**INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022**
https://doi.org/10.1017/pds.2022.199

# Modeling of an Interface between System Models and FEM Models for the Support of Model-Based Development in Modular Lightweight Design for Aircraft Cabins

L. Schwan ✉, M. Hanna, J. Schwenke and D. Krause
Hamburg University of Technology, Germany
✉ lukas.schwan@tuhh.de

**Abstract**

The modular lightweight design attempts to reconcile the partially conflicting goals between modularization and lightweight design in order to establish a harmonized modular hybrid design. This requires a close exchange of the resulting development data between the two areas. In this contribution a concept for an interface for the data exchange between system models and FEM models is presented and successfully implemented in the Cameo Systems Modeler and applied to examples from the aircraft cabin. With the interface the homogenization step of modular lightweight design can be performed.

*Keywords: design optimisation, modularisation, model-based systems engineering (MBSE), data interface, aircraft cabin*

## 1. Introduction

In methodical product development, the amount of data has increased significantly in recent years, leading to an enlarged use of model-based approaches. This is also evident in the development of modular product families, in which Model-Based Systems Engineering (MBSE) tools are increasingly being used (Seiler et al., 2020; Hanna et al., 2020a). In addition, system models implemented using the modeling language SysML also enable a central data basis for data that accumulates in product development. In the aircraft cabin lightweight design plays a decisive role in addition to the modularization aspect, to save mass as well as fossil fuels. In order to unite the partly conflicting goals of modularization and lightweight design optimization, Modular Lightweight Design (MLD) has been established as an approach, in which the two areas are carried out parallelly to generate a harmonized modular hybrid design (Hanna et al., 2020a). In contrast to the system models, finite element method (FEM) models are used for calculating the product variants and to perform lightweight design optimization (Krause et al., 2018). One problem in harmonizing the two disciplines is that the data from the two models are not linked with each other. For example, system models lack simulation results, which can contribute to decision-making between different product variants. In FEM models, however, information such as product costs is missing. This can lead to inconsistencies and make cross-disciplinary collaboration more difficult.

Therefore, in this contribution a methodical approach for modeling an interface for continuous exchange of data and development statuses between system models and FEM models, which also enables the support of model-based configuration of different product variants is presented and applied. For this purpose, chapter 2 first gives an overview of the state of the art. Subsequently, Chapter 3 shows how the harmonization step between modular and lightweight design can be accomplished with the interface. The methodical approach is presented in Chapter 4 and was subsequently applied to create a suitable interface for data exchange. Afterwards, Chapter 5 shows the implementation of the interface in the MBSE software Cameo Systems Modeler using examples from the aircraft cabin. In chapter 6 a summary and an outlook are given.

## 2. State of the art

This chapter first describes the fundamentals in the field of model-based product development and lightweight optimization. Based on this, an overview of the methodical development of MLD is given.

### 2.1. Fundamentals of Model-Based Product Development and Lightweight Design Optimization

Product development is currently changing from document-based approaches to model-based ones. The reasons for this are increasingly complicated products as well as the advancing digitalization due to ever-increasing data volumes. On the one hand, product models are used to represent new products and their environment in an as-is state, focusing on various aspects such as requirements, behavior or structure. Process models, on the other hand, are used to design, communicate, or monitor processes (Eckert et al., 2017; Beckmann et al., 2016). MBSE was developed using abstract system models to further support model-based development (Holt et al., 2012). MBSE tools and diagram types can help implement this model-based product development to increase consistency and continuity. Furthermore, approaches to implement model-based configuration systems for the supporting of decision-making exist (Cicconi et al., 2018; Dambietz et al., 2021b). For the implementation of system models, in which data can be linked to each other and across multiple domains, the associated modeling language, SysML, is used. Here, software such as Cameo Systems Modeler can be used as a modeling environment to create the various SysML diagrams. This includes nine diagrams, five of which are used to create the structure and four of which are used to create the behavior. Unlike other software, Cameo Systems Modeler has the advantage that the diagrams are created based on a consistent data tree. Thus, there is a single source of truth (Holt et al., 2012; Weilkins, 2008).

In addition to model-based development, there is also a goal in the field of product development to make products particularly lightweight. Lightweight design can be divided into the categories of system, structural and material lightweight design (Krause et al., 2018). In order to realize a lightweight design, various tools are available to the designer. One example is structural analysis, in which calculations can be performed based on FEM (Werkle, 2021). In the field of aircraft cabins, virtual models are used for this purpose, which are hierarchically constructed across different structural complexity levels (Heyden et al., 2019; Schwan et al., 2021). Furthermore, optimization calculations in combination with FEM can be used to optimize a product or structure with respect to a specific target parameter (Werkle, 2021). One goal may be to obtain the stiffest possible structure with minimum weight. In different areas of a product, the use of a particular lightweight design may be particularly suitable, which is why different designs can also be synergistically combined within a product to obtain a hybrid lightweight design.

There are commercial applications, such as *Model Center* from *Phonenix Integration* or *iSIGHT* in combination with the *SIMULIA Execution Engine* from *Dassault Systems*, with which it is possible to connect several cross-disciplinary models and perform simulation processes automatically. The *Syndeia* software platform from *Intercax* is a cloud-based solution that can be used to exchange data between modeling tools and simulation programs, among other things. While the solutions mentioned represent a possibility for exchanging data between system models and FEM models, there are specific requirements in aircraft cabin development and especially in MLD that cannot be solved using these commercial programs. For example, there is a large number of product variants, each of which consists of different components. For a close exchange between model-based development and lightweight design optimization, a suitable data structure must be designed in addition to the pure exchange of data between the models, so a consistent database exists and the support of model-based configuration of the exchange data of product variants from these different components is ensured. In addition to the commercial solutions, a few studies could be identified in the literature that have dealt with a model-based configuration of product variants from components and interfaces that enable data exchange between system models and FEM models. Szarazi et al. (2017) have worked on an independent definition of FEM models. This description of discretized elements can also be integrated into system models, allowing model-based processing of FEM data in SysML. However, this is a mathematical approach and its use is not suitable when there are a large number of elements and FEM models stored in the system model. Jagla et al. (2021) show how modeling efforts due to changes in complex systems can be evaluated. For this purpose, the relationships from system components and corresponding modeling efforts are coupled in a system model. However, an interface between system models and FEM models is missing. Furthermore, Russwurm et al. (2021) show the need for an interface for data exchange between system models and FEM models in order to implement a data-driven design process for function-critical components, which is controlled via a process model implemented in SysML.

## 2.2. Methodical Development of Modular Lightweight Design

Modular product structures are often used to reduce internal variety when external variety is high. Methods for modularization such as the Integrated PKT Approach for developing modular product families contain some method units to reduce internal variety while external variety remains the same. For this purpose, special methodical tools are offered that contain different data and visualize their interrelationships (Krause et al., 2014). In methodological product development, tools of MBSE could already be successfully used and support be enabled (Albers et al., 2019). Here, in particular, consistency between different methodological tools was enabled. Thus, data and documents could already be linked within a method (Seiler et al., 2020). In the context of PSS systems, the use of MBSE tools could improve consistency as well as continuity (Dambietz et al., 2021a).

Model-based development of modular product families has also been successfully implemented in aircraft cabin development (Hanna et al., 2020b). However, product development in aviation is not only characterized by a high degree of individualization, which can be countered with modular product structuring, but also by the contrary goal of weight reduction. Thus, the goal is to reduce the weight of aircraft in order to conserve resources. As a result, the entire product architecture is weight-optimized. On the other hand, individual customer requirements result in a high number of different variants being offered to the market. A modular product architecture leads to standardized and thus mostly oversized interfaces, which have a higher overall weight (Hanna et al., 2020b). In terms of data, the different domains of the two sub-areas of modularization and lightweight optimization are of particular importance here and thus represent a challenge in method research. Inconsistencies can occur here not only within the methodological modularization tools, but also in the interface to the lightweight design data (Hanna et al., 2020a). MLD aims to reconcile these two goals and develop a harmonized modular hybrid design. The potential of MLD lies in the possibility of offering a high degree of external diversity in a product family while at the same time exploiting the potential of lightweight design.

Due to the parallel approach of lightweight design and modularization in MLD, continuous data exchange is required throughout the entire product development process, in contrast to the one-time data transfer in the sequential approach. A six-step methodological approach to MLD has already been researched for this purpose, which contains two essential core steps. (Hanna et al., 2021) In the fourth step, a concept for a modular and a lightweight design are developed individually, followed by iterative harmonization to form the one modular hybrid design. In particular, this results in high requirements for data traceability and continuity. The basis is the data-driven linking of product and process data. It is particularly important to know which input and output data are required or generated in each of these steps. This information can be used to establish the link between the process and product data models. With this link, the consistency and continuity of the data can be improved, since uses and changes in one step can be traced back to other relevant steps. (Hanna et al., 2021)

# 3. Analysis of Data Exchange in Modular Lightweight Design Through the Use of an Interface

In order to be able to apply MLD in aircraft cabin development, the aim is to be able to carry out the calculations, optimizations and methodological development in a simultaneous exchange. The concrete implementation of MLD is particularly challenging. As shown in Chapter 2, different data and information are available in the two areas of modularization and lightweight design optimization. However, MLD postulates that both design methods can be combined. Therefore, data exchange across both areas is highly relevant. So far, however, the existing tools have not been linked in a consistent manner. Hanna et al. (Hanna et al., 2020a) have shown a first approach to do this in terms of data management, but a methodical approach for modeling a data exchange interface as well as a software-based implementation is still not described.

In Figure 1 on the top, the static product data model of the modular hybrid design and its links are shown, to enable overarching consistency. There, different data and information are shown, as well as their linkages, which are relevant in MLD. The blue methodical modularization elements are already contained in system models, the white lightweight elements in FEM models, but the cross-tool linking has not yet been implemented on a software basis. In particular, the component information should be linked consistently, especially the variance and lightweight information. Links shown in light blue indicate the required cross-software data exchange between system models and FEM models.

Figure 1 below shows the Process Model to illustrate the data continuity. Here, the parallel methodological approach becomes clear. In contrast to a sequential development, there is no one-time data transfer, but a continuous bidirectional data transfer between the areas of modularization and lightweight design optimization. Since the advantages of both areas must be taken into account, it is not expedient to work only in one software and then transfer data once, as in the sequential approach, but it becomes clear that a cross-software interface is required. In particular, the iterative character that becomes clear in step 5 thus poses a special challenge to data management. There, the modules of both areas are aligned and revised, and the information must thus be changeable over time. In order to make the continuous data exchange efficient, it is necessary to support the model-based configuration of the data exchanged, which must be taken into account in a corresponding data structure.

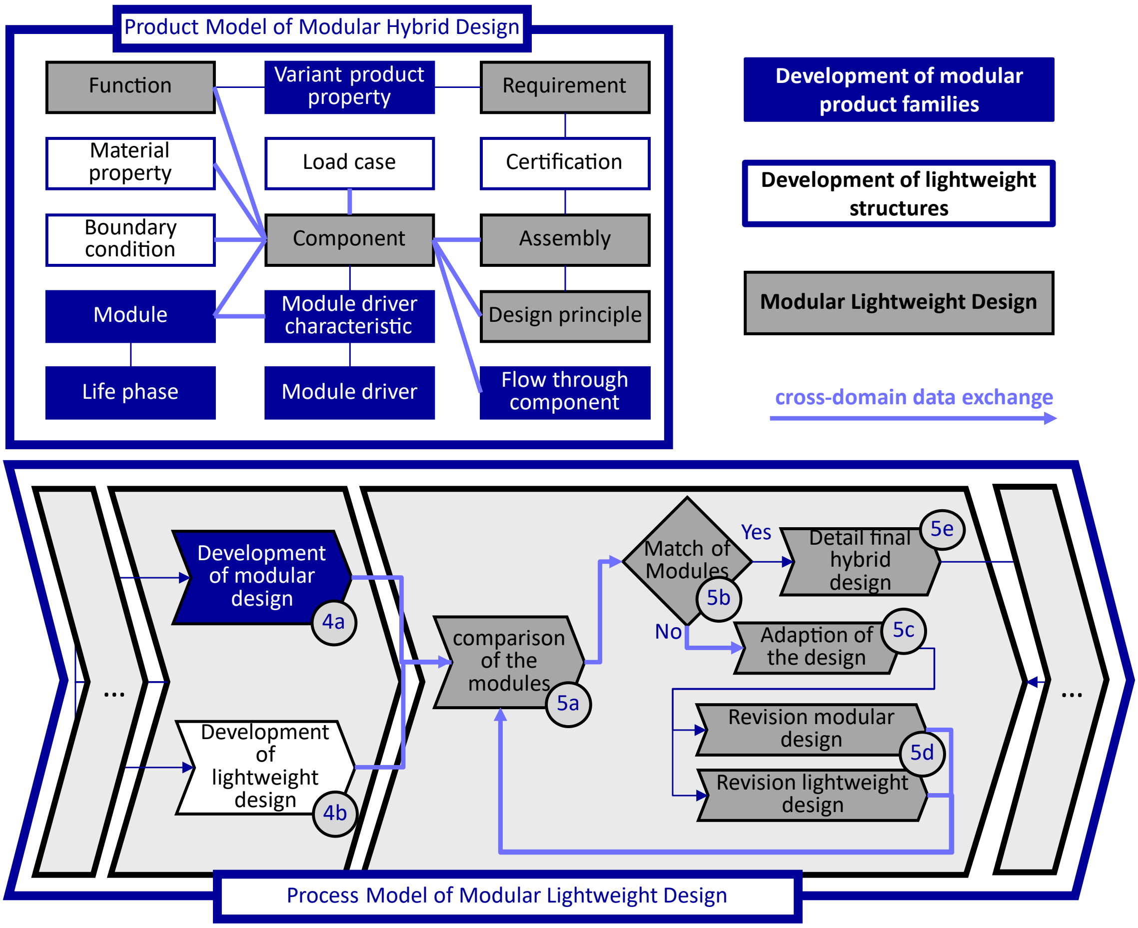

**Figure 1. Data exchange in Product and Process Data Model of Modular Lightweight Design based on Hanna et al. (2021)**

In this analysis, it becomes clear that in particular an interface between system models and FEM models is needed to harmonize both methodical and lightweight data and to implement MLD. On the one hand, this interface must enable data consistency, but on the other hand, it must also support the model-based configuration of the exchanged data and allow for temporal changes. This is because the iterative procedure frequently necessitates changes, which must be reliably implemented. A methodical approach for modeling such an interface is currently also missing.

## 4. Interface for Data Transfer between System & FEM models

In chapter 4.1 a methodical approach for the modeling of an interface for data exchange between system models and FEM models is presented. Afterwards in chapter 4.2 the methodical approach is applied for the modeling of a generic interface for the data exchange in MLD for aircraft cabins.

### 4.1. Methodical Approach for the Modeling of the Interface

The methodical approach for the modeling of the interface for data exchange of system models and FEM models is shown in Figure 2. In an initial analysis phase ①, the data which needs to be contained in the FEM model and must either be stored or referenced in the system model are first defined and recorded in a table. The associated data types are afterwards defined in step ②. Based on this, a data structure and flow are defined in step ③, in which it is specified how the data is structured and exchanged between the models and databases involved. Special attention must be paid in this step to the fact that the data structure supports a model-based configuration of the data to be exchanged. In step ④, the exchange formats for data from system models to FEM models and back are defined. In order to bring the data from the system model into the structure of the defined exchange format, a concept for data preparation is defined in step ⑤.

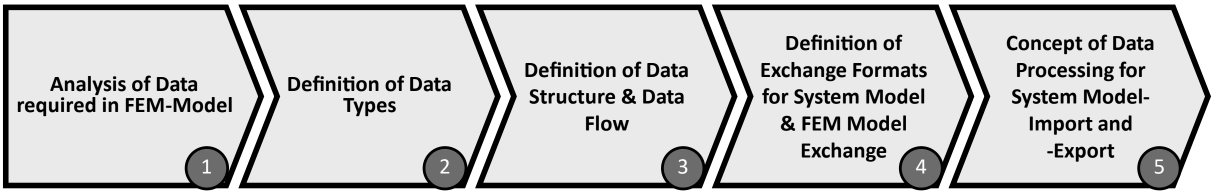

**Figure 2. Methodical approach for the modeling of the interface between system models and FEM models**

### 4.2. Modeling of a generic Data Interface Between System Models & FEM Models

In the following, an interface for the data exchange between system models and FEM models for aircraft cabins, which was created through the application of the methodical approach from chapter 4.1, is presented.

### *4.2.1. Analysis and Definition of Data Types*

In a first step, it must first be determined which data has to be contained in the FEM model and which information must therefore be available in the system model to create a central data basis. First of all, the data is divided into data of product variants and data of components. In the FEM program, the calculation of components requires not only data containing information on geometry and mesh, but also information on the load case, the prevailing boundary conditions and the material used. When calculating a complete product variant, in addition to the component data, an assembly plan is also required that specifies which components are installed and at which position their center of gravity is located in the relative coordinate system of the respective product variant. Through this assembly plan, a support of model-based configuration of the exchanged data and a communal use of components is possible, which contributes to the reduction of inconsistencies in the FEM simulation. If the calculation in the FEM program is completed, the calculation results must be transferred back to the system model and stored or be referenced there. Depending on the application, these results can be, for example, displacements or reaction forces occurring at individual nodes in the model or false-color images.

### *4.2.2. Definition of the Data Structure and Data Flow*

Based on the identified data, the existing data structure and the data flow between the domains involved can be defined. This is shown in Figure 3. For reasons of clarity, the corresponding data, which are required for the methodical development of a modular design (see Figure 1), have not been included in the figure.

Since the components may already be meshed, it is recommended to use external FEM databases for geometry representation, material-models and load cases, which are referenced in the system model, for example, via a corresponding identification number (ID). The data exchange between the system model and the FEM model is realized via the interface, whereby data configuration and preparation must take place for this purpose in order to bring the data into the appropriate data format during export or to assign the data to the correct elements in the system model during import.

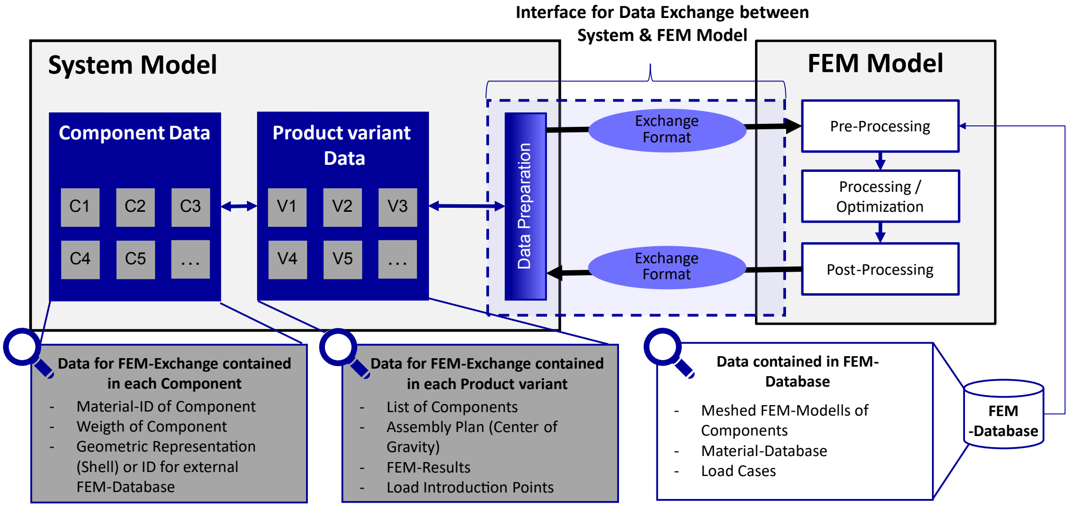

Figure 3. Higher-level data structure with global data flow

### 4.2.3. *Determination of Data Formats and a Concept for Data Preparation*

In order to transfer the data stored in the system model to the FEM program and back again, neutral data exchange formats must be defined. Figure 4 shows the complete interface with the corresponding data flows and specified exchange formats. Besides FEM program-specific interfaces there are further possibilities to structure and store data and to make it available to the FEM program. A compact data format for the data exchange between different applications is for example the XML format, which is recommended for data transfer from the system model to the FEM model. In order to convert the data stored in the system model into the appropriate exchange format, it is necessary to prepare the data. In case of the Cameo Systems Modeler a Report Assistant is recommended for this purpose. It can be used to convert the corresponding data from the system model into a structure predefined in a template script.

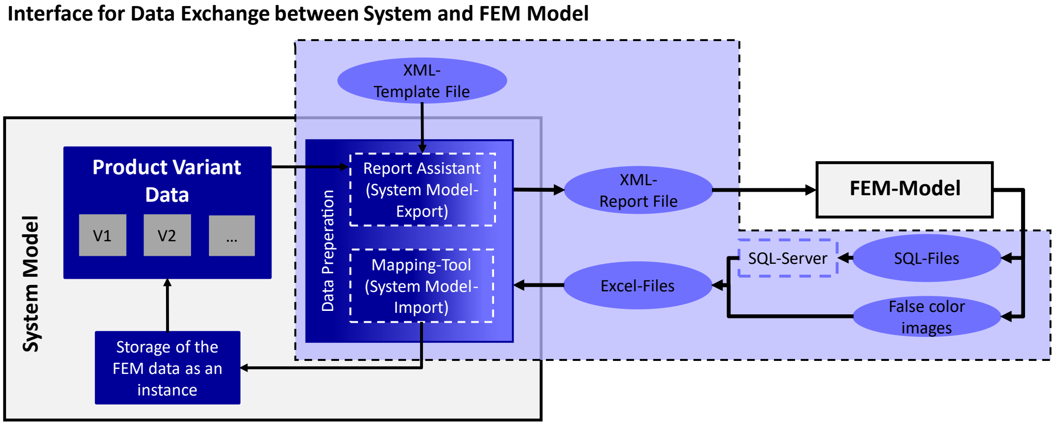

Figure 4. Interface concept for data transfer between system models and FEM models

Once the data from the system model has been imported into the FEM program, the corresponding data can be assembled into a computable FEM model during pre-processing and afterwards be calculated. During post-processing, the corresponding output files are generated, which have to be imported back into the system model. In addition to the output of false-color images, there are also various output values for reaction forces or displacements. If the results are available in a SQL database, it is recommended to convert them into an Excel format first in an optional intermediate step. Furthermore, the storage paths to the false-color images can be saved in an Excel file. To export the calculation results back to the system model, the output values from the available Excel files must be correspondingly reassigned to the correct elements in the system model, for which a mapping is required.

# 5. Implementation of the Interface

In the following chapter, the implementation and application of the modeled interface concept to an example from the aircraft cabin are shown. Chapter 5.1 first shows the implementation of the interface in the Cameo System Modeler using the specific example of the aircraft partition. Chapter 5.2 shows how Multi-Model Optimization (MMO) can be performed efficiently with the modeled interface in the context of MLD.

## 5.1. Application on the Example of an Aircraft Partition

In Figure 5 two product variants of an aircraft partition on the left-hand side, which will be used to demonstrate the implementation of the interface are shown. The installed components were modified compared to the original due to project secrecy reasons. One of the results, which was achieved in the course of a FEM simulation, can be seen in the image on the right, although here, too, the exact values of the calculation cannot be given for reasons of secrecy.

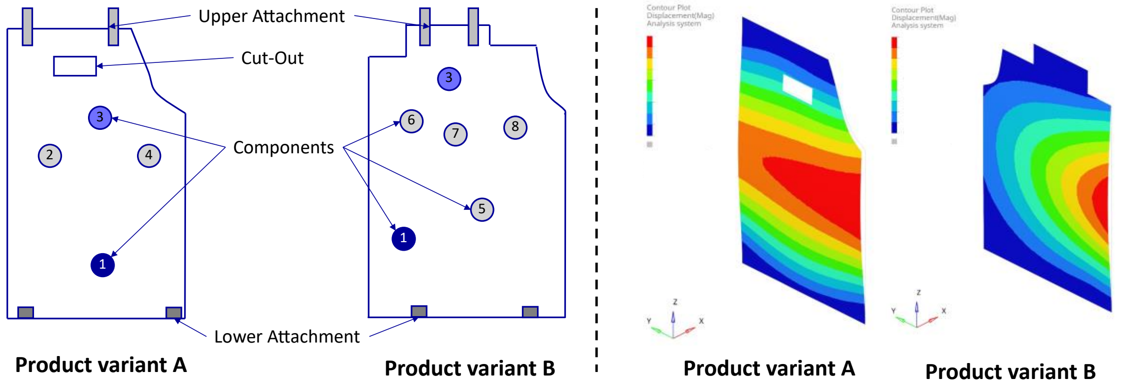

**Figure 5. left: Product variants of the aircraft partitions, right: Example results of the FEM calculation.**

Part of the higher-level data structure implemented in the Cameo Systems Modeler, as well as the data flow for Product Variant A (Aircraft Partition A) according to the data exchange interface concept for aircraft cabins from chapter 4 is shown in Figure 6. The contour of the panels is stored in the system model in the form of a point cloud. In order to access the linked meshed and material models of the other components, a reference is made in each case to an ID in the FEM database. The exact position at which the meshed FEM model of the corresponding component needs to be inserted into the overall FEM model is stored in an assembly block of the respective product variant. This converts the configuration of the data to be exported. To get the corresponding data into the FEM model, the data is converted into the appropriate XML format using an Apache Velocity script. Within the scope of Pre-Processing a computable FEM model is created afterwards from the imported data and information from the system model. After Processing and Post-Processing, in addition to the false-color images further calculation results are available in the form of an SQL file. These are imported back into the system model accordingly after an Excel conversion via the mapping tool. Afterwards, the data is available in the *Cache FEM-Import* Block and must be manually assigned to the corresponding product variant.

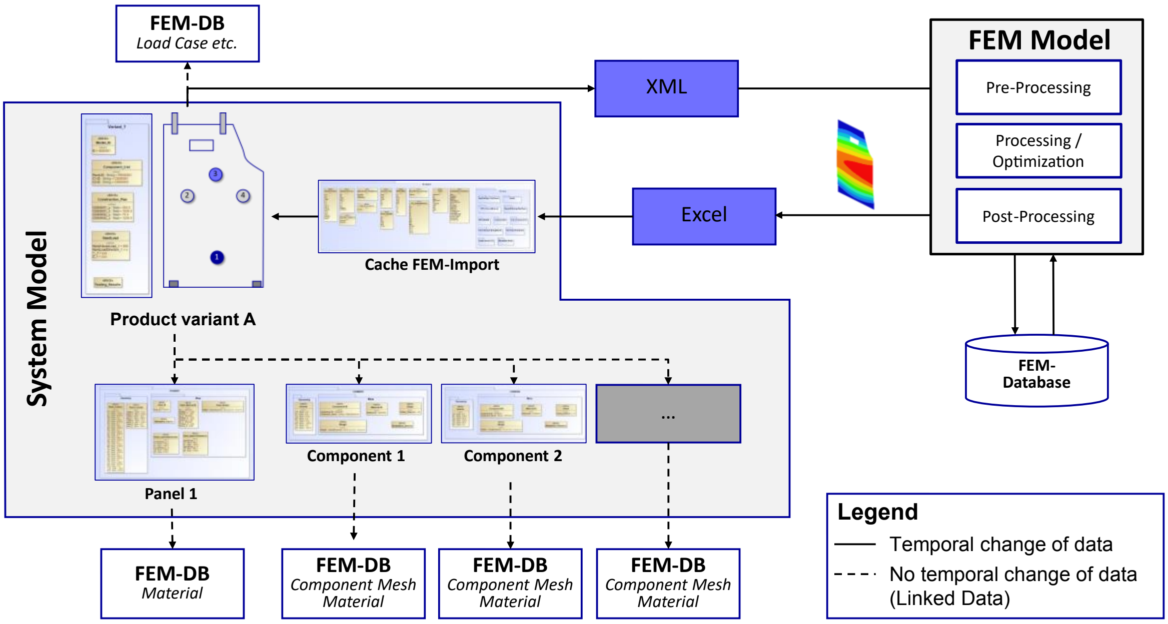

Figure 6. Implemented data structure and data flow for product variant A

## 5.2. Multi-Model Optimization

In order to perform load path optimization for aircraft cabin monuments, the different variants could previously only be calculated individually in a so-called Single Model Optimization (SMO). One approach to taking cross-product-family modularization concepts into account during optimization is to use MMO to determine common load-path-optimized modules or components for several product families or their variants (Hanna et al., 2020b). This will be demonstrated at this point using a simple example, and the result of an MMO for aircraft cabin monuments will be shown for the first time. Figure 7 shows two product families for exactly the same installation space of a simplified cabin monument. The first product family combines a galley area with a lavatory, while the second product family represents a full-size galley. The two product variants considered here also differ in the central area of the left-hand galley section. While ovens are used in one product variant, they are replaced by standard units in the other. Figure 7 also shows the corresponding FE models for the optimization.

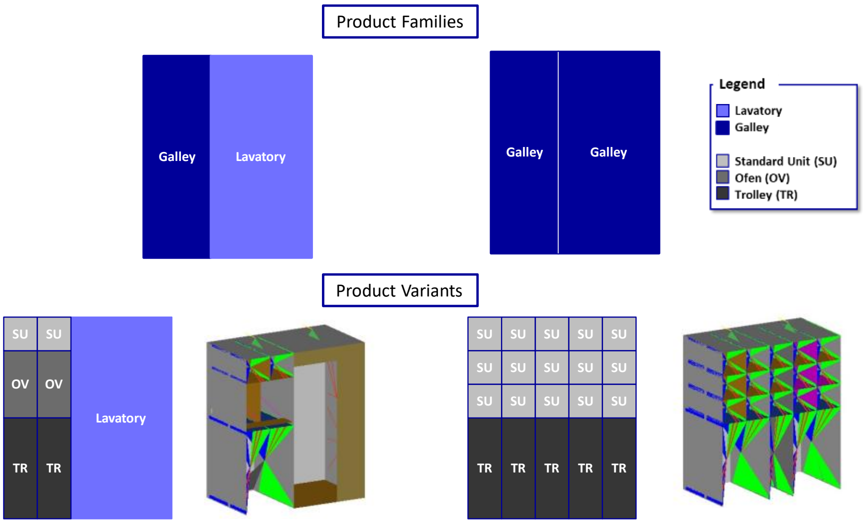

Figure 7. Product families to be optimized and associated variants

Figure 8 first shows the results from the respective SMOs of the two variants. For clarity, only the result for one sidewall was selected. As expected, the results differ from each other. In the lower part, the result of an MMO is shown, where the optimized sidewall is identical for both variants. Compared with the results of the MMO, it is clear that this is a compromise between the results of the individual SMOs.

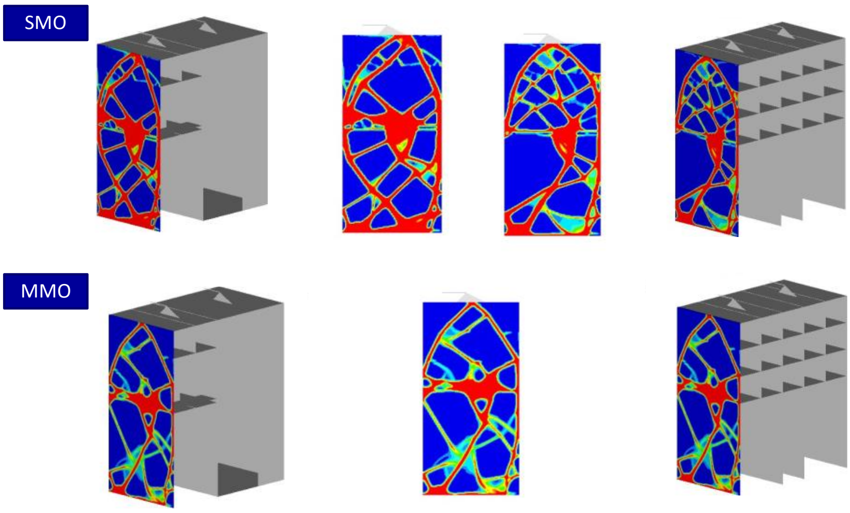

**Figure 8. Comparison of SMO and MMO results**

The use of the MMO can thus be used to evaluate different modularization concepts according to lightweight design criteria and to support the decision which components of the aircraft cabin monuments should be optimized together, individually or not at all. The interface shown will enable this procedure to be carried out efficiently in the future.

## 6. Discussion and Outlook

To enable a consistent data basis and the continuous exchange of domain-specific data, a methodical approach for the modeling of a data exchange interface between system models and FEM models was introduced and has been applied for the aircraft cabin. The interface has been successfully implemented in the Cameo Systems Modeler using the example of the aircraft partition. It was shown that the modeled interface is capable of transferring the data from system models to FEM models and that also the support of the model-based configuration of the exchange data is guaranteed. Further, the results from the numerical calculation can be imported into the system model to contribute to the decision-making process. The interface is suitable for completing the harmonization step between modularization and lightweight design optimization in the context of MLD and makes a contribution to making the aircraft cabin development process more efficient. For the first time, results of an MMO for cabin monuments were shown for this purpose, which can be performed more efficiently with the interface. In further research, the application of the interface to cabin monuments, like galleys or lavatories can take place, because similar data structures and load cases are present. Furthermore, the presented methodical approach can be applied to other applications, to take advantage of the many benefits of the continuous data exchange and make multi-disciplinary product development processes more efficient.

## Acknowledgment

This work was supported by the LuFo VI-1 project "Effiziente Kabine durch digitale Vernetzung von Technologien und Systeme (EFFEKT)”, funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) based on the decision by the German Bundestag.

## References

Albers, A., Bursac, N., Scherer, H., Birk, C., Powelske, J. et al. (2019), "Model-based systems engineering in modular design", *Design Science*, Vol. 5, No. 17. https://doi.org/10.1017/dsj.2019.15

Beckmann, G., Gebhardt, N., Bahns, T. and Krause, D. (2016), "Approach to Transfer Methods for Developing Modular Product Families into Practice", *Proceedings of the DESIGN 2016 / 14th International Design Conference, Dubrovnik, Croatia, May 16-19,* 2016, The Design Society, Glasgow, pp. 1185-1194.

Cicconi, P., Raffaeli, R., Marchionne, M., Germani, M. (2018), "A model-based simulation approach to support the product configuration and optimization of gas turbine ducts", *Computer-Aided Design & Applications*, Vol. 15, pp. 807-818. https://doi.org/10.1080/16864360.2018.1462564

Dambietz, F. M., Rennpferdt, C., Hanna, M. and Krause, D. (2021a), "Using MBSE for the Enhancement of Consistency and Continuity in Modular Product-Service-System Architectures", *Systems*, Vol. 9, No. 3. https://doi.org/10.3390/systems9030063

Dambietz, F. M., Greve, E., Krause, D. (2021b): "Simulation-based performance analysis for future-robust modular product architectures", *Proceedings of the 23rd International Conference on Engineering Design (ICED21), Gothenburg, Sweden, August 16-20,* 2021, pp. 2671-2680. https://doi.org/10.1017/pds.2021.528

Eckert, C.M., Wynn, D. C., Maier, J. F., Albers, A., Bursac, N. et al. (2017), "On the integration of product and process models in engineering design", *Design Science*, Vol. 3 No. 3. http://doi.org/10.1017/dsj.2017.2

Hanna, M., Schwenke, J. and Krause, D. (2020a), “Inconsistency management for product families with many variants through a model-based approach in modular lightweight design", *Proceedings of the DESIGN 2020 / 17th International Design Conference, Cavtat, Croatia, October 26-29,* 2020, The Design Society, Glasgow, pp. 917-926. https://doi.org/10.1017/dsd.2020.309

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

Hanna, M., Schwede, L.-N., Schwenke, J., Laukotka, F and Krause, D. (2021), "Methodical modeling of product and process data of design methods using the example of modular lightweight design", *Proceedings of the ASME 2021 International Mechanical Engineering Congress and Exposition / IMECE2021, Virtual, Online, November 1-5,* 2021, The American Society of Mechanical Engineers, New York City.

Heyden, E., Hartwich, T. S., Schwenke, J. and Krause, D. (2019), "Transferability of Boundary Conditions and Validation of Lightweight Structures", *Proceedings of the 30th Symposium Design for X (DFX2019), Jesteburg, Germany, September 18-19,* 2019, The Design Society, Glasgow, pp. 85-96. https://doi.org/10.35199/dfx2019.8

Holt, J., Perry, S., Brownsword, M., Cancila, D., Hallerstede, S. and Hansen, F. O. (2012), "Model-based requirements engineering for system of systems", *7th International Conference on System of Systems Engineering (SoSE), Genova, Italy, July 16-19,* 2012, IEEE, Piscataway, pp. 561-566. https://doi.org/10.1109/SYSoSE.2012.6384145

Jagla, P., Jacobs, G., Siebrecht, J., Wischmann, S. and Sprehe, J. (2021), "Using SysML to Support Impact Analysis on Structural Dynamics Simulation Models", *Procedia CIRP*, Vol. 100, pp. 91-96. https://doi.org/10.1016/j.procir.2021.05.015.

Krause, D., Beckmann, G., Eilmus, S., Gebhardt, N. and Rettberg, R. (2014), „Integrated Development of Modular Product Families - a Methods Toolkit", In: Simpson, T., Jiao, J., Siddique, Z. and Hölttä-Otto, K. (Ed.): *Advances in Product Family and Product Platform - Design Methods & Applications*, Springer Science + Business Media, LLC., New York, pp. 245-269.

Krause, D., Schwenke, J., Gumpinger, T. and Plaumann, B. (2018), "Leichtbau", In: Rieg, F. and Steinhilper, R. (Ed.), *Handbuch Konstruktion*, Carl Hanser Verlag, München, pp. 487-507.

Russwurm, E., Faltus, F., Laukotka, F., Schwan, L., Brossog, M. et al. (2021), "Methodik zur frühzeitigen Integration prozessspezifischer Einflussfaktoren aus der automatisierten Montage in die Auslegung funktionskritischer Komponenten", *Proceedings of the 32th Symposium Design for X (DFX2021), Tutzing, Germany, September 27-28,* 2021, The Design Society, Glasgow. https://doi.org/10.35199/dfx2021.02

Schwan, L., Hüttich, P., Wegner, M. and Krause, D. (2021), "Procedure for the transferability of application-specific boundary conditions for the testing of components and products", *Proceedings of the 32th Symposium Design for X (DFX2021), Tutzing, Germany, September 27-28,* 2021, The Design Society, Glasgow. https://doi.org/10.35199/dfx2021.04

Seiler, F. M., Hanna, M., Schwede, L.-N., Laukotka, F. and Krause, D. (2020), "MBSE zur Unterstützung der Produktentwicklung von modularen Produktarchitekturen", In Krause, D., Hartwich, T. S. and Rennpferdt, C. (Ed.): *Produktentwicklung und Konstruktionstechnik, Forschungsergebnisse und -projekte der Jahre 2016 bis* 2020, Springer Verlag, Berlin, pp. 111-134. https://doi.org/10.1007/978-3-662-62393-0_5

Szarazi, J., Reichwein, A. and Bock, C. (2017), "Integrating Finite Element Analysis with Systems Engineering Models", *Proceedings of the NAFEMS World Congress, Stockholm, Sweden, June 11-14,* 2017.

Weilkins, T. (2008), *Systems Engineering with SysML/UML: Modeling, Analysis, Design*, Morgan Kaufmann, Burlington. https://doi.org/10.1016/B978-0-12-374274-2.X0001-6

Werkle, H. (2021), *Finite Elements in Structural Analysis*, Springer, Berlin. https://doi.org/10.1007/978-3-030-49840-5_4