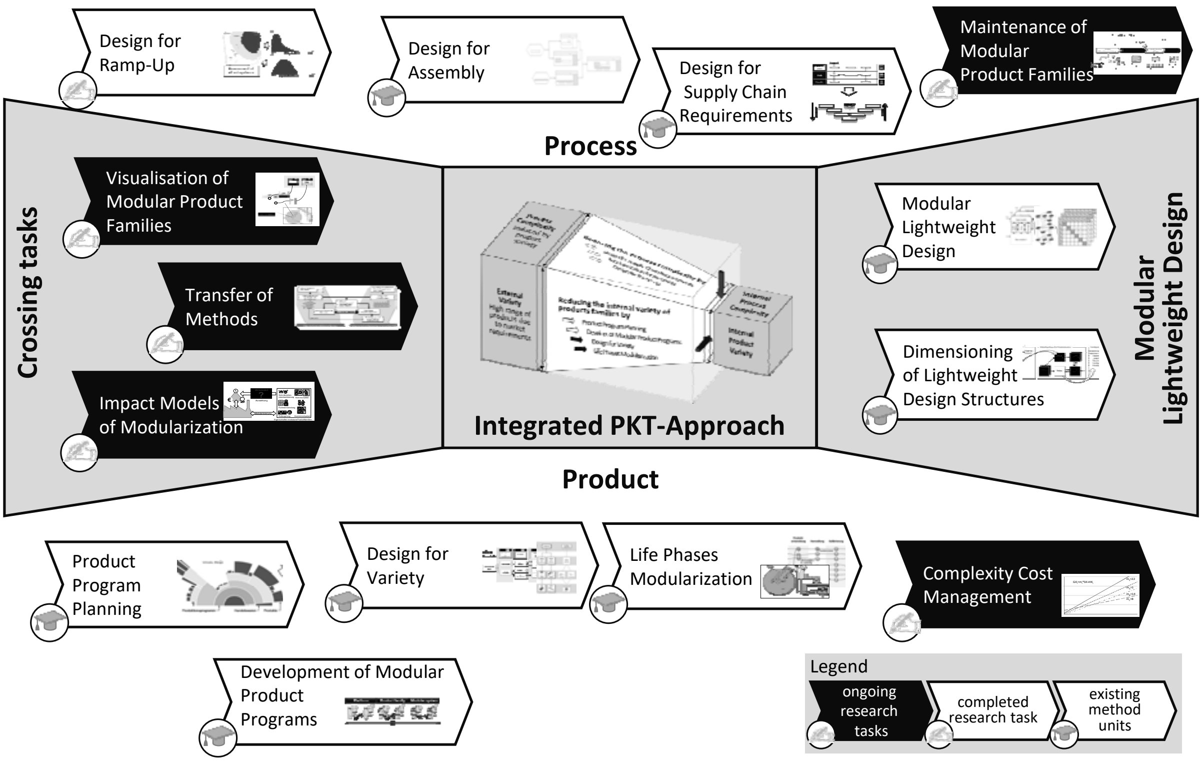

Figure 5: Method units and research topics at the PKT-Approach

In Figure 7 you can see all PhD thesis in the research field of the institute PKT: Above you can see the topics, which are concentrating on the process view, below the product oriented research work with the core methods of the approach, Design for Variety and Life Phases Modularization [BKBK-2010]and the enhancement to the whole product program [KrEJ-2013]. On the right hand side there is the special view on modular lightweight design which is explained in chapter 3.3 in more detail. The crossing tasks are very interested research topics which look to the development of methods especially to the possibilities of visualization in general and to the variety of products in detail [GeBK-2014], to the transfer of research methods into practice and industry [BGBK-2016] and to analyze the relationship between the properties of modularization to the key factors of costs, time and quality in an new impact model. Now eight of these topics are finished in dissertations, one of them will be finished this year and the five blue ones are ongoing research tasks.

3.2 Future Robust Product Family Architecture

One important research trend is to develop not only a good modular product architecture from the status quo but also a modular architecture that is robust against customer demands and wishes in the future. The reason especially in SME companies with an Engineer-to-Order (ETO) strategy is that some customers find new requirements after the start of purchasing a modular product family which isn't fulfilled by the existing modularity. This interested research topic is investigated in the research project ProRobuSt in cooperation with three SME-companies and one consulting companies funded by the German Federal Ministry of Education and Research in the program "KMU-innovativ".

The facts reveal the need of arrangements to reduce the internal variety in a company while keeping the flexibility as high as possible. Like previously described, modular product families offer a trade-off between these two contrary objectives. However, after the implementation of such modular product architectures, the disadvantages can recur after a certain time. Due to technological steps, new markets or new competitors can disperse the variety again. To counteract the occurrences, future changes of requirements must be investigated and considered during the design stage when the future robust product family is created. So it could be achieved that the needed adjustment efforts caused by future requirement changes are as low as possible (Figure 8).

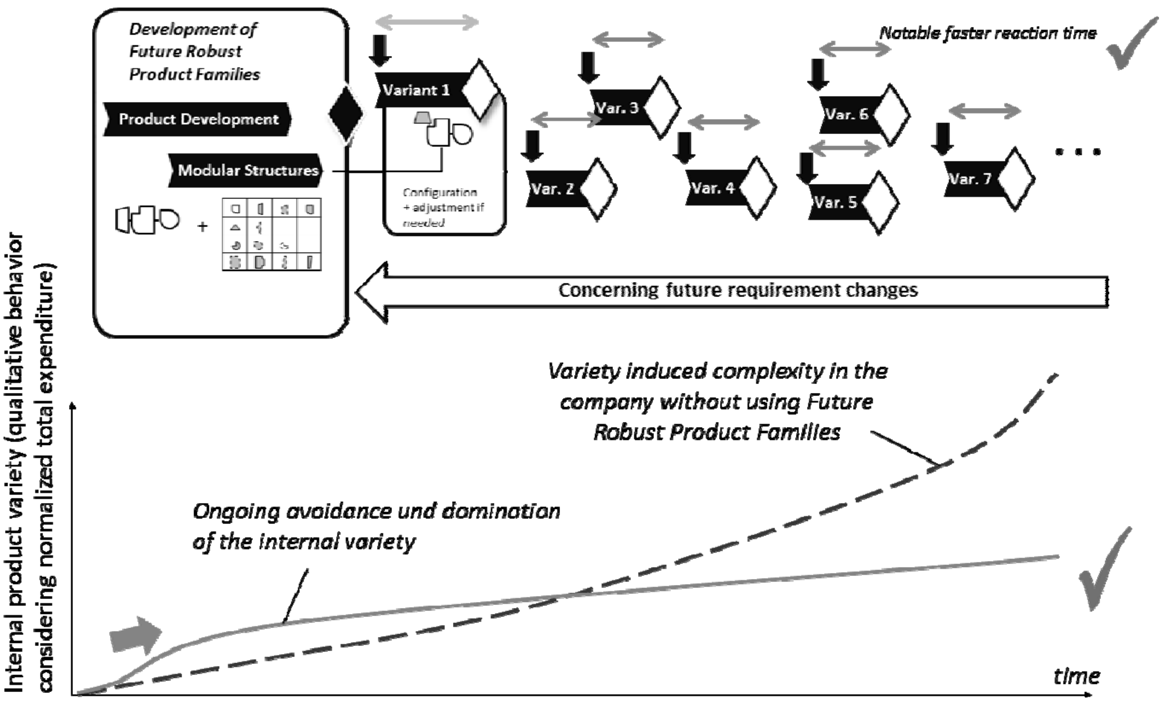

Figure 6: Effect of Future Robust Modular Product Families

For common understanding, a definition of the term “Future Robustness” is introduced. It can be described as *an ability of a product architecture, which allows the realization of necessary adjustments due to temporal changing requirements (e.g. technological steps, varying markets or costumer requirements) steadily with minimized effort and costs*. The benefits of such future robust product architectures can be essential for SMEs - for example resulting in notable faster reaction time based on less adjustment effort. To create such product architectures the changing requirements must be observed and translated into robust and flexible elements of the product architecture. Hence, the affected components can be designed in a way that further changes can be avoided or applied with minimal effort and additional costs.

One of the biggest challenges in the area of the development of future robust product architectures is the estimation of dynamic changes within a suitable accuracy. Often companies have to deal with too high uncertainties and can't predict changes with influences on the product architecture in a workable manner. In further consequence, they avoid the design of future robust product architectures or chose the wrong elements that are expected to be changed. This, however, could lead to increasing complexity again, induced by increasing variety.

In literature, miscellaneous approaches exist to handle product variety. Most of them include a procedure to plan strategic product programs, developing special product structures (e.g. modular structures), or managing the variety of IT-systems used.

In the area of planning strategic product programs the field of market analysis and future planning is most relevant. A comprehensive overview about pertinent methods and tools in the topic of market analysis can be referred to Jonas [Jona-2014]. Important methods in future planning are e.g. the Scenario technique developed by Gausemeier [GaPW-2009], Roadmapping [Behr-2003] or the Delphi Technique [FiSi-2006]. These methods offer possibilities to estimate future changes, but don’t link the gained information to the product architecture. Existing methods in structuring products often pursue just the design of product architectures itself, but neglect the term of future requirement changes.

Creating future robust product structures, both the management of the variety to reduce the complexity and the simultaneous consideration of future changes, must be joined up. Here the literature offers just a few approaches. In “Planning and development of change-robust platform architectures” by Bauer [Baue-2016] a platform-based approach is presented, which focuses on the identification of robust elements, but neglects the management of variants. In the DFG funded project “Scenario-based development of product architectures” a method has been developed that applies the Scenario Technique by Gausemeier and provides a tool to evaluate the uncertainties of product specifications for future robust product architectures [SSSR-2014]. This method is suitable for bigger companies, but inappropriate for the application in SME companies and validation is not finished yet. Often the optimization regarding external variety and costs is done by using modular product architectures, while the dynamic of requirements isn’t considered enough [Pirm-2011]. The link between the two aspects is crucial to address the revealed benefits of future robust product architectures and opens an area of investigation, which is worthwhile to look at in more detail.

3.3 Modular Lightweight Design

Despite the conflicting objectives of the modular design on the one hand and the lightweight design on the other hand, it has to be the goal for variant lightweight products to combine both aspects. Therefore the new approach of modular lightweight design will be characterized. The aim is to combine the positive aspects from both side into one new approach, to find out the right compromise between weight reduction and increase of complexity.

In addition, the third relevant target value in lightweight design is to find the lowest possible weight of a product. In contrast to pure lightweight strategies, the focus on modular lightweight design is on the lowest possible weight of the whole product family. This is not the weight optimization of a product variant, but it is the so-called fleet weight, the weight of the entire product family with the count of possible sales numbers per variant. With this different focus on weight reduction, a new combined approach can help to solve this conflict to meet the requirements of modular lightweight design [KOSR-2016].

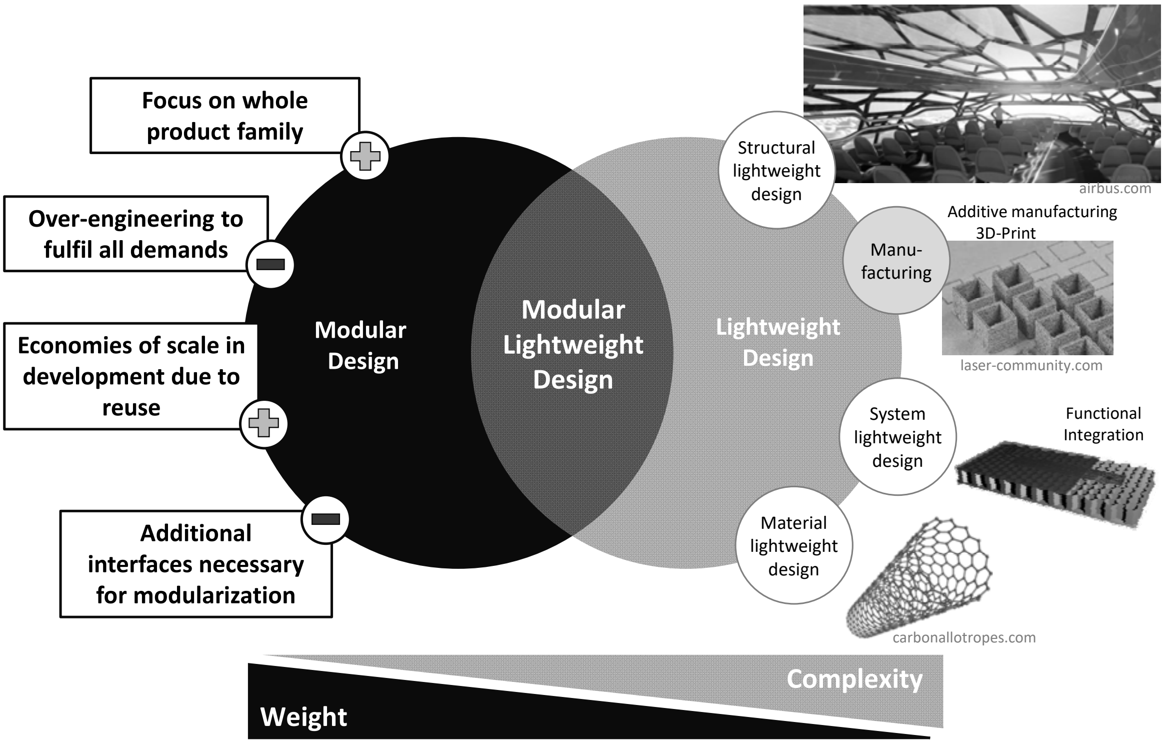

Figure 7: Area of conflicts caused by a combination of modular and lightweight design to modular lightweight design [KOSR-2016]

A further positive aspect is the effect of scales in case of the reuse of modules, which e.g. also reduces the test effort (see blue arrows in Figure 10). Due to a reduced complexity of a product that consists of clearly defined modules with standardized and simple interfaces, the dimensioning and testing of such modules is simplified. It is often also easier to perform only tests on the module level (level B: sub-structure level) instead of more complex tests on the overall product (level C: product level).

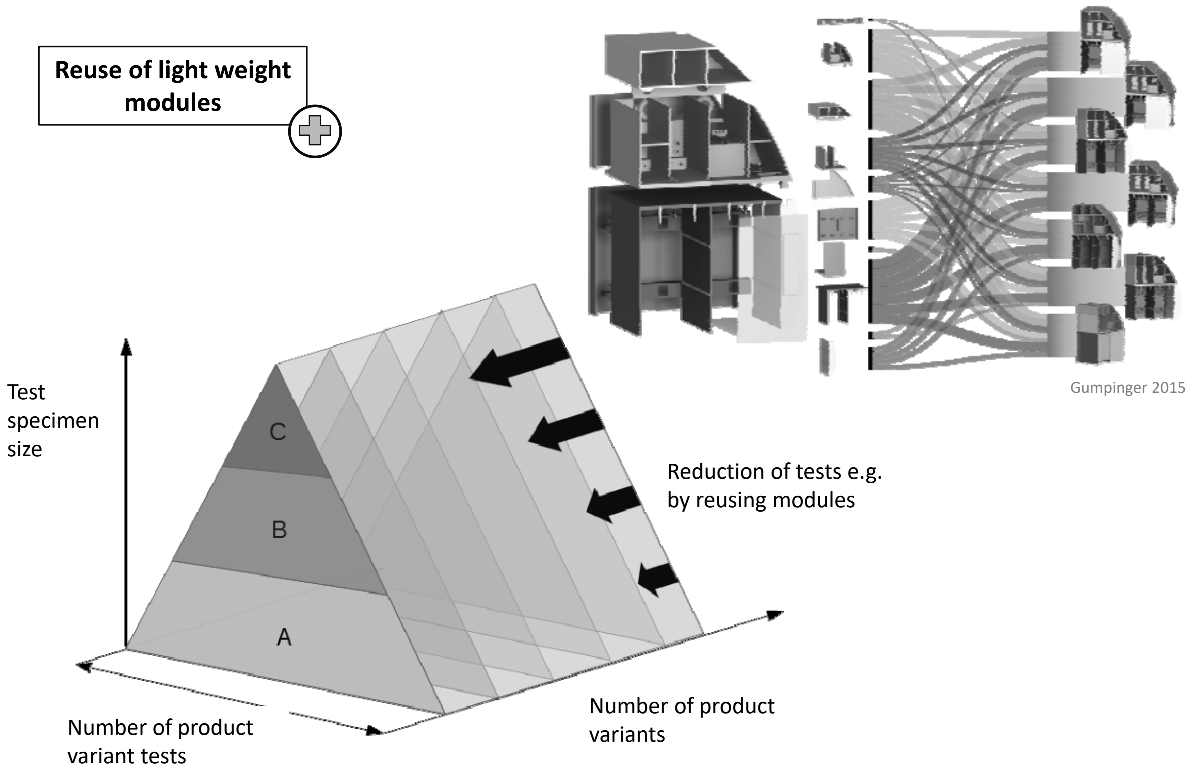

Figure 8: Reduction of testing effort based on the reuse of modules [KOSR-2016]

However, it is disadvantageous that a modular product usually does not exactly meet the requirements of the customer and therefore it will in some cases be oversized, resulting in additional weight. In order to perform the module design, additional interfaces are usually required, which also lead to a weight penalty. These two aspects often argue against a modular design in lightweight products. In the aircraft industry, a weight increase is not accepted and represents a clear knock-out criterion. Therefore in lightweight design material, structural or functional design is preferably used in combination with special manufacturing processes in order to achieve the lightest possible design (Figure 9 right).

In Figure 10 a modularized product family of an a/c galley is shown, which is, however, not weight-optimized yet. It can be seen that the modules are frequently used in different product variants, as indicated on the right hand side. Each variant leads to different requirements for the modules, e.g. due to different equipment features, such as the number of coffee machines in the middle blue module. Hence, due to different configuration, different stress conditions can result based on the individual modules. However, this also means that certain modules are over-engineered for other product variants.

In order to avoid this oversizing with respect to the entire product family, an interactive method was developed to find modules that are highly oversized [Gump-2015]. For this purpose, the over-engineering from the actual tension to the allowed strain is determined by means of FEM for each variant as well as each module in each variant. In the case of an existing oversizing, a prepreg layer is removed or a layer is added in case of too high tension. After several iteration stages the oversizing in the shown example is reduced from about 27% to a value below 10% and thus significantly reduce the fleet weight. The full description of the method can be found in [Gump-2015].

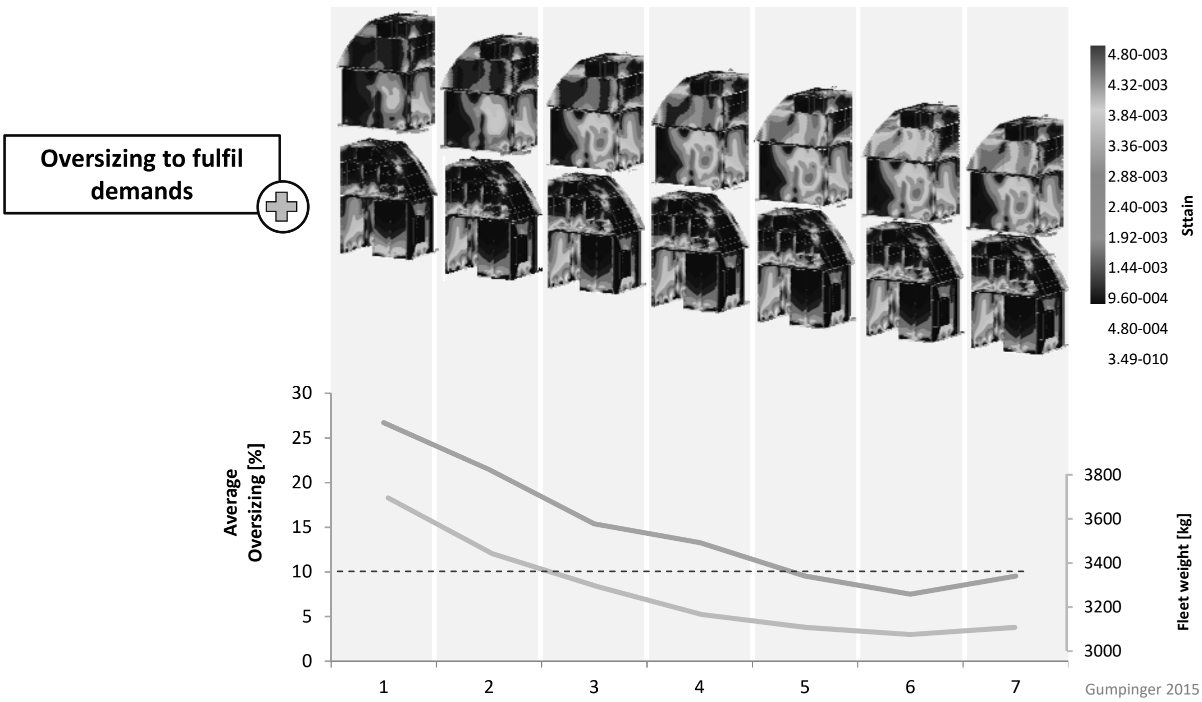

Figure 9: Fleet weight reduction

Another methodological approach takes into account the dynamic design of lightweight product families (Figure 12). The important feature of the approach is that the modular product structure is equally used for substructuring and for FEM modelling. For the individual modules, either FEM simulations or tests are performed to determine the frequency response functions (frf). In an overall model, this information is configured from the modules according to the desired product variant. Thus, a series of FEA simulations or tests of each module are necessary at the beginning, but these can be reused for all product variants in a product family. New modules can easily be added in the same way without the need to execute necessary tests of the whole product variant. The challenge of this approach is the exact specification of the module interfaces for the modelling of a substructure [Plau-2015]. In Figure 12 the example of a galley is shown, it becomes apparent that you can decrease not only the effort because of small module tests – here e.g. a coffee machine - or FEA simulation - here the structure of the galley - instead of complete test – here called validation - but also the results are better than the state of the art simulation – here shown on the left side top -. In this example the galley structure was used as a FEA simulation without any equipment. The oven module was tested on the hexapod test rig from the institute and the results are integrated as a substructuring model, based on the modular product architecture. As a validation test the complete galley with the oven modules were tested on the hexapod test rig. In the diagram you can see that the results of the dynamical substructured model is very close to the validation test results in contrast to the results of the FEA simulation of the current method [PlKr-2014].

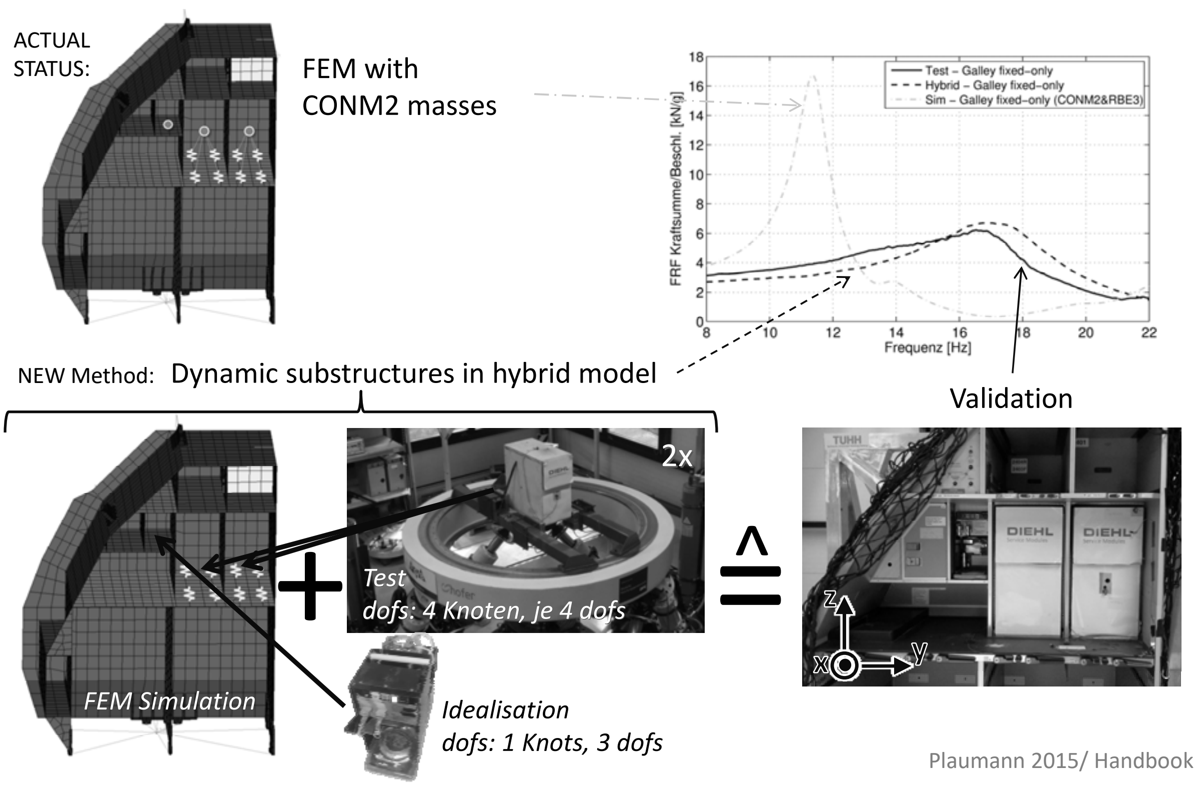

Figure 10: Example of dynamic substructuring for modular product families [PlKr-2014]

3.4 Mass Personalization

A predefined product portfolio is based on patterns of customer requirements and generally designed without direct relation to the individual customer [Gräß-2004]. Such a product variety contains the risk, that the predefined product variants do not meet the individual customer demands optimally. Despite of the uncertainty of the particular demand, high effort for the design of the product variety is necessary in advance [LiRZ-2006]. In addition to a variant product family, the adaption of the product variant to the individual customer requirements, also called personalization, is not easy to do.

Mass Personalization is the tailoring of a product accordingly to customer-specific needs for receiving an advantage in product differentiation in comparison to the competitors [RePi-2009]. The individual customer value is increased by designing a product aware to the use of this individual customer. The product as well as the product architecture is distinguished by the high adaptability and reconfigurability, whereby essential design elements may be also changed if necessary [Jiao-2011]. The mass personalization enables the adaption of the product features to the individual customer preference, so that the benefit growth from the customer's perspective is enhanced [RePi-2009]. However, this improved product family also needs additional internal processes and higher component diversity. Therefore the definition of stable processes is important, which flexibly integrates the mass personalization of products [RePi-2009]. The individual customer benefit and the added value based on the product personalization must significantly predominate the resulting complexity and in all product life phases.

Additive manufacturing (AM) as the collective term for layer-by-layer manufacturing technologies offers a high geometrical freedom of end-use-parts as well as increased production flexibility compared to conventional production technologies, so that AM is an enabler of customer-specific product design [KoMO-2015]. The make-to-order (MTO) strategy is the main application of AM for mass personalization containing high potential for companies [SpSK-2016]. AM makes it possible to offer high external variety while the internal processes remain lean and standardized.

The modular product family architecture provides a suitable basis for mass personalization. Modular product families are characterized by their structure consisting of separable modules with defined interfaces, through the combination of which the individual product variants can be combined. The standard modules, variant and / or optional modules are supplemented for mass personalization with personalized modules as additional module types [BeWH-2013]. By analogy to the variant modules, they should be decoupled as far as possible from other components and only realize the customer-relevant property for personalization. Within pre-planned product architectures, the personalized modules are later internal adapted and elaborated according to customer-individual requirements [LiRZ-2006]. The personalized module has standard interfaces to the modular product architecture and is designed and produced for each order and with the predefined standard, variant and optional modules combined into a customer-specific product variant. Various predefined levels of the personalized modules can be distinguished, depending on the extent to which the modules are already predefined and/or which parameter space is allowed for mass personalization. This results in different product development processes [SpSK-2016]. Beside the one-off design, two types of design processes are meaningful in mass personalization: (1) specific adaptation and (2) standardized individualization [SpKr-2016]. The types of personalization processes differ in degree of customer integration, preplanning of personalization, and influence on the design process.

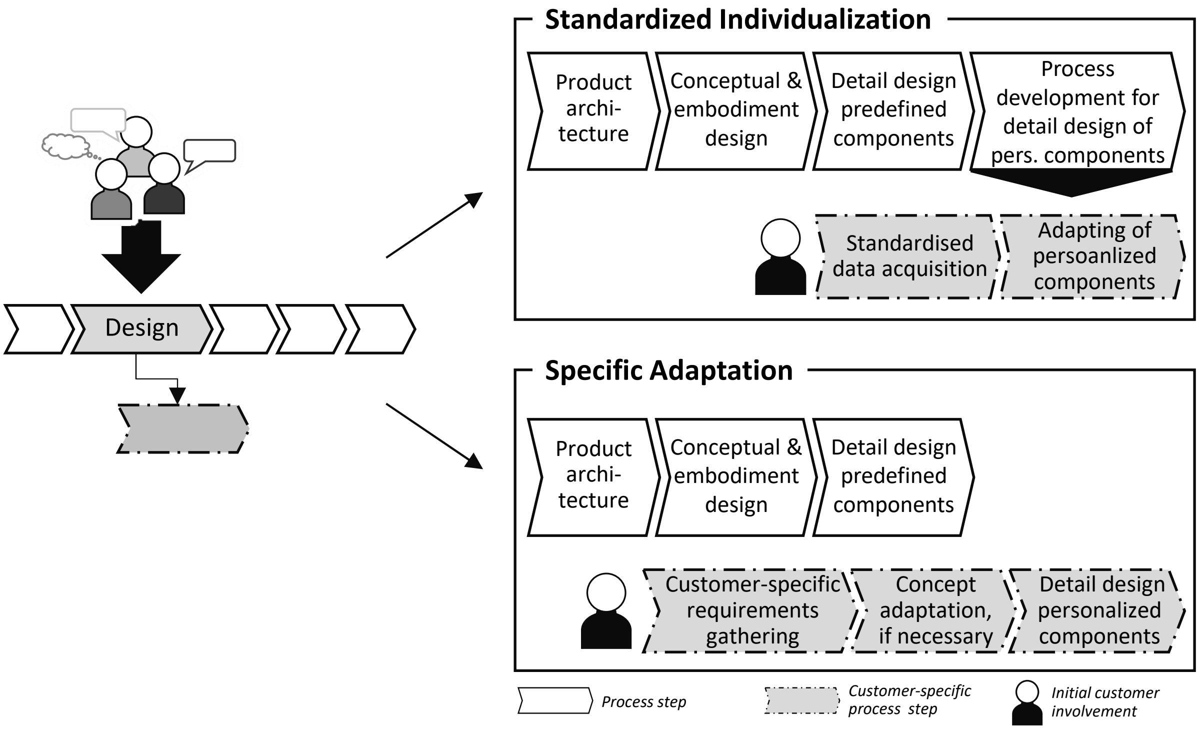

Figure 11: Influences of Additive Manufacturing on design processes for customization (adapted to [SpSK-2016])

In the case of product attributes that are difficult to predict, the personalization process has to be at most flexible. Based on individual requirement gatherings, single modules are adapted in the specific adaptation providing a personalized product with special functions. The adaptation is located within a fixed solution space without changing or new-designing the main product attributes, as in one-off design, though customer-specific design effort can be necessary. In the first step of the design process this adaptability needs to develop detailed product architecture for the definition of a personalization scope. It circumscribes the core product architecture limits with changeable and adaptable features and open zones for personalization (see Figure 13, below). The relatively high adaptation effort has to be compensated by the additional benefit through the fulfilment of customer-specific requirement. A high degree of process flexibility with clearly defined adaptation scope has high relevance [SpKr-2016].

In the second case frequently, the expected characteristics are known or can be predicted, for example in the case of a body-specific adaptation of products. With such a high predictability of customer-specific product design it is important to predefine the personalized module to a very high degree and to implement a standardized individualization process (Figure 13 above). During the conceptual and embodiment design phases the constraints of personalization are assessed without being performed. The main part of standardized individualization is the process for the detail design of the personalized component, and particularly its process development. In this standardized individualization process, defined customer data are recorded and the customer-tailored production data are generated, without demanding for customer-specific requirements. While the product architecture and product functionality remain the same, a customer-specific product variant is implemented in this standardized - and if possible automated - individualization process with resulting internal costs as low as possible. The customer-specific component increases the user experience, and limited product change is realized [SpKr-2016].

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