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Methodical Approach for the Model-Based Development of Aircraft Cabin Product Families Under Consideration of Lightweight and Cost-Based Design

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Abstract

Aircraft cabin monuments must be optimized in terms of lightweight design, cost structure and variance. Model-based approaches support the aircraft data and help to modify them consistently during further development. In this paper, a holistic methodological approach for product families of aircraft cabin development is shown, which integrates lightweight and cost-efficient aspects, in addition to the variance focus. For this purpose, the development of cost-efficient and ligthweight optimized cabin modules is supported in a model-based way.

Keywords: lightweight design, cost management, modularisation, model-based systems engineering (MBSE), aircraft cabin design

1. Introduction

Aircraft cabin development is currently undergoing a transformation and requires ever new innovative solutions, thus posing special challenges for methodical product development. In particular, the monuments like galleys, lavatories and overhead bins are areas in which the product architecture is being further developed. In the development of aircraft cabins, two conflicting requirements must be met. On the one hand, there is a high variety due to individual customer requirements by the airlines and, on the other hand, a weight reduction due to lightweight design. (Krause et al., 2018b)

Harmonization of the two can be enabled with Modular Lightweight Design (MLD) methods, leading to a modular hybrid design (Hanna et. al., 2019). In addition, aircraft cabin monuments are characterized by the use of sandwich panels, which require complicated design (Seemann and Krause, 2018). Furthermore, their production and aircraft cabin assembly are mainly done manually. This leads to high costs with simultaneously increasing cost pressure for the airlines and subsequently also for the aircraft cabin manufacturers. Cost-based approaches to the further development of product families promise to remedy this situation (Ripperda and Krause 2017). For these three areas described here (MLD, cost-based design and sandwich design), approaches have already been presented individually and used in part for the development of new designs.

The problem addressed in this paper is that new aircraft cabins are often designed from only one point of view. The three levels of consideration described are not applied in a linked manner and a common approach is missing, which combines the different aims and procedures at the same time. Here for the development of future aircraft cabin concepts partly contradictory special fields have to be brought together.

The aim of the paper is to present a holistic approach to the development of product families in the aircraft cabin, the development opportunities this opens up, and the use of digitalization. Model-based support during development helps to process the complicated and extensive data volumes of aviation

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and to modify them consistently during methodical further development. The benefits for an eco-efficient design play an essential role. For this purpose, the 2nd chapter shows the state of the art in the three areas under consideration. Chapter 3 analyzes the existing methodological approaches and their integration possibilities. Chapter 4 shows the new holistic approach and the integration of the fields. For this purpose, a new approach for the sandwich design optimization is presented. In Chapter 5 the results are shown. Summary and outlook form the conclusion.

2. State of the art

In this chapter, the state of the art for modular and lightweight optimized aircraft cabins is presented, as well as on sandwich design, cost-based design and Model-Based Systems Engineering (MBSE).

2.1. Modular and lightweight optimized Aircraft Cabins

Increasing external variety to meet customer requirements is accompanied by an increase in internal, product variety (Krause and Gebhardt, 2018a). In the context of modular product architectures, modularity is a gradual property described by different modularization properties and characteristics (Salvador 2007). Several methods for developing modular product families are presented in the literature, for example modular function deployment (Erixon, 1998), structural complexity management MDM (Lindemann et al., 2009) or design structure matrices (Pimmler and Eppinger, 1994). In the aircraft cabin industry, methods for developing modular product families, such as the Integrated PKT approach, are ideal for meeting individual airline customer requirements with the lowest possible number of internal, variant components (Krause and Gebhardt, 2018a). A key stakeholder in the aircraft cabin is the airline, which places various requirements on it. For example, the galley should be able to heat meals and stow food as well as make coffee. Furthermore, the number of ovens, storage boxes and coffee machines varies. Depending on the airline and flight route, the galleys are equipped differently.

In aviation, the energy input of the propulsion depends directly on the mass to be moved, therefore a lightweight design to reduce the self-weight of the aircraft and its components represents the main economic goal (Klein, 2013). Weight reduction can be realized by different principles, which are summarized under the term lightweight design. A distinction can be made between economy, purpose and eco lightweight design (Krause et. al., 2018b; Wiedemann, 2007).

Since a modular product architecture can often lead to oversizing due to interface standardization, among other things, they have a higher weight, because interfaces often tend to be oversized and therefore possibly heavier than needed. Therefore, methods have been developed at the Institute PKT to combine lightweight design with modularization (Hanna et al., 2019).

Modular Lightweight Design (MLD) is characterized by the fact that modularization and lightweight design can be considered simultaneously to create a new design. The process structure is considered and data management is improved by implementing consistent product and process models in SysML. Potentials of MLD are the possibility to offer a high external variety of a product family while at the same time exploiting the lightweight design potential. Standardized processes and integrated data management can accelerate the development of new variants, reduce the number of errors and simplify the implementation of an innovation process. (Hanna et al., 2021)

2.2. Cost-based effect of modular product families

The literature often describes the influence of product design on production and thus also on costs (Boothroyd et. al 2001). Porter, for example, deals with the comparison of economies of scale and economies of scope (Porter 2014). Economies of scale describe the strategy of cost leadership. The aim is to achieve the lowest possible costs of service provision in order to be able to sell large numbers of units. The strategy of differentiation is described by economies of scope. An impact model of modular product families with a linkage of the boundary conditions has already been developed for this purpose and implemented in SysML, which enables a consistent and thus continuous data model (Schwede et. al., 2019).

The methodical support for the cost-based selection of modular product architectures includes, among other things, the complexity cost effects, which also result from modular product families, in the decision phase of the selection of a modular product architecture (Ripperda, 2017). Product variant-induced complexity describes

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here the additional efforts and resources, whose cause lies in an increased product variety (Krause and Gebhardt, 2018a). In addition, the correlations between costs and internal variety and sales and external variety are also contrasted. The methodological approach to support a cost-based selection of modular product architectures can be divided into the phases cost prognosis, semi-quantitative evaluation and cost reduction measures and was validated on the basis of an aircraft cabin monument to obtain a monetary estimation of modular product architectures concepts (Ripperda, 2019). Based on the Time Driven Activity Based Costing (TD-ABC) approach (Kaplan and Anderson, 2007), this approach forecasts the costs for developing alternative concepts of the product family. An approach to develop cost-effective modular product families based on cost analysis can support the development and evaluation of cost-effective concepts. For this purpose, the process and product architectures should be analyzed with regard to their process and material costs and incorporated into the concepts (Hanna et. al., 2017).

2.3. Model-Based Systems Engineering

Model-Based Systems Engineering (MBSE) includes processes and methods as well as modeling with methods of systems, system requirements, design, analysis, verification and validation. By linking different data in one system, MBSE enables easier document management based on a common database (Walden et al., 2015; Holt et al., 2012; Friedenthal et al., 2009). Various modeling languages and tools can be used to create models. For example, one way to create models is with the software Cameo Systems Modeler (No Magic) and the modeling language SysML, which is based on the Unified Modeling Language (UML) (Weilkins, 2007; Holt et al., 2012). MBSE tools have already been successfully used for methodological development (Albers et al., 2019).

2.4. Sandwich design in aircraft cabins

Nowadays, cabin monuments are usually made of several sandwich panels. These are characterized by high weight-specific material properties. They consist of face sheets, which primarily absorb the in-plane tensile and compressive loads, and a honeycomb core, which increases the moment of inertia and absorbs shear forces (Zenkert, 1997). To introduce local forces into the sandwich structure, local reinforcements in the form of sandwich joints, such as inserts, are used (Bitzer, 1997). These are particularly needed to attach the monuments to the primary structure of the aircraft via attachments, to connect the individual panels to each other, or to attach a variety of add-on parts. Component tests are performed to verify the load-bearing capacity of the individual fasteners (ESA, 2011). In these component tests, usually only already approved materials and sandwich composites are used. The maximum reaction forces that must be verified in the component tests are determined using a global FEM analysis. When setting up the global FEM models, a determination of the occurring loads and a detailed analysis of the boundary conditions to be defined must be carried out first. This is particularly relevant for the application of loads by the individual attachments and fixtures, such as the trolley, standard unit or ovens, as well as the mounting of the monument to the upper and lower attachments. Initially, a single load case must be considered for each of the six spatial directions, which are superimposed in the overall design model. With the help of the individual masses of the attachments and fixtures and the maximum acceleration for the respective spatial direction from the regulations, a static force is calculated that acts at the respective center of gravity. In addition to the test verification of all individual sandwich connection elements and the global FEM verification, a full-size test is also performed on the entire aircraft monument, like galley or partition, for approval.

3. Analysis of the integrated areas in modular aircraft cabin families

In this chapter, the three relevant areas are analyzed and respective methodological approaches used for the development of new aircraft cabin structures are shown.

3.1. The Modular Lightweight Design for product families of aircraft cabins

The MLD has already been researched for aircraft cabins and the six-step procedure was further detailed. In particular, the iterative character was highlighted. Lightweight design optimization and the development of a modular product architecture are on an equal level here and are harmonized in order

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to be able to achieve the optimum granularity between the two areas (see Figure 1, left). The result of the application represents the modular hybrid design. An example of this is an aircraft galley used in the rear entrance area of an aircraft (Figure 1., right). Visible there are different modules in different designs.

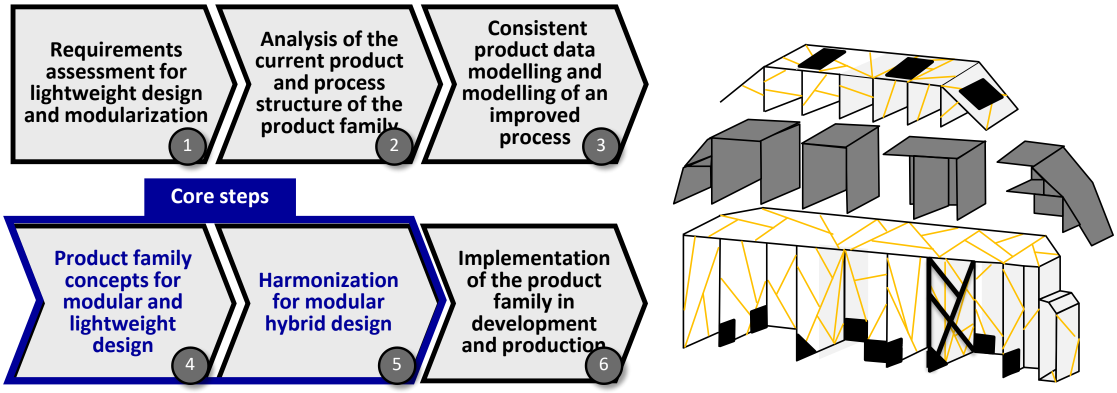

Figure 1. Modular Lightweight Design and the resulting modular hybrid design for an aircraft galley (Hanna et al., 2021)

With this approach, a compromise between the two areas could be achieved and the oversizing of the interfaces and thereby the weight can be minimized (Hanna et al., 2021). Although this methodical approach allows the two opposites of lightweight design and modularization to be harmonized, the detailed design of optimized modules in sandwich design is only marginally supported. However, this is essential in the development of aircraft cabin monuments. In addition, costs play an increasingly important role in aviation, which are not yet considered in detail in the approach. Therefore, the MLD is an essential component for the future successful development of modular product families of aircraft cabin monuments. However, it is not yet fully comprehensive and should be combined with other aspects.

3.2. Sandwich design and optimization

Since the most heavily loaded area in the panel dictates the design of the core and face layer, all less heavily loaded areas of the panel are oversized. Conventional sandwich design thus does not represent a load-path-compatible design for the application case of aircraft cabin monuments. Therefore, a lightweight design potential arises in the development of new designs using load path optimization in the context of MLD. Global optimization on simplified shell models is sufficient to detect load paths and identify highly loaded areas. However, massive local reinforcements of the sandwich panels in the form of metal reinforcements or hard fabric blocks are sometimes necessary, especially at the highly loaded load introduction points. The reinforcements result in additional mass and locally increased stiffness within the panel at the transition to the core, which is why the full lightweight potential is not exploited in the local load introduction. To predict the structural behavior in this case, detailed FE models are required, which also adequately represent the failure behavior of the structure in the simulation. The design of such models is complex due to the large number of constituents with partially anisotropic material behavior and the large number of contacts to be modeled. Therefore, a hierarchical model design under constant comparison with physical test results is required (Heyden et al., 2019; Schwan et al., 2021). A first approach for creating virtual models for testing sandwich joints was created and successfully applied in previous work (Seemann and Krause, 2018). Furthermore, a methodological approach for the optimization of load introduction points integrated into the sandwich structure was developed and implemented (Schwenke and Krause, 2020). A successive extension of the models to the structural and product level of the hierarchical test pyramid as well as an optimization based on the detailed models have not yet taken place.

3.3. Cost-efficient aircraft cabins

The methodical approach to complexity assessment of modular product families according to Ripperda can effectively achieve cost prognosis, cost estimation and cost reduction (Ripperda and Krause, 2017). This has already been applied to aircraft cabin monuments (Ripperda 2019). In this work, a product

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family of aircraft galleys was modularized in the front door entrance area and three different concepts were developed (Figure 2). These concepts were then evaluated in terms of cost. It became clear that all of these concepts can effectively reduce aircraft cabin costs.

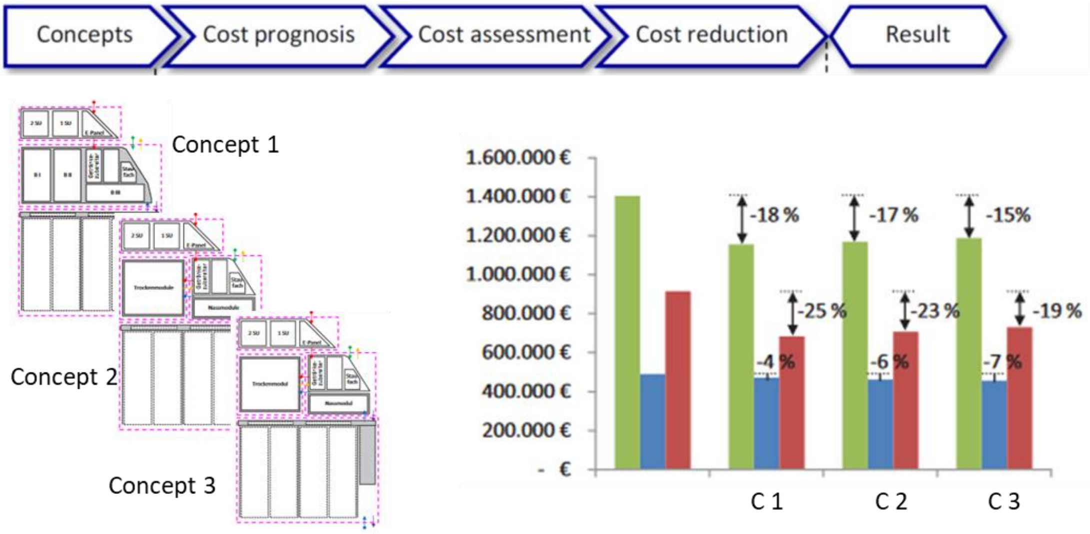

Figure 2. Complexity cost management approach and cost assessment for aircraft galleys (Ripperda and Krause, 2017; Ripperda, 2019)

The methodical approach to complexity costing thus enables a cost-based evaluation of the concepts and thus cost-reduced aircraft cabin monuments. Another approach was given with the cost-accompanying development of modular product families, but not yet applied in aviation (Hanna et. al., 2017). Here, linking modular product architecture concepts to cost information through a model-based implementation could clarify quantitative results. A model-based approach can support end-to-end data management between process, cost, and product architecture.

3.4. Overview of the relevant topics

The analysis of the different aspects has shown that the three areas all have a high relevance for future aircraft cabin development. It also becomes clear that the pure focus on the procedure and the resulting design of one of the three topics is not sufficient. An overarching approach that connects the areas is thus missing. The following Figure 3 illustrates these influences on future aircraft cabin development and the influence on a climate neutral product life cycle.

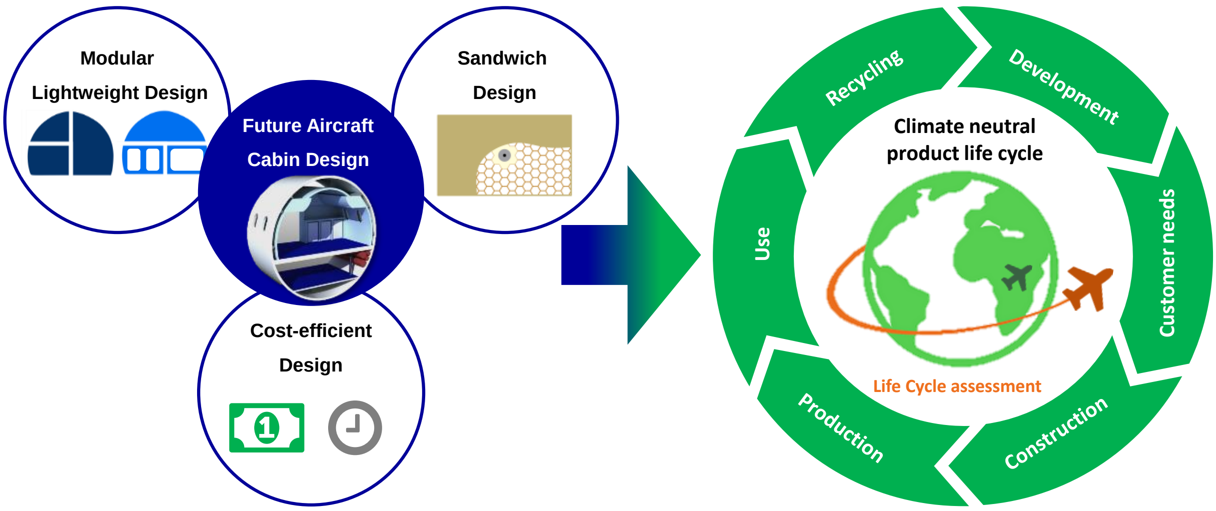

Figure 3. Future Aircraft Cabin Design

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An essential aspect of the topic is that green aviation will be the most important future topic in aircraft development. Through a holistic view this can be made possible by an integration of the areas of MLD, cost efficiency and optimized sandwich design. The combination of these areas thus forms the basis for implementing sustainability in the product life cycle and thus making a decisive contribution to resource reduction.

4. Methodical procedure

The analysis has shown that a holistic approach is necessary. Before this is shown, a new methodological approach for sandwich design optimization is first presented.

4.1. New methodical approach for sandwich design optimization in aircraft cabin design

In chapter 3.2 it was analyzed that a process to identify global load paths in the cabin monuments exists. However, due to the simplified shell models used, the local system behavior is not adequately represented and thus the lightweight potential of the sandwich design is not exploited. For this reason, in Figure 4 a procedure for detailed sandwich optimization of aircraft cabin monuments is shown.

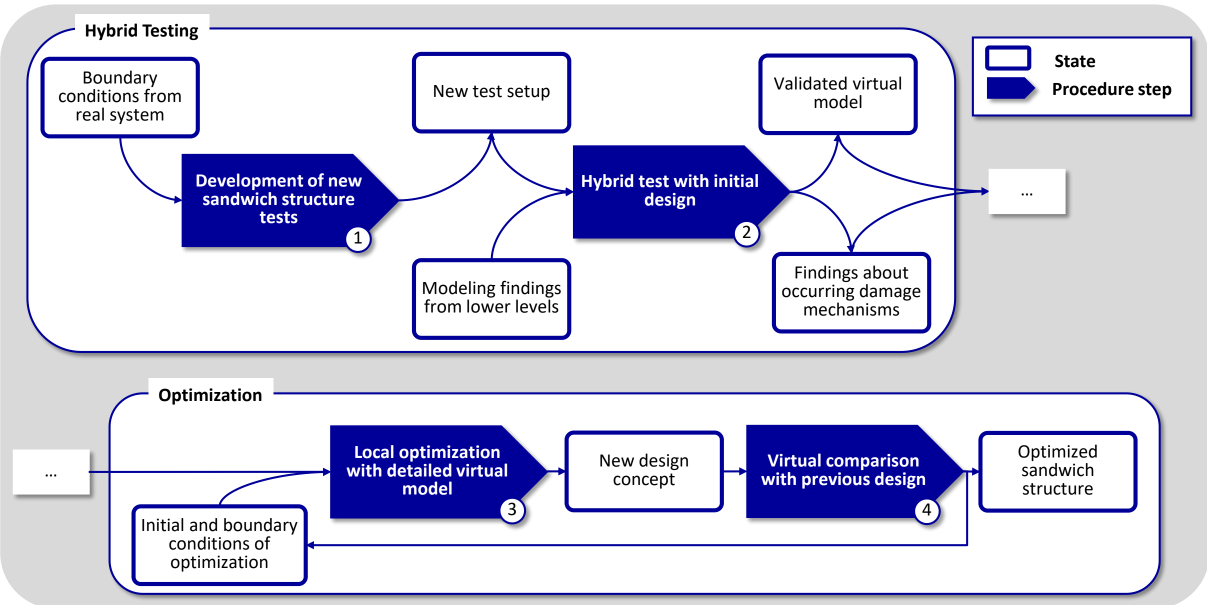

Figure 4. Methodical approach for sandwich optimization

If necessary, in step ①, existing tests must be redeveloped and boundary conditions approximated to those of the real installation situation. This is also important in order to perform optimizations later on, since the initial and boundary conditions have a decisive influence on the optimization result. In step ② a hybrid test with the initial design based on the findings and material models from lower structural complexity levels is carried out. In the context of hybrid testing, synergetic effects between real testing and numerical simulation of these newly developed product tests are used to achieve a deeper understanding of the failure modes that occur. These obtained insights, especially those about the initially occurring damage mechanism, can subsequently be used in step ③ for the local optimization with the virtual model. A new design concept is then created, which can be virtually compared with the previous design in step ④. If the design concept does not yet meet the requirements, iteration loops need to be performed.

In contrast to the conventional sandwich design approach, the new methodical approach and the detailed models make it possible, on the one hand, to optimize sandwich structures locally and, on the other hand, to check design changes quickly in a virtual environment. With detailed models at the product level, global optimizations could also be carried out more efficiently. In addition to weight savings in

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the aircraft cabin, resources can be saved by reducing real tests and the product development process can be accelerated, thus saving costs.

4.2. Integration through a new holistic approach for future aircraft cabin design

From the areas analyzed, it can be concluded that information would have to be stored in a model-based manner in order to enable the linking of information. This poses a particular challenge to data management. Process models are particularly important here, since the different methodical procedures with their individual steps must be taken into account. All three methodical procedures presented start with a specific data structure and are characterized by a methodical procedure, at the end of which a design concept emerges in each case. These concepts should then be harmonized iteratively with the other areas. For this purpose, the holistic approach in Figure 5 was developed, which takes the three areas into account.

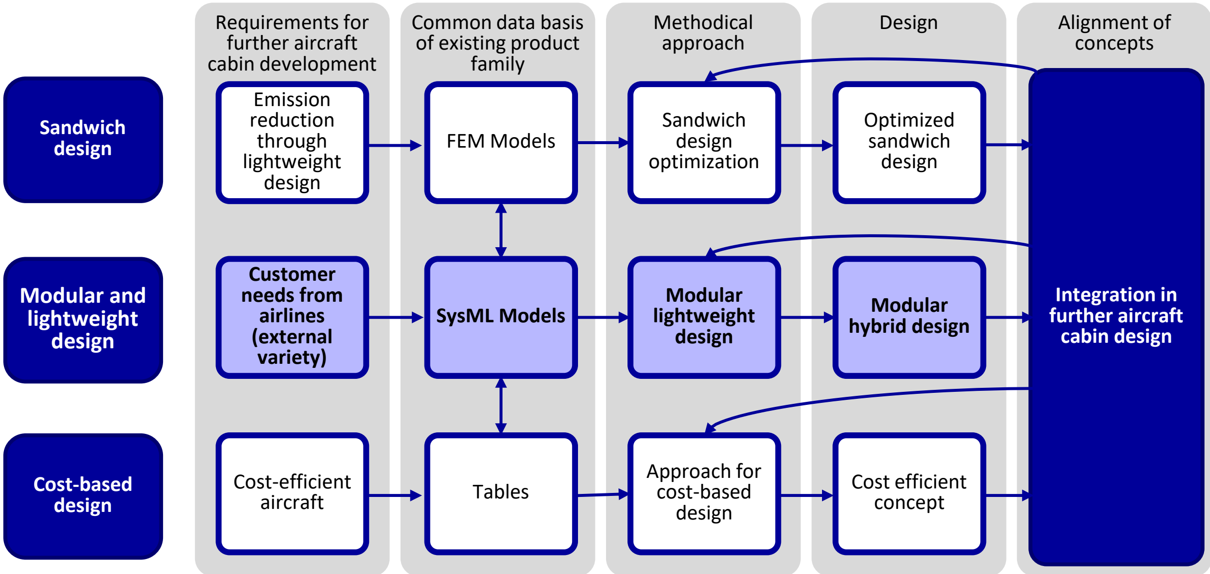

Figure 5. Holistic approach for future aircraft cabin design

The steps of this approach are divided into 5 phases. The upper strand represents the aspects of sandwich design, the middle strand those of modular and lightweight design and the lower strand those of cost-based design.

The first phase covers the specific requirements for the aircraft cabin. In modular and lightweight design, these are shaped in particular by the customers, who have special requirements for the design. In sandwich design, the external requirements for the cabin design are mainly the certification aspects. Furthermore, for emission reasons in particular, attempts are made to save as much weight as possible while maintaining the same mechanical properties. In addition, a cost-efficient design is required, as aviation is under enormous cost pressure.

These requirements are incorporated into the second phase of the methodological approach, in which a common database is first to be created. The investigations in the previous chapter have shown that the three areas under investigation use different data, information and models. At the beginning of each methodological development, these bases should be available and coordinated with each other. Subsequently, the methodological development in each area is carried out as presented in the previous chapters.

In this process, a modular hybrid design is developed through the MLD methodological approach. The methodical procedure of sandwich design optimization enables a weight-optimized product architecture. A cost-optimized product architecture is ensured by the methodical procedure of cost-based design.

In the final phase of the holistic approach presented here, the concepts are aligned. These are integrated for the future aircraft cabin design and a common design method is determined. Through the respective iteration loop, further optimizations can be made within the individual areas if there is a need for

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adaptation, in which the corresponding aspects are adapted in each case in the methodical procedure. On the one hand, MLD makes it possible to implement effective variant management, but on the other hand it also allows lightweight design to be taken into account.

5. Results and reflection

This chapter describes the results of the presented holistic approach. First, a model-based support for the approach is shown. Also, an application for aircraft cabin design projects is addressed.

5.1. Model-based support of the approach

Since it has already been established in this paper that this is primarily a data and communication problem, an attempt is made here to address it by means of a model-based approach. Furthermore, the development of cost-efficient cabin modules can be supported in a model-based way and the developed modules can subsequently be evaluated with regard to economic efficiency and structural connectivity. SysML was used for modeling, since the process of Modular Lightweight Design was also modeled with it and thus overlapping synergies can be used. Figure 6 shows a section of the model.

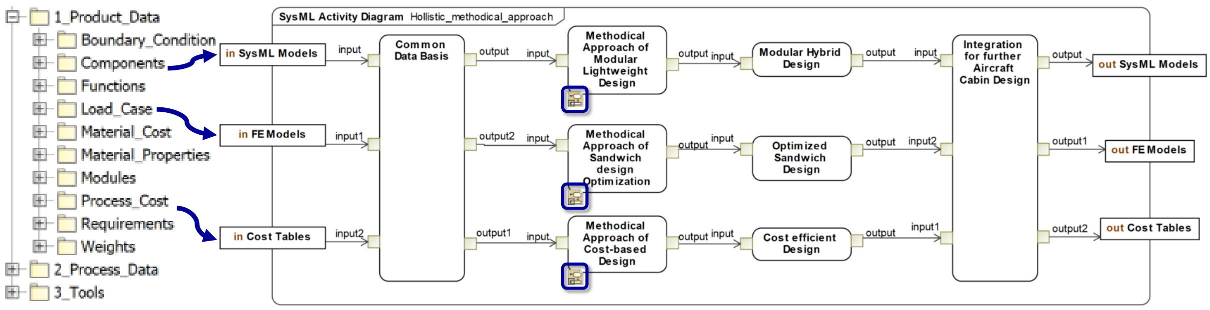

Figure 6. Model-based approach for the integration in SysML

On the left, the containment tree is shown, in which all existing data is consistently represented. On the right, the holistic approach is modeled in the form of a SysML activity diagram. On the left, the data and information of the different areas are visualized as input. The process steps follow in the form of activity blocks, as already shown in abstract form in the previous Figure 5. At the end, the final coordinated concept is implemented in the data models of the corresponding areas. The continuity that can be enabled by means of a model-based procedure is also made usable here in addition to consistency and traceability. In the process, subordinate processes are inserted into SysML by means of further activity diagrams (blue outlined) in the third phase, in which the individual areas go into the respective methodological approaches. These can be inserted on subordinate level into the superordinate processes. The methodical development of aircraft cabin concepts is thus carried out with the involvement of stakeholders from different life cycle phases (co-design).

5.2. Application in projects with the aircraft industry

The holistic approach has been and is being applied in numerous aviation projects as case studies. In the project MICHEL a multifunctional lightweight design for variably configurable monuments has been developed. Based on the MLD a modular hybrid design could therefore meet the requirements of a modular product architecture for high customer-based external variety while internal variety is reduced. Additionally, weight reduction could be implemented. The requirement of a further lightweight design is currently being realized with a link to the methodical sandwich design in the project EFFEKT, in which virtual testing of sandwich cabin monuments is researched on component and substructure level. This approach is being pursued with promising results so far also in the project CabinJoint. In order to reduce costs, these interim results are currently being combined with cost-based design in the project ANKA, where an autonomous sustainable cabin is developed.

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Through the project's applications with the industrial project partners, it appears that the holistic approach presented meets the different requirements and can provide a common solution. For the first time, the three areas have been combined for aircraft cabin development and are currently being applied in more detail.

6. Summary and outlook

In this paper, it was shown how future aircraft cabins can be designed more effectively and comprehensively by integrating the three methodological approaches sandwich design optimization, Modular Lightweight Design and cost-based design in a holistic approach. This makes it possible to overcome the previous development of new aircraft cabin monuments, which was previously only focused on the design of one area, and to enable a holistic approach. For this purpose, existing procedures and developed concepts of the respective areas for the aircraft cabin were analyzed. It was found that an extended procedure for sandwich design optimization is particularly necessary to enable a detailed design and integration with the other areas. Sandwich design optimization enables the detailed implementation of lightweight design in order to achieve maximum weight savings in the design. Through a cost management, resource-saving measures can be quantified and thus a monetary added value in relation to the effort can be shown. The enhanced process was presented and subsequently the holistic methodological approach, which efficiently links the three investigated areas and supports a harmonized aircraft cabin development. Furthermore, the presented model-based support can help to address issues via consistent data management. Sustainable development is a key future issue for society in general and aviation in particular. Resource-saving mobility is a particular challenge for aviation. The holistic approach shown here can help to develop more efficient aircraft cabin monuments that enable reduced resource consumption.

In the future, digitalization can be further advanced and other areas can be integrated in the holistic approach.

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