Development of a dynamic complexity costs assessment approach in aviation development

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Abstract

The development of avionic products is subject to high-cost pressure due to increasing international competition and small batch sizes. To compete on the global market in a long-term view, potentially arising complexity costs must already be considered in the early phases of the product generation development process. Existing approaches to cost evaluation concentrate on a subsequent evaluation of developed product family concepts alternatives. To avoid a cost- and time-intensive subsequent evaluation of complexity costs, a generic approach for the dynamic consideration of complexity costs within the product generation development process is to be developed by integrating existing approaches for the product generation development and evaluation of variety-induced complexity costs.

Keywords

complexity costs, product generation development, cost assessment, product family evaluation

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1. Introduction

Due to the increasing competition caused by globalisation in combination with small batch sizes and high product requirements in the aviation industry, aviation manufacturing companies are struggling with decreasing competitiveness on the global market and are facing significant cost pressure. Often, aviation manufacturing companies counter this declining competitiveness with an expansion of their product variety and individual solutions to their customers [1], which increases the component variety in the company [1]. This leads to an increased process variety and thus in long term to variety-induced complexity costs [1, 2]. To cope with the increased complexity, indirect costs rise in the companies [3, 4].

In order to survive on the global market in the long-term view, variety-induced complexity costs must be reduced by developing a modular product architecture that offers the necessary product variety at competitive prices [5]. For companies, this raises the question how their knowledge related to modularity of their product can be used to reduce the total costs incurred [6]. In order to develop product family concepts in a targeted manner to economic factors, variety-induced complexity costs must be integrated dynamically in the product generation development as a target variable [6, 7]. This dynamic consideration can significantly reduce the variety-induced complexity costs that arise in the downstream life phases like *distribution*, *production* and *use* [8, 9], as they are influenced by the decisions made in the concept design phase. Moreover, a subsequent evaluation of several developed product family concepts is no longer necessary, which can save process time and thus process costs in the product generation development of aviation products [7].

In addition, the integration of variety-induced complexity costs as a new target variable has a fundamental influence on concept development in the development process. By considering the economic factor of complexity costs already during the concept phase, the solution space will be influenced and increase.

2. State of the art and analysis

In the following chapter, the state of the art regarding the integration of variety-induced complexity costs in the product generation development process is discussed. The product generation development is characterized by the focused development of new product generations, which is characterized by the adjustment or the development of subsystems of existing product generations [10]. Since in practice new developments are not usually implemented without a previous solution status, product generation development uses existing product generations, solution ideas or reference products as a basis. By taking several product generations into account, the long-term potential of modular product families can be achieved [2]. The relevant research fields are shown in Figure 1 with the help of an Areas of Relevance and Contribution diagram (ARC diagram) according to Blessing [11].

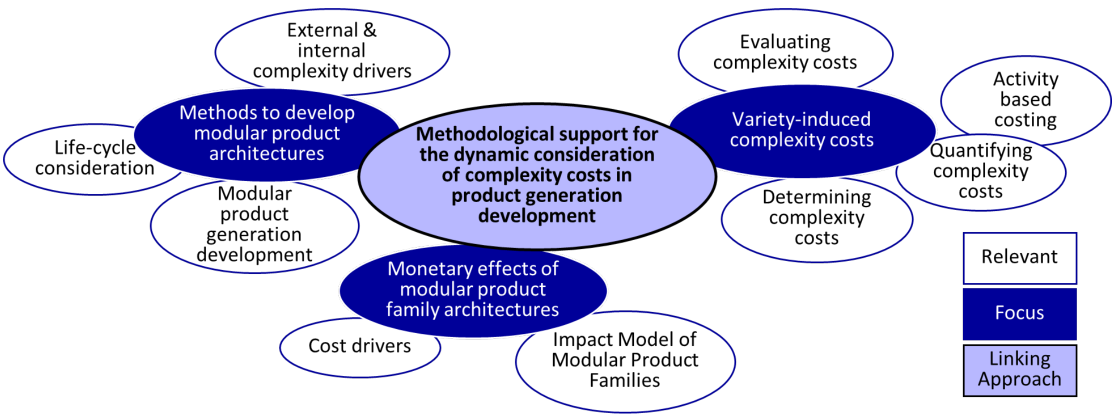

Figure 1: Relevant research fields of this work

The relevant research areas can be basically divided into the three areas *Methods for developing modular product architectures*, *Variety-induced complexity costs* and *Monetary effects of modular product family architectures*.

There are numerous approaches in the literature that can be thematically assigned to one or more of the research fields presented in Figure 1 and integrate relevant factors in their approach. The following approaches mainly focus on the research field *Methods for developing modular product architectures* and partially address the *Variety-induced complexity costs,* concentrating on the evaluation of complexity costs (see Figure 1).

A modularization method frequently cited in the literature is the *Modular Function Deployment (MFD)* according to Erixon [12], which supports the module creation considering product strategy aspects by using product strategy module drivers for module creation. With regard to these module drivers, components are identified that should form individual modules or be the basis of modules from a strategic point of view [12]. Through module drivers such as *carry-over*, economic targets can be indirectly considered in the module creation by reducing process times through lower development costs, as modules can be carried over into the next product life-cycle.

A holistic approach for the development of modular product families is the *Integrated PKT Approach for the Development of Modular Product Families* (PKT Approach) by Krause [2]. It can be used to reduce internal variety within the company while improving the external variety on the market. The approach includes several method units that can be used depending on the application area. The focus for the development of modular product families is on the Design-for-Variety to improve the variety of component variants, and the subsequent life-phase modularization to optimize the module structure taking into account all product life phases [2]. As a method unit of the PKT Approach, the method *Methodical Support for Cost-Based Selection of Modular Product Structures* according to Ripperda enables an evaluation of product structure concepts regarding variety-induced complexity costs [1]. The method is based on *Time Driven Activity Based Costing (TDABC)* [13] and is divided into three phases: *Cost Forecast*, *Cost Evaluation* and *Cost Reduction*. The focus is on the *Cost Forecast* by forecasting the monetary effects of changes to the product structure and thus the associated changes in the process structure. The method focuses on the processes that drive costs and are affected by a variety of componentes in order to be able to determine the variety-induced complexity costs. A further method for the rough estimation of potentially arising complexity costs with regard to developed product structure concepts is the *part number cost method* by Eilmus, which is also part of the PKT Approach. Here, the average complexity costs in the company are determined and the average complexity costs per part number are calculated afterwards. This is a rough estimation of potentially arising total costs per concept alternative, which represents an initial cost orientation in the concept phase [14].

Another method for developing modular product family architectures is the *Methodology of developing product family architecture for mass customisation* according to Jiao [15]. Here, the product family architecture should be developed regarding a high and cost-effective product variety and be geared to the necessary flexibility of mass customisation. In order to allow a holistic view, the *functional*, *technological* and *physical* perspectives are taken into account. The technical modularization is finally achieved using design matrices. The final product family architecture results from the subsequent economic evaluation of the modules created by assessing the individual physical modules in terms of costs and customer benefits. The goal is to identify cost-efficient or inefficient modules with high and low customer benefits to optimize the product architecture [15].

All three approaches support the development of modular product structures by means of a structured procedure. While Erixon focuses on product-strategic modularization [12], Jiao supports module creation according to technical-functional aspects [15]. Due to the different method units, the PKT Approach supports both technical-functional and product-strategic module creation [2]. About the consideration of cost factors, the three approaches above differ significantly from each other. Although the Erixon approach only allows an indirect consideration of potentially arising costs through the integration of module drivers, a direct consideration of costs is possible in the concept phase [12]. Jiao enables a subsequent cost evaluation of the modules. Although this enables a rough assessment with regard to economic target variables, a targeted avoidance of complexity costs in the development process is not possible [15]. By integrating the methodical support for the cost-based selection of modular product structures according to Ripperda, variety-induced complexity costs of pre-developed concept alternatives can be determined and evaluated by the PKT Approach. Although a detailed quantitative listing of the resulting variety-induced complexity costs is possible, taking into account all life phases, only a subsequent monetary evaluation of concept alternatives is carried out. The method does not allow for a dynamic consideration of potentially arising complexity costs during the product generation development process [1, 2].

One way of identifying economic effects that can be achieved by means of a modular product architecture is offered by the *Impact Model of Modular Product Families (IMF) [16]*, which is also integrated in the PKT Approach and can be allocated to the research field *Monetary effects of modular product family architectures* (see Figure 1). Using the properties of modularity, impact chains can be used to identify effects on economic targets that can be achieved with the degree of modularity of a product family. Furthermore, current work focuses on the integration of module drivers and the possible cost effects of a modular product architecture. The IMF therefore provides an overview of qualitative cost effects resulting from a modular product architecture and thus supports with regard to emerging cost effects already during the concept phase [17]. A quantification of the potentially arising costs, especially the variety-induced complexity costs, is not possible at the moment.

Furthermore, there are numerous approaches concentrating on the determination and evaluation of product costs or *variety-induced complexity costs* (see Figure 1) in the literature, which are analyzed below.

The *Activity-Based Costing* by Thyssen uses the *ABC* analysis [13] to evaluate the profitability of individual product structure concepts. The potential process costs of several product structure concepts with different degrees of commonality are forecasted to be able to select a concept on the basis of the potential total costs. With the help of *Activity-Based Costing,* the costs of different concepts can be predicted and then evaluated in terms of variety-induced complexity costs [18].

The *Calculation of Complexity Costs Method* according to Park enables an approach to the adjustment of the product program by identifying unprofitable product variants on the basis of allocated complexity costs. The assigned complexity costs are determined on the basis of life-cycle complexity cost factors, so that the influence of the life phases on complexity costs is taken into account holistically [19].

The *cost-oriented evaluation of modular product architectures* according to Skirde enables the possibility to forecast the cost effects of alternative product architectures. Here, the product is classified into one of six modularization levels after the modularization degree of the product has been determined before. In the following step, the cost composition of the actual status is determined, quantified and then extrapolated to the remaining five modularization levels. Based on this extrapolation, recommendations for actions can be given for increasing or decreasing the modularization level of the product. The recommendations for actions are mainly based on qualitative characteristics [20].

The *Variant Mode and Effects Analysis* according to Caesar represents a method for the early control of variant diversity by supporting early variant recognition and avoidance. This is a cost-oriented design methodology that is intended to contribute to the technical and cost-related control of variants. With the help of this procedure, alternative design solutions can be evaluated with regard to technical and economic key figures and the additional and reduced costs of these alternatives can be shown [21].

The approaches presented above [18–21] concentrate mainly on the subsequent evaluation of costs or complexity costs incurred. The approaches [18–20] do not or only insufficiently [21] take into account the technical-functional modularization and only give procedures for cost evaluation. Thyssen and Skirde do not include the integration of variety-induced complexity costs as a target value to be optimized in the concept creation. Caeser does allow an early evaluation of manufacturing and complexity costs, but also concentrates on the evaluation of design alternatives. In addition, Park [19] and Skirde [20] only allow a rough evaluation and consideration of the cost factors.

In summary, there are various methods that propose an approach for the development of modular product architectures and other methods that focus on the determination and evaluation of potential complexity costs. The above presentation has shown that existing modularization methods do not support all the requirements of a holistic concept development [22], especially when considering economic targets [23]. Methods such as Jiao [15] or the PKT Approach [2] support for the technical-functional development of modular product architectures and allow an evaluation of complexity costs, but do not continuously integrate variety-induced complexity costs as an economic target variable in their concept process steps. Other methods according to Thyssen [18], Park [19] and Caesar [21] allow the determination of complexity costs on a quantitative basis, but also here only a subsequent evaluation of pre-developed concept alternatives is supported.

3. Research problem and research goal

The approaches presented in Section 2 have shown that there are several of methods for developing modular product architectures that focus either on technical-functional or product-strategic aspects. Latter methods partly consider potential complexity costs, but mainly concentrate on the subsequent determination and evaluation of complexity costs arising from product family concept alternatives (see Figure 2). Approaches that take cost factors into account during concept development, however, do not take these into account in all relevant process steps and in some cases do not explicitly address the consideration and avoidance of complexity costs.

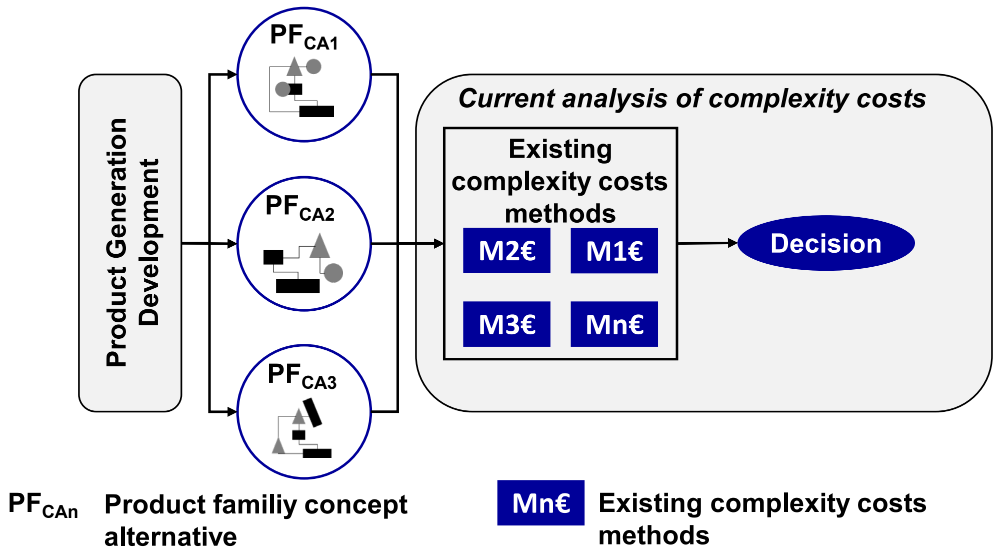

Figure 2: Current consideration of complexity costs in the Product Generation Development

To be able to take complexity costs into account at an early stage, existing methods for quantifying complexity costs must be developed further and integrated as elementary process steps in the development of modular product architectures. The aim is therefore to develop a framework for continuously integrating variety-induced complexity cost considerations into the steps of product generation development.

This leads to the research question: *Where and when should variety-induced complexity costs be considered as a target variable in the product generation process?*

4. Material and methods

The research approach is based on the *Design Research Methodology* (DRM) according to Blessing and Chakrabarti (see [11]). At the beginning, the existing literature was analyzed regarding approaches for the development of modular product architectures as well as approaches for the determination and consideration of complexity costs in the development of modular product architectures about relevant research fields. Based on this analysis, the relevant research gap was derived, and relevant research questions were formulated regarding the research gap identified.

Subsequently, the research gap that emerged from the previous literature review was empirically confirmed. Industry representatives of an European aviation manufacturing company were interviewed regarding the relevant research fields and identified research gaps to confirm the relevance of the topic from an industrial perspective.

Based on the research gap identified and confirmed by the industry, a general framework has been developed to enable the dynamic consideration of complexity costs during product generation development by integrating relevant methods of modular product development with usable methods of complexity cost calculation. Finally, the need of the integration of variety-induced complexity costs in the product generation development process was explained by the product family of a galley as an industry example from the aviation industry.

5. Results and discussion

To enable the consideration of variety-induced complexity costs dynamically in der product generation development process, a generic framework is presented in the following Section to support the consideration.

5.1. Empirical review of the literature-based research gap

To provide empirical support for the research gap identified in Section 3, three interviews have been conducted with industrial representatives of an European aviation manufacturing company.

The results from the interviews confirmed that a dynamic integration of complexity costs as a target variable in the product generation development process can have a positive effect on the total costs of the products. Approaches used in industry do not yet allow for a targeted consideration, quantification and avoidance of variety-induced complexity costs. Furthermore, existing approaches for the subsequent evaluation of variety-induced complexity costs have proven to be very time-consuming and inefficient.

Moreover, it has been confirmed that there is a lack of visual support to be able to consider variety-induced complexity costs at an early stage. There is no way to efficiently integrate existing cost data visually into the development process and make it recognisable.

A final problem identified by industry representatives is the lack of possibility to allocate and quantify costs to individual product variants and components at an early stage. Therefore, it is difficult to quantify the cost potential of modular product architectures. The possibility of being able to identify and take into account potential cost savings directly in the concept phase can lead to a more targeted product generation development.

5.2. Generic framework for the dynamic integration of complexity costs in the product generation development

To be able to take complexity costs into account at an early stage as an elementary target variable in the product generation development process in the aviation industry, a generic framework has been developed as shown in Figure 3 to answer the asked research question. Here, the conventional procedure to evaluate developed product family concept alternatives based on variety-induced complexity costs are replaced by the dynamic consideration of these in the steps of product generation development. The aim is to avoid process costs and thus development costs by developing the concept in a targeted manner about avoidable complexity costs.

As shown in Figure 3, the consideration of variety-induced complexity costs already takes place during the analysis of relevant internal and external complexity drivers, like manufacturing restrictions and airline requirements, as well as cost drivers like the number of different suppliers. All drivers must be recorded and evaluated based on its influences to arising complexity costs. Those analyzed drivers serve as an input for the generic process of product generation development.

The focus is on product generation development and is divided into three essential generic steps according to Pimmler and Eppinger [24] for which no explicit methods are given in this research. Additional literature on concrete methods is given by Otto (see [25]). Here, among other things, a method overview is given for the generic steps [25]. The first step is the *decomposition of the system* into existing components. In a next step, these are analyzed regarding its potential for change in terms of their potential differentiation and standardization (*analysis of the system*). Based on this step, the system is reintegrated into modules in a final step (*recomposition of the system)* [24].

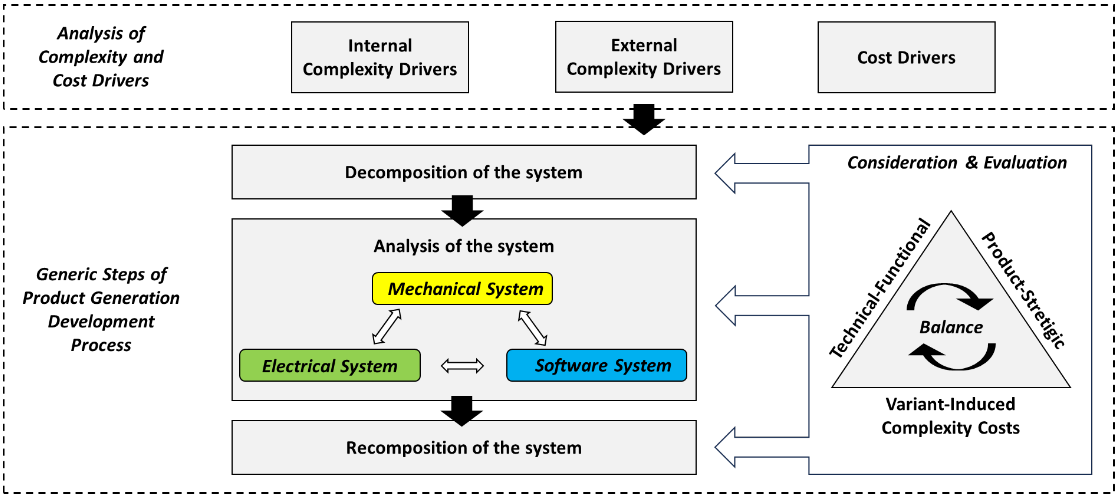

Figure 3: Generic framework for the dynamic consideration of complexity costs in the Product Generation Development Process

Since existing modularization methods do not yet allow for a reliable consideration of variety-induced complexity costs in these phases, evaluation steps should be integrated into the phases of *decomposition*, *analysis* and *recomposition of the system.* Therefore, the consideration of complexity costs as a target value must be integrated besides to the technical-functional and product-strategic consideration (see Figure 3).

During the decomposition of the system, the product is decomposed into cost-driving components based on its impact to complexity costs. The decomposed system is analyzed in the second step. To enable a holistic view on the product, the *mechanical*, the *electrical* and the *software system* are considered, including their existing interactions between each other. The aim of the integration of complexity costs in this phase is the quantification of potentially arising variety-induced complexity costs related to product components and modules. Here, existing dependencies of variant product components of the different systems are considered. In doing so, variant product components are to be checked for the properties of modularity.

During the final recomposition of the system, the revised product components are reintegrated into modules. Generally, the target of the built framework is to integrate the target value of complexity costs in all mentioned steps and to consider a balance during the development in addition to the technical-functional and product-strategic aspects.

5.3. Applied example from the aviation industry

The integration of complexity costs is discussed in more detail using an industrial example in form of a galley. It will be exemplarily clarified why a continuous consideration of variety-induced complexity costs in the product generation development is needed. The chosen example and its explenations focus on the phase *decomposition of the system*.

Figure 4 shows the galley installed in the A320 in its *As-is status* and as a modular developed *concept 1* using a *Modular Interface Graph* to clearly illustrate the variety and module division of the galley [26]. The *As-is status* on the left side is characterized by a highly variant module architecture, which results in high variety-induced complexity costs [26]. Since a dividing level of the galley is necessary due to assembly reasons, in the actual *As-is status* it is cut through variant components, which results in high variety-induced complexity costs. In the *decomposition step* of product generation development, modules are divided in a targeted manner regarding the factors under consideration. In *Concept 1* (see Figure 4), it can be seen that, compared to the *As-is status*, a second dividing level has been added to create standard modules and significantly reduce the degree of internal variety, thereby reducing variety-induced complexity costs [26].

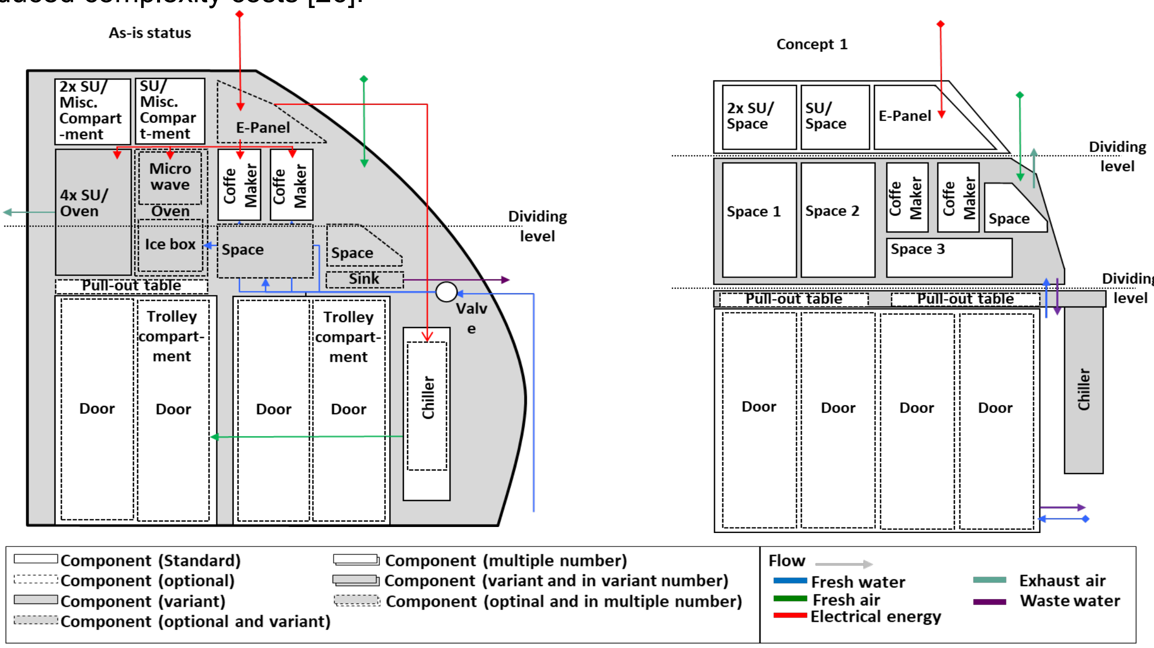

Figure 4: As-is status (left) and modular concept 1 (right) of a galley to reduce variety-induced complexity costs

By adding another dividing level, the necessary variant components can be bundled in a variant module without having a technical impact on possible standard components. Due to the added dividing level, the standard modules and its components are not influenced by changes made in the variant module of the galley. The number of variant components is thus significantly reduced compared to the *As-is status*.

Although the subdivision into further modules means an increase in weight due to added interfaces, which should be avoided as far as possible in the aviation sector, the subdivision into further modules has positive effects on the complexity costs incurred by reducing the variety.

The example of the galley illustrates why a consideration of complexity costs during the concept phase is necessary and has a positive effect on the resulting total costs of the product family. While the subdivision into further modules has negative effects related to weight optimization, variety-induced complexity costs can be reduced through economies of scale across the product family [26].

5.4. Discussion and outlook

This research has shown that variety-induced complexity costs must be considered in the product generation development in a dynamic way. Furthermore, the example of the galley has illustrated that the consideration of variety-induced complexity costs has an impact on the modular architecture of the product families. However, to be able to take variety-induced complexity costs into account in the early concept phase, following research must focus on two subjects. In a first step, a procedure must be developed in oder to how variety-induced complexity costs can be considered at the module and component level. The second subject is the possibility to quantify variety-induced complexity costs in an early stage and to allocate it to variant components and modules. Without the quantification of potentially arising complexity costs, the consideration and evaluation is only possible in a qualitative way. Moreover, the visual support has not been considered in this research and will be addressed in subsequent research.

In general, the dynamic consideration of variety-induced complexity costs is also relevant in other sectors besides the aviation industry. Consequently, future research should focus on the extension and application of the approach in other industry sectors.

6. Summary

A continuous consideration and integration of complexity costs as a target value in the product generation development can contribute to lower process costs in the concept phase. At the same time, the variety-induced complexity costs can be reduced. The aim of this reearch is therefore to clarify the relevant research gap based on the literature and to present a generic framework for the dynamic consideration of complexity costs in the aviation development. In Section 2 it was clarified that existing approaches either concentrate on the technical-functional modularization of product families or allow a subsequent evaluation about the complexity costs of several concept alternatives. A comprehensive dynamic consideration of complexity costs as a target value in the product generation development process is not supported by any of the procedures shown. Based on the generated research questions in Section 3, a generic framework has been developed in Section 5 to explain the needed integration of considering variety-induced complexity costs in the product generation development.

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