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Model-based application of the methodical process for modular lightweight design of aircraft cabins

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Abstract

In this paper the concept of the modular lightweight design as a method to combine the opposing views of lightweight-optimized- and modular product family-design is presented. Therefor specifics of these views are presented based on the use-case of civil aviation and aircraft cabins. Subsequently the concept of modular lightweight design and its concomitant benefits and challenges are outlined as well as the Model-Based Systems Engineering to assist the implementation of the approach into the product development processes for developing the modular hybrid design.

Keywords: Modular Lightweight Design, Model-Based Systems Engineering, Aircraft Cabin

1. Introduction

In terms of product development, aviation is characterized by the conflicting goals of weight reduction and simultaneous high individualization. On the one hand, the aim is to reduce the weight of aircraft in order to save resources. This induces the complete product architecture to be optimized in terms of weight. On the other hand, individual customer wishes, in this case by the airlines, effectuate a high number of different variants offered to the market. The respective requirements are particularly pronounced in the aircraft cabin, as this is where airlines have to differentiate themselves the most from their competitors. A modular product architecture leads to standardized and, thus, usually oversized interfaces, which have a higher overall weight. [1,2]

In addition, with such a historically grown product architecture of variant-rich product families, data management is often inefficient, since changes are constantly made, which are often insufficiently documented, but on the other hand the data basis is usually document-based, which means that the effort of the maintenance process is high. Only a few models of current development statuses are available, which is particularly evident in finite-element (FE) modeling and the product architecture. A uniform development process that incorporates the opposing views of lightweight vs. modularization is missing. This leads to considerable effort, since a complete development process must be run through for each newly developed variant, which is usually not clearly defined. A standardized process optimized for lightweight design and modularization can provide a remedy, if it is supported by a consistent, holistic and digitalized data management system [3,4]. The problem discussed here is on the one hand on the process level, where different data and information are used in different steps of the development process. On the other hand, there is a deficit in the description of a design that is both modular and lightweight optimized.

The aim of this paper therefore is to demonstrate a methodical procedure with which modular lightweight design can be implemented but also to show how a modular hybrid design can be implemented in an aircraft cabin. The question here is in particular how the iterative process of modular lightweight design can be implemented and how its data can be linked consistently and traceably in order to develop a design that does justice to both; modularization and lightweight.

Therefore section 2 described the state of the art. Whereas in section 3 the analysis of modular lightweight design with regard

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to temporal consistency is described. Section 4 presents the process model for the development of modular lightweight design. Section 5 uses the example of aircraft cabins to show how the application can be implemented.

2. State of the art

2.1. Methodical development of modular product families

Modular product architectures are often used to reduce internal variance when external variance is high. According to Salvador, modularization can be understood as a gradual property, which can be described by the five gradual properties of *decoupling*, *interface standardization*, *commonality*, *combinability* and *function binding* [5]. In the literature different methods for the development of modular product families are presented. These methods can be divided into two strategies: technical-functional modularization and product-strategic modularization. The *Integrated PKT Approach for the Development of Modular Product Families* by Institute of Product Development and Mechanical Engineering Design (PKT) combines these two strategies and includes numerous method modules for reducing internal variance. A modular product architecture can achieve advantages in all lifecycle phases, but can sometimes lead to oversizing and an increased weight due to the standardized interfaces [2].

2.2. Lightweight design

In the literature, a distinction is made between economical, functional and ecological lightweight design [4]. In the case of functional lightweight design, the realization of the function requires a reduction in weight, while in the case of economical lightweight design, a reduction in costs is aimed for by reducing the material required, and in the case of ecological lightweight design, an indirect cost saving is aimed for over the life cycle of the product. Furthermore, lightweight design is divided into three different strategies [6,7]: In lightweight material design, materials with high weight-specific stiffness and strength are used, e.g., fiber-reinforced plastic composites or sandwich structures. In lightweight structural design, on the other hand, the load spectrum is fulfilled by optimizing the structure with a minimum of dead weight, while in lightweight system design, material requirements and connection points are reduced by integrating additional functions into the load-bearing structure. The design methods, which represent an implementation of the product architecture, can be distinguished between integral, differential and integrated design methods [7,8,9]. In the integral design, a combination of components is used to achieve a compression of functions with minimal interfaces. In contrast, in the differential design, sub-functions are realized by individual components and combined into an overall function via intersections. The integrating design attempts to combine the advantages of the integral and differential design positioning of individual interfaces. However, this must be distinguished from the modular design, which considers product family variants, in which products are divided into modules that have close internal relationships, while the modules are strongly decoupled [2].

2.3. Modularization in combination with lightweight design

Laufer et al. described an investigation into the influence of mass distribution on conceptual lightweight design [10]. In order to solve the contrast between lightweight design and modularization, Gumpinger presented a first methodical procedure consisting of four phases [3]. First, a system model is created, a module layout is revised, the module dimensions are adjusted, and only then are module-specific lightweight design measures derived [3]. Graessler and Yang described an approach to estimate the product life cycle cost for modular lightweight design [11]. In the sequential forms of modular lightweight design, lightweight design is carried out first, followed by modularization, or modularization is carried out first, followed by optimization of lightweight design. In both approaches, data is exchanged only sequentially). In contrast to these two forms of modular lightweight design, in which one of the two areas is focused on, in the parallel form the aspects of modularization and lightweight design optimization are not considered one after the other, but simultaneously. This enables a continuous exchange of data throughout the entire product development process, in contrast to the one-off transfer of data in the sequential approach. [4,12] The considerations so far have just focused on the product architecture of a combined design, but have not yet taken the influence of the specific development process into account.

2.4. Model-based System Engineering

In product development, there are different types of models. Some show products, while others, for example, show processes. The product models represent new products and their environment in an as-is state. The focus is on different aspects, such as requirements, behavior or structure. Process models are used for other reasons. They are used to design, communicate, plan or monitor processes. They can also be used to enable process transfer. However, the use of the workflow approach for product development is considered insufficient because the product data and the process are closely linked and dynamic [13,14].

Paetzold describes that process model and a product data model should be used and consistently coupled with each other, whereby workflow approaches can be used for documentation and communication [16]. Konrad et al. enable the complexity management through merging business process modeling with Model-Based Systems Engineering (MBSE) [17].

MBSE can further strengthen collaborative design based on models. Model-Based Systems Engineering was originally developed using abstract system models [18]. For example, the language SysML, which was developed specifically for this case, is used for the description. Software like the Cameo Systems Modeler software can be used as the modeling environment. With the help of software like this, the various SysML diagrams can be created. In contrast to other software, partly also free software, the advantage of the Cameo Systems Modeler is that the diagrams are created based on a consistent data tree. There is therefore a single source of truth. [18, 19]

Based on this aspect, there already are approaches to support the data management of extensive product architectures as they can be found for example in aircraft cabin development. [20]

3. Analysis of Modular Lightweight Design with regards to the product and process viewpoint

In this section the product model of modular lightweight design and the existing process models for methods are presented.

3.1. Product model of Modular Lightweight Design and its challenge

In section 2.3 was presented that modular lightweight design is characterized by the fact that modularization and lightweight design should be considered simultaneously and not consecutively. However, the particular challenge lies in the fact that different data are used in both areas. In order to satisfy the divergent requirements of both areas, an optimal strategy requires comprehensive requirements management, in which all relevant requirements should be recorded, analyzed and related to the developed product architecture. The methodical product development should start from the customer requirements in order to align the modular product architecture with the variant customer-relevant product characteristics [2]. Regarding lightweight design, product development should start from the required design process. For example, for obtaining the data the finite element models used and the tests carried out should be taken into account. Implicit knowledge should be fully documented and linked together with explicit knowledge to support data management. Previous approaches to link the two areas do not take their respective special features into account. So, there is a need for a closer linkage of modularization and lightweight design. A product data model is a good choice for modular lightweight design, which links both the models and data of modularization and lightweight design with one another and thus provides a redundancy-free and consistent basis for the development of a modular lightweight design strategy (see Fig. 1).

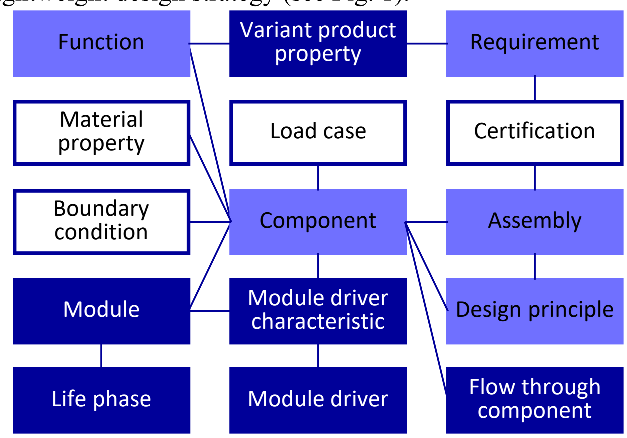

Fig. 1. Product data model of Modular Lightweight Design, adapted from [12]

The existing data model of the modular lightweight design for identifying and presenting the links between different types of data (see Fig. 1) helps to enable consistency across the divisions development of modular product architectures (blue colored) and design of lightweight structures (white colored). However, it does not support the process aspects, and changes over time are not yet taken into account. Different process steps should, however, also be taken into consideration. In modular lightweight design, development runs in parallel and iteratively, which poses a particular challenge for data management. [12]

Thus, a process model is needed due to the missing process situation and the parallel and iterative approach of modular lightweight design. In addition, the aerospace industry is characterized by the use of implicit knowledge and different types of data in the methodical development of modular product development and in lightweight design optimization. This can be improved by end-to-end data management and data linking of different data types. Dynamic product data due to iterative product development process occurs, which can be remedied by a consistent data model linked to an end-to-end process model. A digital implementation can provide support here.

3.2. Existing process models for methods

Process-oriented methods are used in product development. They are used to divide complex problems into individual sub-problems, which are then easier to handle [2, adapted from 8]. In this context, methods are therefore procedures. The development of modular lightweight design is also a complex problem, which can be divided into individual sub-problems if a process view is taken, see 4.1. The idea of storing process models with a kind of data repository has already been presented by Albers [21], but here the data store is rather to be understood as a continuous ideas store.

4. Process model of Modular Lightweight Design

In this section the process model for the development of modular lightweight design is presented.

4.1. Meta-model of the development process

The Meta-model of the development process of the modular lightweight design is presented in Fig. 2.

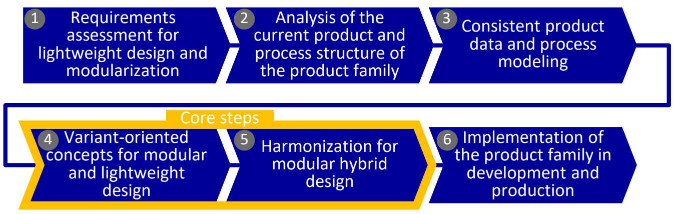

Fig. 2. Meta-model of the parallel development process of Modular Lightweight Design

The first step is a detailed requirements analysis to take the requirements of all relevant stakeholders into account. The specific requirements must be determined and analyzed from the perspective of lightweight design and modularization. For example, the variant-relevant properties and their characteristics are important from the variant-oriented product design, which can be determined and visualized for example with a tree of external variety. From a lightweight design optimization point of view, weight-influencing requirements are decisive. These include, for example, the design-relevant loads acting on the structure, the materials used and their mechanical properties, and the position and number of load application points.

For the second step, the analysis of the actual state of the product architecture, design data such as CAD models are taken into account, as well as, when using the Integrated PKT approach for the development of modular product families, the Module Interface Graph, in which all components of the product family, the kind of their variance, their location and their connecting flows are identified. With regard to lightweight design, existing design processes and existing data, for example from FE models, are analyzed.

The collected data and documents are then implemented in a consistent data model. This enables consistent data management for the use case, in which the existing models from the different areas are linked. On this basis, a concrete process model of the use case can be created with the networking of the product model.

Based on this, the development of the product architecture is started, with concepts for modular and lightweight design being developed iteratively. In the sense of modular product structuring, concepts are developed for a modular design on the one hand and for a lightweight design on the other. Within the concrete product data model created in step three, the concepts developed in both areas will be modeled and existing data adapted. In addition to technical and functional aspects, the modular product family design should also take product strategy aspects into account in order to consider the advantages of all life phases. For example, there are numerous module drivers in the production life cycle phase that should be taken into account in the modular product architecture.

This is followed by harmonization to the modular hybrid design, in which the module and lightweight design concepts are merged. In an iterative process, the concepts are harmonized to achieve optimum graduality between modularization and lightweight design. In the modular hybrid design, for example, individual modules can have different lightweight designs. The resulting concept is then consistently incorporated back into modularization and lightweight design in the product data model. The fourth and fifth steps (outlined in orange in Fig. 2) are the core steps of modular lightweight design. In them, the consistent data exchange of the product architectures developed in parallel and their harmonization takes place through data networking.

Finally, the product family is implemented in development and production. For this purpose, the development procedure should enable the maintenance and further development of the product family. The application of the modular lightweight design to other product families within the product range can be easily adapted via the steps of the process model for methodical procedure using the existing consistent data management of the modular lightweight design, since the recorded data on the requirements, the product and process structure, the concepts and the harmonized modular lightweight design can be consistently adopted and adapted.

4.2. SysML-based process model of Modular Lightweight Design

As already described in previous sections, the storage of a consistent data model for processes can lead to the added value that the data relationships, as well as decisions, can be traced. For this reason, the meta model for the development process (see Fig. 2) was implemented in SysML in the Cameo Systems Modeler.

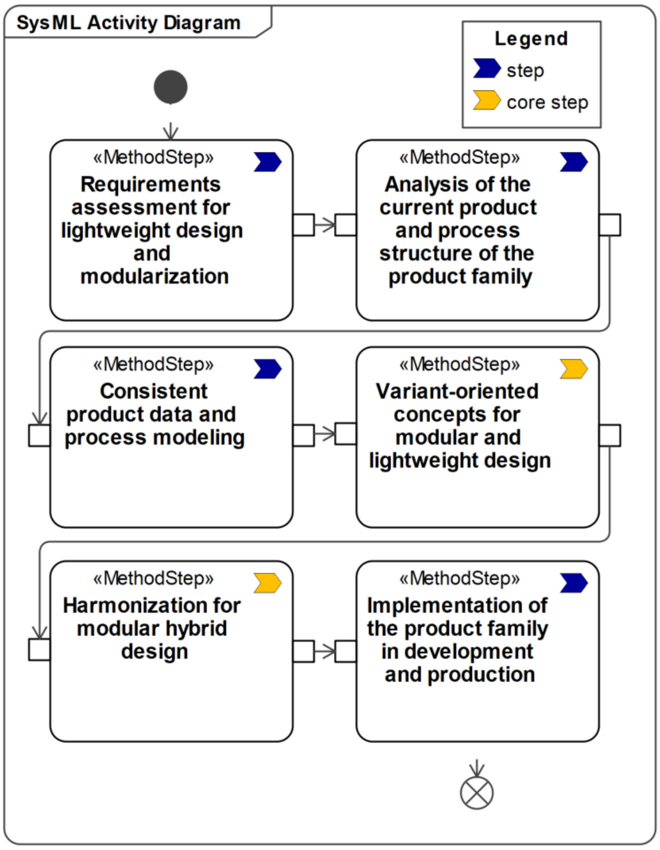

Fig. 3. SysML-based process model of Modular Lightweight Design

The individual steps of the process are implemented using an activity diagram, as in [12]. The steps each provide an output that serves as input for the next step. Thus, a continuity is given. Based on this, individual steps of the process can be detailed and also stored in the SysML-model. Example contents can be seen in section 5.

5. Application on aircraft cabin for development of modular and lightweight optimized galleys

In this section, it is shown how modular and lightweight aircraft cabin monuments can be developed with the process model of modular lightweight design, presented in section 4.

The rear entrance area of the A320 aircraft type has a larger installation space at the back, in which the so-called AFT monument is installed, and two smaller installation spaces in front of it. The AFT monument is often used as a complete galley area, whereas the other two installation spaces are each occupied by a lavatory or another galley area. However, some airlines are currently demanding that additional seats be accommodated in the aircraft cabin in order to increase efficiency, and a large galley storage area is no longer considered so important. At the same time, a flexible adaptation of the configuration to the corresponding airline wishes is required. For this reason, in step four of the process model (see Fig. 2) a new variant-oriented and modular concept was developed for the AFT Monument, see Fig. 4.

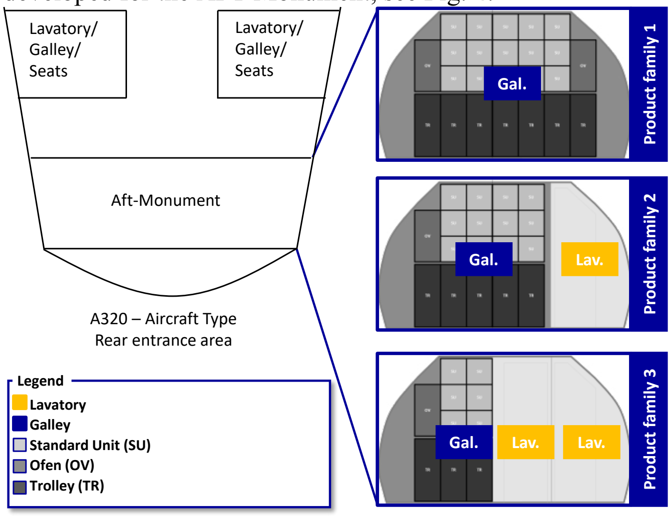

Fig. 4. Modular product program for the AFT monument, adapted from [22]

Conventional sandwich design techniques do not represent a load-path-compatible design for the application case of aircraft cabin monuments. Therefore, there is a lightweight design potential in the development of new design methods with the help of load path optimization. Such an optimization in the form of a topology optimization for an aircraft cabin monument was implemented in step four of the process model. In addition, different variants should already be taken into account during lightweight design optimization. The approach pursued is to determine load-path reinforced panels or modules for several product families or their configurations by means of multi-model optimization (MMO), which can be used for several variants, since the variants have already been taken into account in the lightweight design. Fig. 5 shows two possible product families and their variants for the same installation space of the simplified cabin monument.

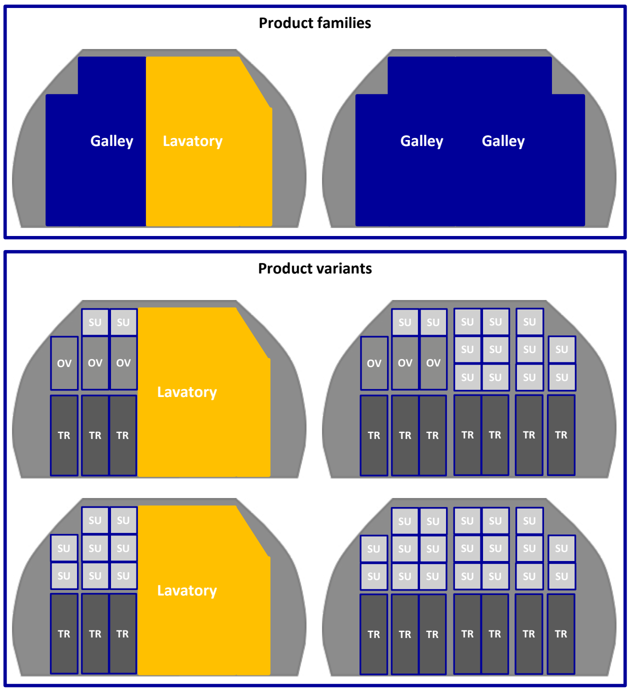

Fig. 5. Possible product families and product variants for the AFT monument

Due to parallel development and consistent data exchange, the two views of modular design and load-path-optimized lightweight design are merged in step five into the modular hybrid design in Fig. 6. It combines several lightweight design methods in a sensible way in order to exploit the lightweight potential as far as possible on the one hand and to implement an effective variant design across all life phases on the other. The data of the resulting concept are consistently entered in the product data model to support continuous development.

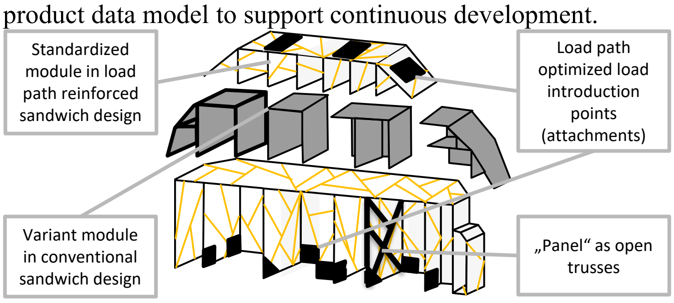

Fig. 6. Modular Hybrid Design of an aircraft galley

In order to achieve optimal graduality between modularization and lightweight design, the approach is iterative, aligning the two concepts. In modular hybrid design, for example, individual modules can be designed in different lightweight design methods. The focus here is particularly on lightweight structural design. Different designs can now be used for the individual modules, so that certain areas can be designed in a load-path reinforced or open design method [12].

6. Outlook and conclusion

The potential of modular lightweight design lies in the possibility of offering a high degree of external variety in a product family while at the same time exploiting the lightweight potential. Standardized processes and consistent data management can accelerate the development of new variants, reduce the number of errors and simplify the implementation of an innovation process. Further development processes can also be implemented on this basis. This makes modular lightweight design particularly suitable for aviation. It is also mainly due to the fact that it enables a more efficient development of new variants. Inconsistencies are also reduced throughout the development process.

The particular challenges, however, are that the requirements must be clearly defined and there must be explicit documentation of the product and process structure.

As this need for a detailed documentation of the product, even after its production, is a currently uprising topic, there are approaches to create these required digital representations, for instance in form of Digital Twins. The accumulation of information of Digital Twins of already existing lightweight products makes for a good base of data to use for further optimizations. Combining this information for instance with detailed data about the flight missions of the fleet's aircrafts allows to get a better picture about the actual use and, thus, actual requirements of these lightweight structures. [23,24,25]

The combination of modularity and lightweight design exploits the various potentials. The support of this process for process-oriented methods leads to the fact that this process can be reproduced and thereby optimized. The application of a model-based procedure leads to the fact that the decisions, which are transacted during the execution of the method, are traceable. The storage of the data model plays a major role in this process. The long-term goal is the integration of this information. The description of the method should identify the method steps for which access to the stored data model must be enabled. Additional information, such as the effects of modular product architectures, will also be included in order to strengthen the methodical process for modular lightweight design in aircraft cabin [26]. In addition, the consistent linking of the product data model and the process data model could be implemented in the future in order to facilitate the exchange of information about the development process.

References

[1] Krause, D. et al.: New Trends in the Design Methodology of Modularization, 11th IDE Workshop, 5. – 7. April 2017, Magdeburg.

[2] Krause, D. et al., Integrated Development of Modular Product Families: A Methods Toolkit, In: Simpson, T.W., Jiao, J.R., Siddique, Z.and Hölttä-Otto, K., Advances in Product Family and Product Platform Design, Springer, New York, 2014, pp. 245-270.

[3] Gumpinger, T.: Modulleichtbau - Methodische Unterstützung des Leichtbaus modularer Produktfamilien, Dissertation TUHH, 2015.

[4] Hanna, M., Schwenke J. and Krause, D., Modularer Leichtbau – Chancen und Herausforderungen im digitalisierten Entwicklungsprozess, 30. DfX-Symposium, Hamburg 2019.

[5] Salvador F.; Towards a Product System Modularity Construct: Literature Review and Reconceptualization, in: IEEE Transactions on Engineering Management, 2007, 54; S. 219-240.

[6] Krause, D. et al.: Leichtbau. In: Rieg, F.; Steinhilper, R. (Hrsg.): Hand-buch Konstruktion, Carl Hanser Verlag, München, 2018, S. 487-507.

[7] Klein, B.: Leichtbau-Konstruktion. Berechnungsgrundlagen und Gestaltung, Springer Vieweg, Wiesbaden, 10. Auflage, 2013.

[8] Pahl, G., Beitz, K., Feldhusen, J., Grote, K.-H.: Pahl/Beitz Konstruktionslehre. Grundlagen, Springer Verlag, Berlin, 7. Auflage, 2007.

[9] Ehrlenspiel, K., Meerkamm, H.: Integrierte Produktentwicklung. Denkabläufe, Methodeneinsatz, Zusammenarbeit, Carl Hanser Verlag, München, 6. Auflage, 2017.

[10] Laufer, F, Roth, D., Binz, H. An investigation into the influence of mass distribution on conceptual lightweight design, Procedia CIRP, Volume 84, 2019, Pages 1041-1047, ISSN 2212-8271, https://doi.org/10.1016/j.procir.2019.04.304.

[11] Iris Graessler, Xiaojun Yang, Product life cycle cost approach for modular lightweight design, Procedia CIRP, Volume 84, 2019, Pages 1048-1053, ISSN 2212-8271. https://doi.org/10.1016/j.procir.2019.03.199.

[12] Hanna, M.; Schwenke, J.; Krause, D.: Inconsistency Management for Product Families with many Variants through a Model-Based Approach in Modular Lightweight Design, Proceedings of the Design Society: DESIGN Conference, 1, 2020, pp. 917-926. https://doi.org/10.1017/dsd.2020.309

[13] Eckert, C.M. et al, On the integration of product and process models in engineering design, Design Science, Vol. 3No. 3. 2017. http://doi.org/10.1017/dsj.2017.2

[14] Beckmann G.; Gebhardt N.; Bahns T.; Krause D.: Approach to Transfer Methods for Developing Modular Product Families into Practice. 14th International Design Conference DESIGN 2016, Dubrovnik, 2016, pp. 1185 - 1194.

[16] Paetzold, K.: Workflow-Systeme im Produktentwicklungsprozess, Design for X, Beiträge zum 15. DfX-Symposium, Neukirchen, 2004.

[17] Konrad, C., Jacobs, G., Rasor, R., Riedel, R., Katzwinkel, T., Siebrecht, J.: Enabling complexity management through merging business process modeling with MBSE, Procedia CIRP, Volume 84, 2019, Pages 451-456, ISSN 2212-8271, https://doi.org/10.1016/j.procir.2019.04.267.

[18] Holt, J., Perry, S. and Brownsword, M, "Model-based requirements engineering", The Institution of Engineering and Technology, London, 2012.

[19] Weilkins, T., Systems Engineering with SysML/UML: Modeling, Analysis, Design, Morgan Kaufmann, 2008.

[20] Laukotka, F.; Hanna, M.; Krause, D.: Digital Twins of Product Families in Aviation based on an MBSE-assisted approach, Procedia CIRP, 2021, Paper accepted.

[21] Albers, A.; Burkhardt, N.; Meboldt, M.; Saak, M.: SPALTEN Problem Solving Methodology in the Product Development. 2005. DOI: 10.5445/IR/1000007075

[22] Hanna, M.; Schwenke, J.; Heyden, E.; Laukotka, F.; Krause, D.: Neue Trends in der Flugzeugkabinenentwicklung, in: Krause, D.; Hartwich, T. S.; Rennpferdt, C. (Hrsg.): Produktentwicklung und Konstruktionstechnik, Forschungsergebnisse und -projekte der Jahre 2016 bis 2020, Springer Verlag, Berlin, Heidelberg, Germany, 2020, pp. 207-228. https://doi.org/10.1007/978-3-662-62393-0_9

[23] Laukotka, F.; Seiler, F.; Krause, D.: MBSE als Datenbasis zur Unterstützung von Konfiguratoren und Digitalen Zwillingen modularer Produktfamilien, Proceedings of the 31th Symposium Design for X (DFX2020), Bamberg, Germany, 2020, pp. 61-70. DOI: 10.35199/dfx2020.7

[24] Tuegel, E.J.: The Airframe Digital Twin: Some Challenges to Realization, 53rd AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf, pp. 1812, 2012. DOI: 10.2514/6.2012-1812

[24] Laukotka, F.; Hanna, M.; Schwede, L.-N.; Krause, D.: Lebensphasen-übergreifende Nutzung Digitaler Zwillinge - Modellbasierte Produktfamilienentwicklung am Beispiel der Flugzeugkabine, Zeitschrift für wirtschaftlichen Fabrikbetrieb (ZWF), Vol. 115, 2020, pp. 101-104. DOI: 10.3139/104.112332

[26] Schwede, L.-N., Hanna, M., Wortmann, N., Krause, D.: Consistent Modelling of the Impact Model of Modular Product Structures with Linking Boundary Conditions in SysML, Proceedings of the 22nd International Conference on Engineering Design (ICED19), Delft, The Netherlands, 2019, pp. 3601-3610. https://doi.org/10.1017/dsi.2019.367