CEAS Aeronautical Journal
https://doi.org/10.1007/s13272-023-00683-w

ORIGINAL PAPER

Model-based design and multidisciplinary optimization of complex system architectures in the aircraft cabin

Yassine Ghanjaoui[1] · Mara Fuchs[1] · Jörn Biedermann[1] · Björn Nagel[1]

Received: 13 February 2023 / Revised: 31 August 2023 / Accepted: 6 September 2023

Abstract

The aviation industry is currently facing major challenges due to environmental and socio-economic trends toward sustainable and digitalized aviation. Revolutionary, more powerful and efficient technologies must be rapidly integrated into aircraft, while aircraft manufacturers must demonstrate the required safety. To support the implementation of new concepts, the DLR Institute of System Architectures in Aeronautics is researching methods for end-to-end digitalization from the preliminary design phase to assembly and production. In this context, Model-Based Systems Engineering (MBSE) and Multidisciplinary Design Optimization are important approaches for the development of complex systems. This paper presents a method for the end-to-end use of digital models for multidisciplinary optimization of system architectures. The Systems Modeling Language (SysML) is used to represent the system architecture. The focus is on the cabin and cabin systems, since they are highly coupled to other aircraft systems and have dynamic, customer-specific configuration requirements. The system architecture in SysML is instantiated and configured by the interface to the aircraft fuselage and cabin design parameter sets in the Common Parametric Configuration Schema. The subsequent coupling of the generated system architecture model with the cabin system design model developed in Matlab allows a multidisciplinary optimization of the system properties. A sensitivity analysis is performed using the Passenger Service Unit as an example. The effects of different cabin configurations on the system architecture are investigated and interdisciplinary synergies are identified and analyzed. The results of this analysis are discussed in this paper.

Keywords Digital thread · MBSE · Multi-objective optimization · Aircraft cabin

Abbreviations

API	Application Programming Interface
ATA	Air Transport Association
CPACS	Common Parametric Aircraft Configuration Schema
CS	Certification Specification for Large Aeroplanes
DLR	German Aerospace Center
FAS	Functional Architecture for Systems Method
INCOSE	International Council of Systems Engineering
MBSE	Model-Based Systems Engineering
MDO	Multidisciplinary Design Optimization
MOO	Multi-Objective Optimization
OEM	Original Equipment Manager
OHSC	Overhead Storage Compartment
PSU	Passenger Service Unit
SE	Systems Engineering
SPDB	Secondary Power Distribution Boxes
SysML	Systems Modeling Language
TLAR	Top-Level Aircraft Requirement
VR	Virtual Reality
XML	eXtensible Markup Language

✉ Yassine Ghanjaoui
yassine.ghanjaoui@dlr.de

Mara Fuchs
mara.fuchs@dlr.de

Jörn Biedermann
joern.biedermann@dlr.de

Björn Nagel
bjoern.nagel@dlr.de

[1] Institute of System Architectures in Aeronautics, German Aerospace Center (DLR), Hein-Saß-Weg 22, 21129 Hamburg, Germany

Published online: 05 October 2023

1 Introduction

The aviation strategy of the German Federal Government and the German Aerospace Center (DLR) is based on enabling an environmentally friendly, safe, efficient and competitive aviation system of the future [1, 2]. The aviation industry must, therefore, be able to react quickly and efficiently to new requirements. To achieve this, DLR envisions itself as a virtual OEM in the future and therefore needs to holistically combine its disciplinary competencies and research agile, digital and automated approaches. These will enable the rapid integration and evaluation of new, more climate-friendly technologies, such as fuel cells, as well as design and performance optimization. At the DLR Institute of System Architectures in Aeronautics, researchers are working on a digital and end-to-end approach that supports development and optimization from product concept to production. As part of this approach, methods and processes are being developed to link all models and architectures from top-level planning to detailed geometries and analytical models. Concepts such as the "*digital thread*" are essential for optimal, automated and error-free data communication throughout the product lifecycle. Information must be consistent and semantics must be preserved, requiring precise synchronization between process participants. A fundamental approach in this context is Model-Based Systems Engineering (MBSE), which provides methods and tools for managing and integrating information models of complex systems. Cabin systems are an example of such complexity, which is constantly growing due to the needs of stakeholders (e.g., airlines, suppliers, aviation authorities), strict safety regulations, and the large number of system functions to be integrated. Furthermore, MBSE enables the integration of interdisciplinary and domain-specific models as well as the optimization of the system architecture. This paper presents a framework for model-based design and multidisciplinary optimization of cabin system architectures. This is a functional complement to the classical Multidisciplinary Design Optimization (MDO) and the plausibility of this framework is investigated using a Multi-Objective Optimization (MOO) in which cabin characteristics are considered. Thus, the functional aspects of the cabin can be added to the multi-fidelity and multidisciplinary analyses derived from Common Parametric Aircraft Configuration Schema (CPACS)-based datasets [3]. The framework will incorporate approaches that enable knowledge-based and highly detailed cabin assessment based on existing data and design rules [4, 5]. It will also extend methods for conceptual cabin system design and virtual reality (VR) interaction to allow reconfiguration and analysis of new cabin variants [6, 7]. The developed framework includes methods for requirements traceability, synergistic investigation of interactions between systems, and virtual verification of the optimized system architecture. This work is a contribution to the digitalization vision of the DLR and shows how the applied approach leads to an efficient aircraft development within the digital thread.

2 Fundamentals

This section presents the theoretical and methodological foundations for this work. First, the main goals and concepts of MBSE are explained. In the next step, the model-based methodology for functional system analysis and cabin system design is presented. This provides the basis for the design and optimization framework developed in this research. Finally, the physical principles for the considered system component to be optimized are presented. This establishes the present state of research on leveraging MBSE for multidisciplinary design optimization in aircraft cabins, serving as a foundational point for the objective of this work.

2.1 Linking model-based systems engineering to multidisciplinary optimization

MBSE is an interdisciplinary approach that supports the development of modern complex systems through the application of models. It has been particularly driven by the aerospace industry in recent years and is predominantly applied in the context of activities such as requirements management, structural and behavioral analysis, performance analysis, simulation, or testing [8]. The vision and promise of MBSE is that system models and analysis are tightly integrated in an automated, collaborative, easily accessible, and secure framework [9]. Through the model-based approach, the system is represented and analyzed in a comprehensive computer model to enable better traceability of the system architecture at different levels of abstraction (e.g., functional, logical, or physical) and consistency of information throughout the product lifecycle. The Systems Modeling Language (SysML) has emerged as the primary modeling language in the context of MBSE [10]. SysML should not be viewed as a replacement for existing systems development tools or languages, but as a useful complement to them. It defines a common foundation for the many disciplines that collaborate in systems engineering [11]. As a graphical modeling language, SysML is based on the concepts of object orientation, and its notations, semantics, and syntax support standardized system development and analysis. While the graphical elements of the language are important for visually representing model information, they do not represent all of the knowledge in the model, which can be found in the model database (repository) [12]. The data there, modeled with the language, represent the elements and interactions within the system architecture and can be processed and manipulated to take advantage of the MBSE approach, such as traceability, external integration, or multidisciplinary optimization of the architecture.

By applying the MBSE approach to systems analysis and modeling, a foundation for Multidisciplinary Design Optimization (MDO) is provided. MDO is a discipline that aims to study and exploit the mechanism of synergistic interaction between subsystems and components to optimally design complex engineering systems that span a number of disciplines [13]. The optimization problems usually involve multiple objectives from different disciplines. The optimization problem is then a multi-objective optimization, which allows designers to specify multiple conflicting objectives and the corresponding tradeoffs [14]. In this way, a set of non-dominated solutions (Pareto front) can be derived. In MOO, the design parameters specified in the system architecture can be used in the optimization process and related to the objective functions [15]. The exchange between the MBSE system design process and the optimization models is critical. In this exchange, it is important that the information and data remain consistent and are understood in the same way by the disciplines involved. For this reason, this research uses the discipline-neutral language SysML to model the interdisciplinary and abstract system architecture. The SysML model is the basis for the connection and interaction with external optimization models.

2.2 Model-based methodology for functional analysis and design of cabin systems

DLR is researching approaches for the digital design of aircraft cabins. The aim is to integrate new technologies more quickly, to evaluate the interrelationships of interacting cabin systems and thus to enable a better understanding of cabin architectures at an early stage and to exploit synergetic optimization potential. To this end, an automated design methodology for cabin systems has been developed [6, 7, 16]. The extension of this methodology with an integrated functional system analysis was published in the authors' previous paper [17] and the overall descriptive process is shown in Fig. 1. The process begins with the preliminary aircraft design, where preliminary mass distributions and aircraft geometries are calculated based on input parameters. These parameters come primarily from the Top-Level Aircraft Requirements (TLARs), such as maximum payload, range, or cabin class layout. CPACS is used to import the preliminary design results and serves as a link between the preliminary aircraft design and the cabin system design. Cabin configuration data is also extracted from CPACS and incorporated into the SysML model to instantiate the cabin system architecture. The system architecture is based on a stakeholder and system context analysis [18]. Based on the so-called Functional Architectures for Systems (FAS) method [19], the system is functionally analyzed in a further step and a modular segregation between the system functions and the corresponding technical solutions is achieved. Various SysML elements and diagrams are used to link the generated analytical, functional, and logical system elements and thus enable high traceability in the system architecture [17]. The parameters of the generated system architecture are exchanged with a geometric design model in Matlab, where a rule-based and optimized placement of the cabin components is performed. The design rules for the placement are derived from component properties and safety requirements from the Certification Specification for Large Aeroplanes (CS-25) [6]. The design algorithm combines these rules with the CPACS preliminary design parameters and the logical system architecture imported from the SysML model. Using simple geometric shapes, the design model provides a representation of the cabin, including the systems, and gives a first impression of the final cabin design. By exporting the generated data to the Blender graphics software, the simple shapes are replaced by realistic 3D models. The geometric placement in Matlab is performed on SysML elements that represent cabin objects through the body assignment for spatial placement, using simple geometric elements that are placed within the cabin space. This method provides a simple and fast verification process for cabin layouts in different configurations, without the need for detailed 3D modeling. The reason for performing a first geometric placement in Matlab is to implement numerical operations using placement algorithms, which can easily and quickly generate low fidelity 3D models. These are, in turn, linked to a high-fidelity 3D CAD model in Blender, which is an open source tool that provides a programmable interface to create high-fidelity geometry modeling of the cabin based on the library of single cabin object models. These models can be created, for example, by collecting data with high-precision 3D scanners that capture a research environment in detail. Current DLR research shows how such 3D scanners are used to regularly capture real-world geometries and display them in the digital shadow of the aircraft [20]. The interface between Matlab and Blender is based on xml. Blender has an integrated python interface that parses data from xml files to position 3D objects in the cabin. The reason why the placement of cabin objects is not implemented directly in a 3D CAD model is due to the numerical processing required and different fidelity levels. Finally, the models and placement results can be automatically imported into the virtual environment in Unity. This VR tool does not require additional data preparation for VR representation, as it can import and read information related to the cabin objects using the xml-based interface with Matlab. Unity automatically imports the 3D models generated in Blender from the fbx-files and

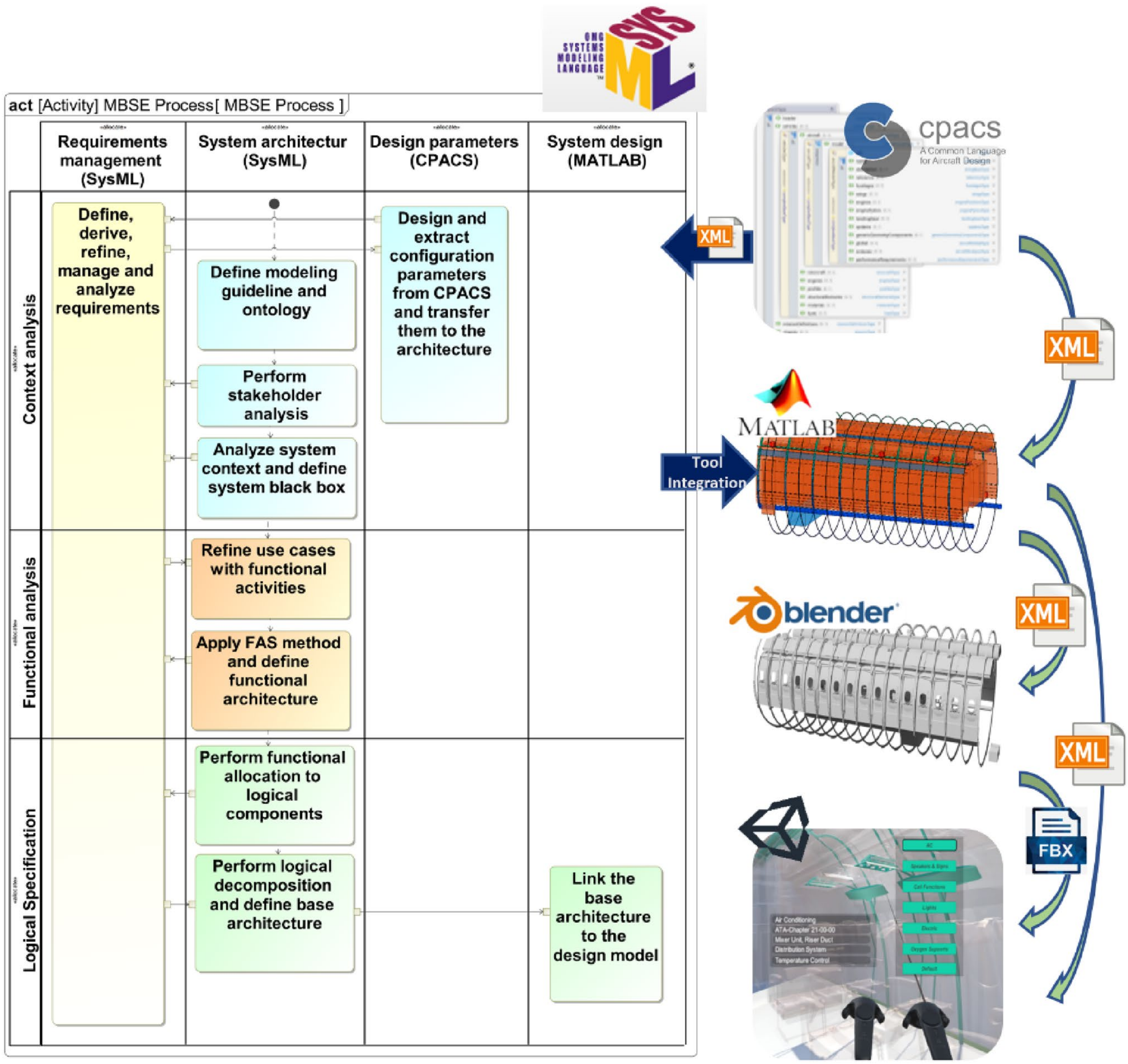

Fig. 1 Process flow for functional system analysis, cabin design, and visualization in VR

combines both information to save it in the VR repository structure required for visualization. In the VR environment, the results of the cabin design can be experienced and evaluated by humans through interaction possibilities with the VR hardware [16].

The presented process makes the dependencies between the individual system components visible and supports the fast and efficient integration of new technologies and system ideas. The main concept behind this process is using and linking different tools that are adequate for the required fidelity levels, benefiting from each tool and its capacity in the corresponding optimal development environment. In addition, the visualization in VR makes it possible to highlight the requirements as well as the properties of the cabin objects and their relationships to other system components. In this way, cross-system dependencies can be taken into account in the further design process and cost-intensive design changes can be avoided at a later stage.

The provided method establishes a foundation for analyzing and modeling system architectures in complex cabin systems. The utilization of a discipline-neutral modeling language enables the execution of multidisciplinary engineering activities on this foundation. Additionally, the integrated interfaces of the models facilitate their expansion

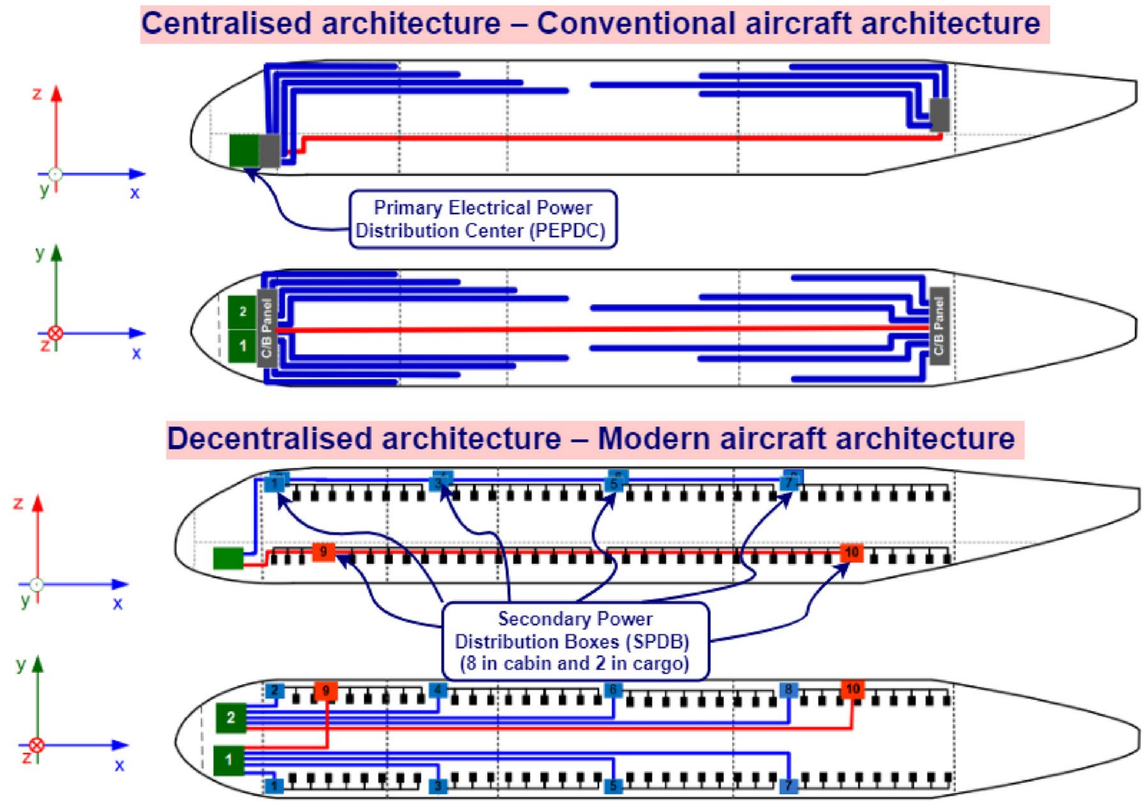

Fig. 2 Architectures for electrical power distribution (adapted from [21])

and integration with supplementary models and tools. Consequently, this potential can be harnessed by incorporating discipline-specific and multidisciplinary optimization models into this procedural framework. This leads to the central research question of this study, which revolves around the development of a methodology to adapt the MBSE-based approach and its interfaces for the seamless integration of multidisciplinary analysis and optimization models. Further elaboration on this research question can be found in Sect. 3.

2.3 Electrical design of the passenger service unit

The Passenger Service Unit (PSU) is a component of the Cabin Management System and is considered as a use case for the evaluation of the design and optimization methodology developed in this work. The numerous interfaces to external systems, the variety of implemented functions, the interactions with the cabin design for installation and assembly or the required flexibility and configurability for individual customer requirements; all these aspects increase the complexity of the PSU and make it an ideal candidate for the MBSE methodology. The PSU implements key cabin functions and includes related components such as reading lights, flight attendant call buttons, information signs or loudspeakers. It also includes integrated electronics that provide power, data communications, and control of the PSU components. Cabin concepts vary from airline to airline, allowing for individual designs and passenger preferences. This often affects the location of the PSU in the cabin. Typically, they are installed in the Overhead Storage Compartment (OHSC), which in most modern designs is located above the passenger seats. PSU interfaces can vary depending on the cabin configuration and affect a number of aircraft technical parameters. This paper focuses on the electrical power supply and the interface of the PSUs with the power distribution boxes, called Secondary Power Distribution Boxes (SPDBs). This new component in the power system architecture supports a distributed configuration (see Fig. 2) characterized by power supply distribution, reduced system weight and easier installation in the final assembly [21]. It is integrated into the electrical system and supplies 28 V DC to the cabin loads. Cables with certain physical properties are used to connect the electrical loads to the SPDBs. The electrical model in Fig. 3 illustrates the interface between the PSUs and SPDBs.

The SPDB power is required to supply the connected loads. Due to thermal effects, part of the power supplied is lost during transmission over the cable. The load then consumes the remainder of the power. The nominal power, which is the maximum allowable power consumption of the

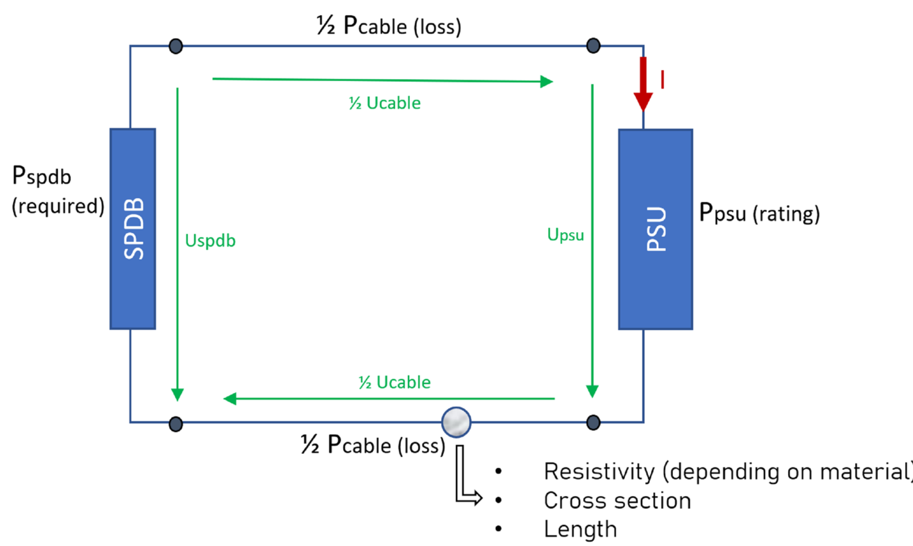

Fig. 3 Electrical power supply of the PSU by the SPDB

component, is used as the model parameter. Considering Kirchhoff's rules [22] in the model presented, the total electrical supply power P from the SPDBs to the PSUs in the cabin can be mathematically described as follows:

$$P_{\mathrm{SPDB}} = \sum_{i=1}^{n} P_{\mathrm{cable}\,i} + P_{\mathrm{PSU}\,i}. \tag{1}$$

Applying Ohm's law to the power loss in the cables and defining the resistivity gives the formula for the cable power [22]. The power delivered by each SPDB can then be formulated using the rated power of the power supplies as follows:

$$P_{\mathrm{SPDB}} = n \cdot P_{\mathrm{PSU}} + 2 \cdot \rho \cdot \frac{1}{A} \cdot I^2 \cdot \sum_{i=1}^{n} l_i, \tag{2}$$

where ρ is the resistivity of the material, l is the cable length, A is the area of the cable cross section, and I is the current in the line. The value n represents the number of PSUs connected to the SPDB.

The physical relationships explained above describe the electrical interface between the PSUs and SPDBs. They serve as input to the optimization use case presented in Sect. 5.2.

3 Research scope and goal

In the development of complex, multidisciplinary systems such as an aircraft, the various disciplines tend to analyze and optimize their domain-specific models. However, system engineers on aircraft level must consider the entire system and achieve a holistic evaluation of the overall design concept through the integration of different disciplines. Therefore, it is important to integrate discipline-specific optimization models into abstract general MBSE models. In previous research, the authors presented a process to design and generate a functional system architecture for aircraft cabins and cabin systems (see Sect. 2.2). This work's main goal is to answer the question how to extend the existing process to integrate disciplinary optimization models and parameters. It should demonstrate which modeling techniques can help the disciplines find themselves within the overall architecture model. To practically demonstrate this process using a use case as a proof of concept, the data flow from abstract models to detailed optimization results should be shown. This will demonstrate whether an interdisciplinary system can be optimized and scientifically evaluated through the extension of the existing methodology. The use case should demonstrate how aircraft configuration parameters can be linked from the system architecture to optimization models to evaluate their impact on disciplinary parameters through sensitivity analyses. Furthermore, it should illustrate how disciplines may differ in their architecture choices based on their optima and how decision-making is supported by acquiring feedback of all disciplinary results and integrating them into top-level system architecture.

Moreover, this work aims to provide support for both the systems engineer of the aircraft integrator and the discipline expert or computational engineer who, in turn, focuses on specific disciplinary aspects of the system, subsystem, or components. The systems integrator analyzes the system and its behavior holistically and is responsible for making decisions about the system architecture. To facilitate this, it is necessary to provide a model that allows each discipline expert to locate themselves and attach their disciplinary analysis and optimization models. It is also essential for the experts to provide feedback on their results to the architecture model to evaluate the impact of their disciplinary parameters on the overall architecture. As a result, the methodology proposed in this work aims to integrate and interface both the overall system integrator and domain experts.

4 Methodical design and multidisciplinary optimization of the model-based system architecture

The methodology for the functional design and visualization of cabin systems presented in the Sect. 2.2 provides an important basis for the analysis and verification of different cabin designs and system architectures. Using the discipline-neutral language SysML to model the system architecture, system parameters from different development domains and their interactions can be analyzed and optimized at a higher level of abstraction. In this work, the tool Cameo Systems Modeler is used for SysML modeling. Linking the functional system architecture elements to the requirements analysis and visualizing the design results in VR allows an early verification of the system concepts from the perspective of different disciplines. To enable these targeted multidisciplinary analyses, optimizations and verifications on the basis of the model-based system architecture, a framework was developed as part of this work, which is depicted in Fig. 4.

The core idea of the framework is to export the data available in the SysML system architecture model to an analysis and optimization model and to validate the results for corresponding CPACS cabin configurations directly in the architecture model. The framework is essentially divided into two blocks: the linked system architecture in the SysML model and the analysis and optimization environment in a mathematical evaluation model (e.g., in Matlab). In the architecture model, structural SysML elements and diagrams enable the modeling of the parameterized properties of the system components as well as their interfaces and interactions. On this basis, component properties can be assigned to the various development disciplines. This provides a direct link between the system parameters and the system requirements formulated from the perspective of the respective disciplines. This allows a separation of interests and the objectives of the disciplines can be quantified with the parameters. To account for the interactions between disciplines, these are mapped as parameters for mathematical or physical system relationships using '*constraint*' blocks. Linking through the SysML *satisfies* relationship also allows verification of the formulated system requirements.

The next step is to initialize the cabin model and place the cabin systems (see Sect. 2.2). For this purpose, the aircraft preliminary design parameters from CPACS are used, as already mentioned. The relevant cabin information for each configuration, such as the distribution of passengers and cabin modules in cabin classes, is imported from CPACS. Thus, the cabin context for the instantiated system architecture is defined and optimization can be performed. The input variables and optimization objectives are integrated by linking the *value-properties* of the system blocks to the variables in the optimization model. To specify the design space of the optimization parameters, the conditions in the "*constraints*" are also linked to the optimization model. Linked data remains consistent between the MBSE and optimization domains because of the possibility to execute both models simultaneously. The SysML model has the ability to be executed using the tool cameo systems modeler making parameters available to be processed and exchanged with external tools. These parameters emerged from functional, logical or physical analyses. They specify the performance of the system and subsystems and can either be input or objective parameters, for the intended optimization (e.g., component geometry or electrical performance parameters). In this work, the tool ability to integrate and access the workspace of the optimization model in Matlab is used to link these parameters. The tool provides an integrated interface to Matlab using opaque behaviors or parametric diagrams, where Matlab's workspace variables can be accessed during the execution. The SysML objects are adapted to the defined classes and structures in Matlab and SysML objects and properties must be named identically to objects in Matlab model. During the execution and using the shared workspace, cameo updates parameter values and synchronizes the two models. If another SysML tool is used and does not have the ability to integrate external models or tools, it is recommended to link data using OSLC[1] services or to develop an API interface that provides the data linking and synchronization service.

Therefore, there are relevant aspects to be considered during the modeling and data linking process. The execution of a SysML model is a pre-requisite to link the optimization model. Furthermore, the disciplinary affiliation of the parameters and their corresponding subsystems or component must be specified. A SysML extension profile with specific stereotypes must be first defined to model disciplinary attributes (e.g., to define the ATA chapter/section of the aircraft system components or the physical type of the parameters). By applying these stereotypes consistently during modeling activities, a traceability is enabled to identify the disciplinary affiliation regarding different abstractions (requirements, functional, logical or physical).

Subsequently to MBSE activities, the optimization algorithm is chosen and implemented. The results can also be

[1] Open Services for Lifecycle Collaboration is an open initiative that develops standards for tool interaction. These standards enable the data exchange and the cooperation of separate tools from the product lifecycle software [23].

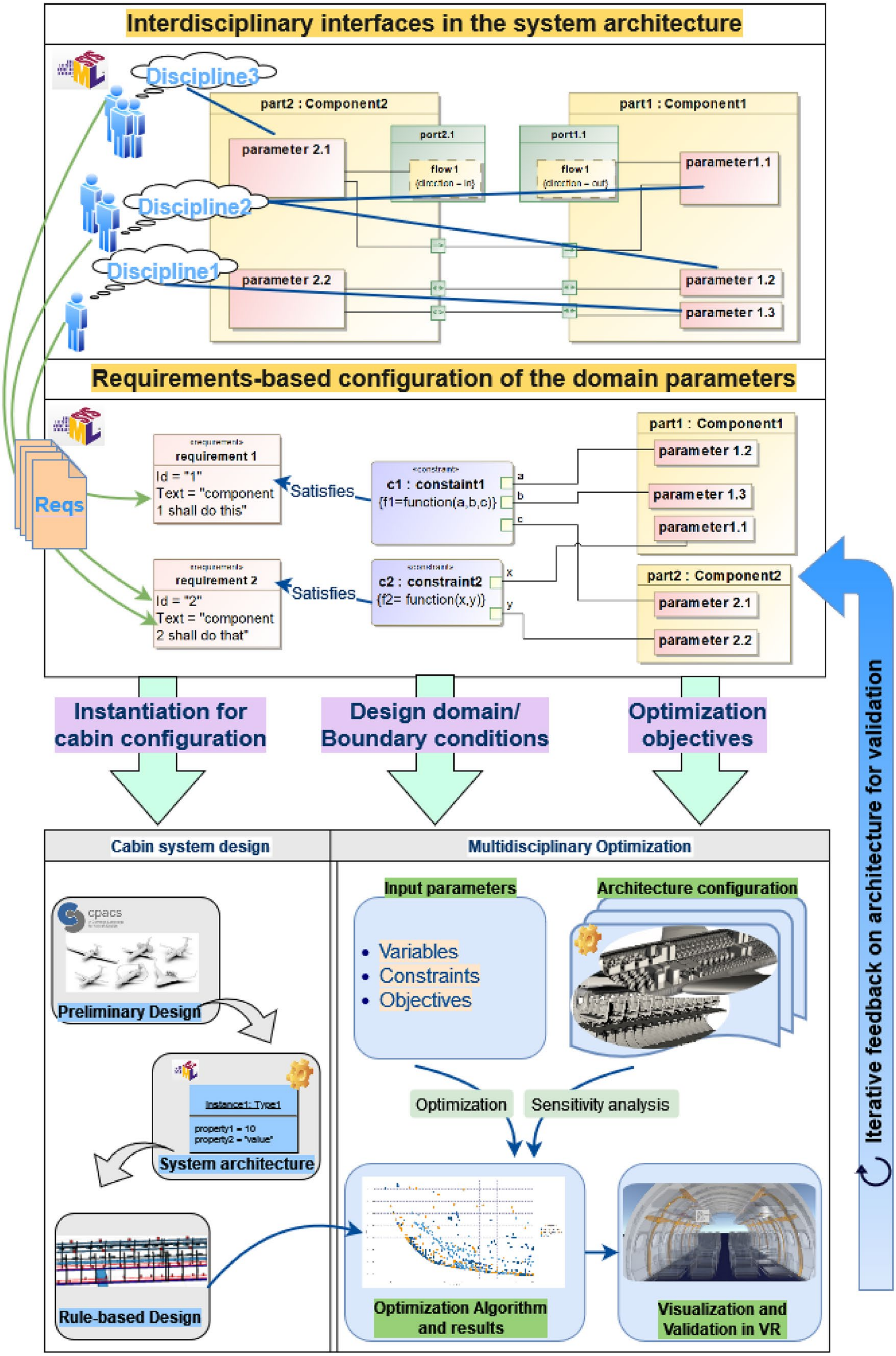

Fig. 4 Framework for model-based design, multidisciplinary optimization and virtual verification of system architecture

visualized, analyzed and validated through the virtual environment interface with the VR. The last important step in the framework is to feed the optimization results for the objective parameters back to the architecture model. There, possible optimal results can be applied and the requirements can be validated. The verification of the results allows the withdrawal of invalid results. Parameters not considered can be analyzed in further iterations of the framework process.

Thus, digital traceability in the architecture model and the interface to external evaluators can be used in this framework for optimization and verification purposes. The automation of the existing process steps in the framework enables fast and early analysis of design parameters and interdisciplinary interactions in the system.

5 Use case: design and optimization of the passenger service unit

In this section, an example from the cabin context is presented for the application and evaluation of the framework described above. First, important modeling aspects are described and optimization parameters such as input variables and optimization objectives are defined. Second, the implementation of model-based design and multidisciplinary optimization within the framework is presented. Finally, the results of the implementation and verification are presented and discussed.

5.1 Use case definition

This use case is about the interface between the PSU and the SPDB, which belong to two different aircraft systems (PSU part of Cabin Management System ATA23 and SPDB of Power System ATA 24). To model this interface, the SysML *association block* is used (see blue block in Fig. 5). This modeling element can associate two blocks and has its own internal structure and properties. It allows the specification of parameter exchange over the cable between the SPDB and the PSU. By creating *constraints* within the *association block*, a framework of mathematical relationships can be defined for the interaction.

After examining the core parameters of the two components and their interfaces, two design disciplines are recognized: electrical design and aircraft installation. From an electrical design perspective, there is a requirement for a uniform distribution of power to all SPDBs. This allows the design of equal, non-oversized components, resulting in ease of installation and low cost. In addition, the interfaces to the electrical loads should be designed to minimize power dissipation in the supply. On the other hand, from the point of view of installation in the aircraft, it is necessary to achieve a small installation space and a low mass of the entire system. The requirements are interpreted as optimization goals and the required input parameters are read from the architecture. The table depicted in Fig. 6 summarizes the mapping of the component properties defined in the use case: The first objective function is related to the electrical design and includes the power distributions between the different SPDBs and the power loss in the cables. The standard deviation is used as a function to represent the power distribution Z mathematically and is defined as follows:

$$Z_{=}\sqrt{\frac{1}{n-1}\cdot\sum_{i=1}^{n}(P_{\mathrm{SPDB}\,i}-\bar{P}_{\mathrm{SPDB}\,i})^2}, \tag{3}$$

where n is the number of SPDBs installed in the aircraft and $\bar{P}$ is the arithmetic mean of the SPDB power. The power can be calculated using the Eq. 2. The first objective function is then formulated as follows:

$$y_1 = k_1 \cdot Z + k_2 \cdot \sum P_{\mathrm{cable}\,i}, \tag{4}$$

with k_1 and k_2 the respective normalization and weighting factors to be selected by the electrical designer. The second objective function refers to the installation of the components and includes the total mass and the integration volume. It is defined as follows:

$$y_2 = k_3 \cdot \sum m_{\mathrm{system}} + k_4 \cdot \sum V_{\mathrm{system}}, \tag{5}$$

where k_3 and k_4 are the respective normalization and weighting factors, m is the mass, and V is the volume of the system consisting of the total SPDBs, PSUs, and connecting cables.

In addition to the constant multidisciplinary input parameters from the architecture, an input variable is defined. This is used to describe the physical interfaces between each SPDB and the power supplies connected to it. Figure 7 represents the concept of the interface. Each PSU is connected to the SPDB, which is located in the same area. The coordinates for the beginning of each new range are given as $x_1, x_2, \dots, x_{\frac{k}{2}-1}$. These are the variables that allow the width of each range to be adjusted. As the range varies, the SPDB interfaces to the PSUs change.

The conditions for the variables are imported from the *constraints* in the architectural model and the input variable can be specified as follows:

$$X = (x_1, x_2, \dots, x_{\frac{k}{2}-1}), \tag{6}$$

$$\text{with}\begin{cases} k\,:\ \text{Number of SPDBs}\\ x_1 > \text{Cabin start}\\ x_{i+1} > x_i\\ x_{\frac{k}{2}-1} < \text{Cabin end}\end{cases}. \tag{7}$$

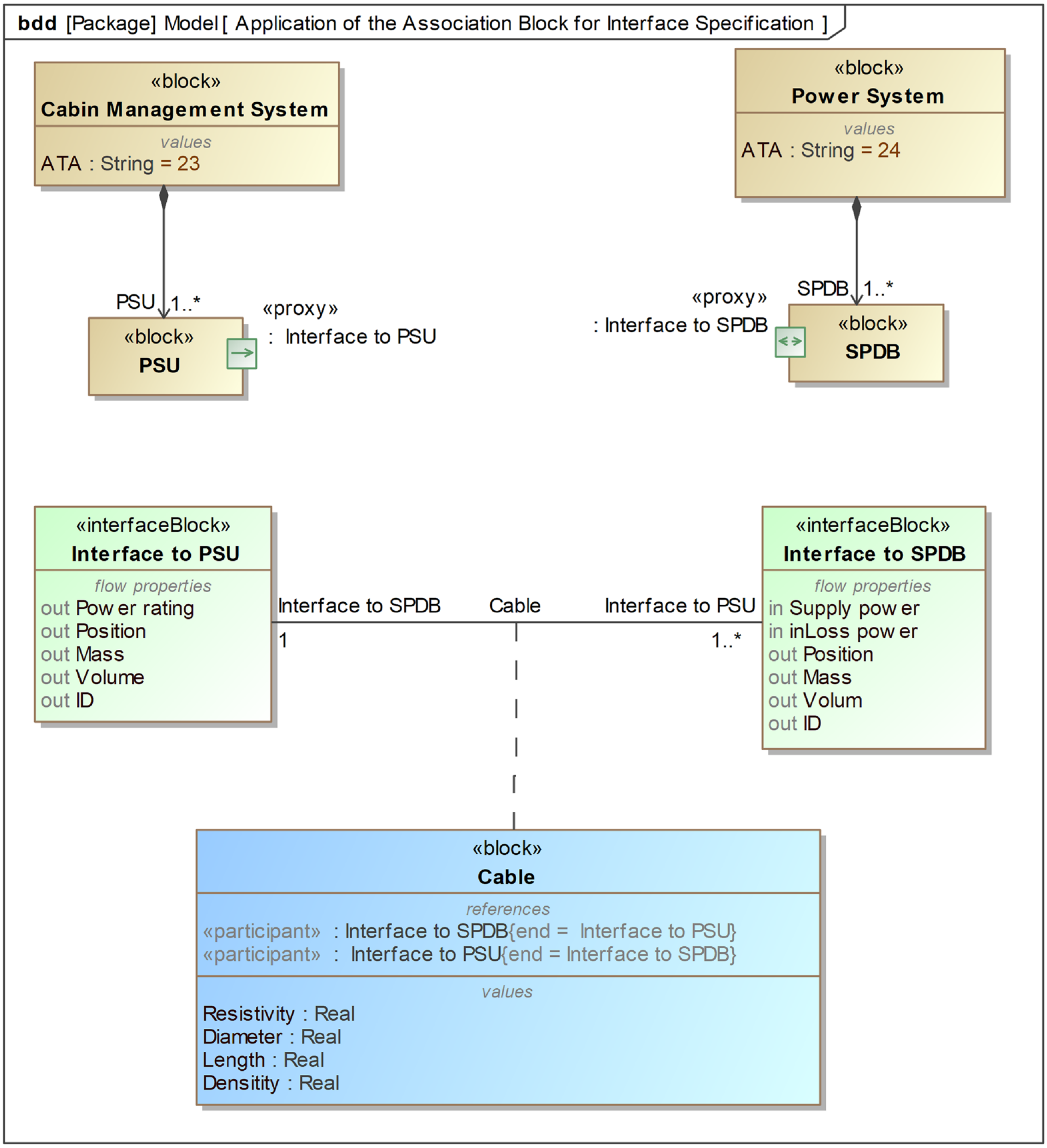

Fig. 5 Modeling the interface between the SPDB and PSU

Discipline	Input parameters	Optimization objectives
Electrical design	- Reisistvity of the cable material - Power rating of the PSU	- Power distribution (between SPDBs) - Power loss in cables
Installation in aircraft	- Density of cable material - Cable cross section	- Total mass - (PSU, cable, SPDB) - Installation volume

Fig. 6 Multidisciplinary input parameters and optimization objectives

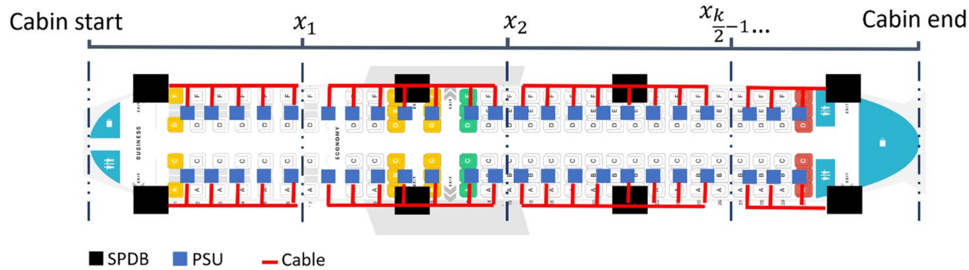

Fig. 7 Input variable for interfaces between SPDB and PSU (A320 Cabin layout modified from [24])

Based on the system architecture, a sensitivity analysis is performed in this paper. Two cabin configurations are considered. The first contains only the passenger area power supplies connected to eight SPDBs. The second configuration includes, in addition to the first, two galley modules located in the front and rear of the cabin. The objective of considering both configurations is to investigate a large cabin load and its impact on the installation and electrical design.

5.2 Implementation of multidisciplinary optimization

As stated before, the SysML tool *Cameo Systems Modeler 2021x* is used to model the system architecture and *Matlab2021b* is used to implement the MOO. The two tools are coupled using integrated Cameo functionalities to access Matlab workspace from the SysML architecture model. Data from the system architecture in the SysML model can be stored and processed as variables in the Matlab model. For example, input parameters shown in Fig. 6 can be imported from the architecture instance and linked to the optimization model. For the respective configuration, cabin parameters such as seat arrangement or module inventory are also imported from CPACS. In this work, the optimization toolbox of *PlatEMO v1.6* and the *Multi-Objective Evolutionary Algorithm (MOEA) NSGA-II* are used to minimize the objective functions and generate the Pareto front [25]. The algorithm maintains a set of individuals, collectively referred to as the population. Each individual represents one solution. During evolution, the population is updated in each generation and new individuals are created. The evolution process ends when the population approaches the Pareto front. To compute the objective functions, the Eqs. 4 and 5 are implemented as functions in Matlab and used by the optimization algorithm. The algorithm then varies the interface parameters in the allowed range according to Eq. 6 and determines the corresponding individuals. A population size of 20 and a number of evaluations of 200 are used for the optimization.

5.3 Analysis and verification of results

The results of the MOO for the two configurations are shown in Figs. 8 and 9. The *x*-axis shows the values for the electrical design objective determined according to Eq. 6 and the *y*-axis shows the values for the installation objective determined according to Eq. 5. The round blue circles show the results of the individual dominated solutions. The red circles represent the Pareto front of the optimization and thus the optimal solutions for each configuration.

First, the distribution of results for all configurations provides an important statement about the relationship between the two optimization objectives. The value ranges show that the two objectives are equally affected by the input variable. High values of $y1$ correspond to high values of $y2$, which means that the interface configuration affects the two optimization objectives equally. This is because an unfavorable placement of the two components leads to long cable lengths, resulting in high cable mass and power losses.

Other important results are obtained from the Pareto fronts. Since the objective functions have been normalized to the same value, the minimum values of the optimization objectives for each configuration can be compared. The optimal result of the electrical design objective for the first configuration is $y_1 = 0.37$, while the optimal value for the second configuration with additional galleys is $y_1 = 9.41$. This means that taking into account the two large cabin loads worsens the electrical power distribution and the power losses in the cable by a factor of 25. This result shows that the electrical design goals are highly dependent on the cabin configuration and the existing electrical cabin loads. However, the two configurations do not affect the installation in the cabin and both have an optimal value of $y_2 = 0.89$ for the objective function. This means that considering the galleys does not affect the mass and integration volume of the power supplies, cables, and SPDBs. This is due to the fact that the positioning with the design algorithm for the PSUs and SPDBs is not affected by the galleys, and thus the interface remains constant.

The input variable that leads to optimal values of the optimization objectives is also analyzed. To understand and validate the corresponding interfaces between the two

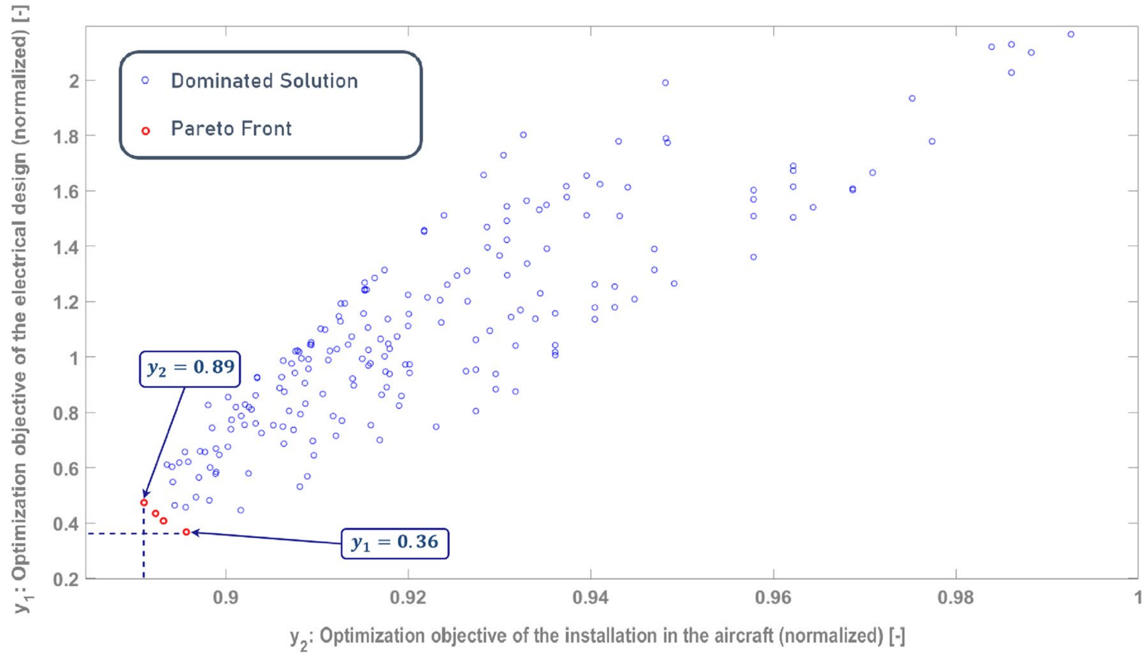

Fig. 8 MOO results for the configuration with 8 SPDBs

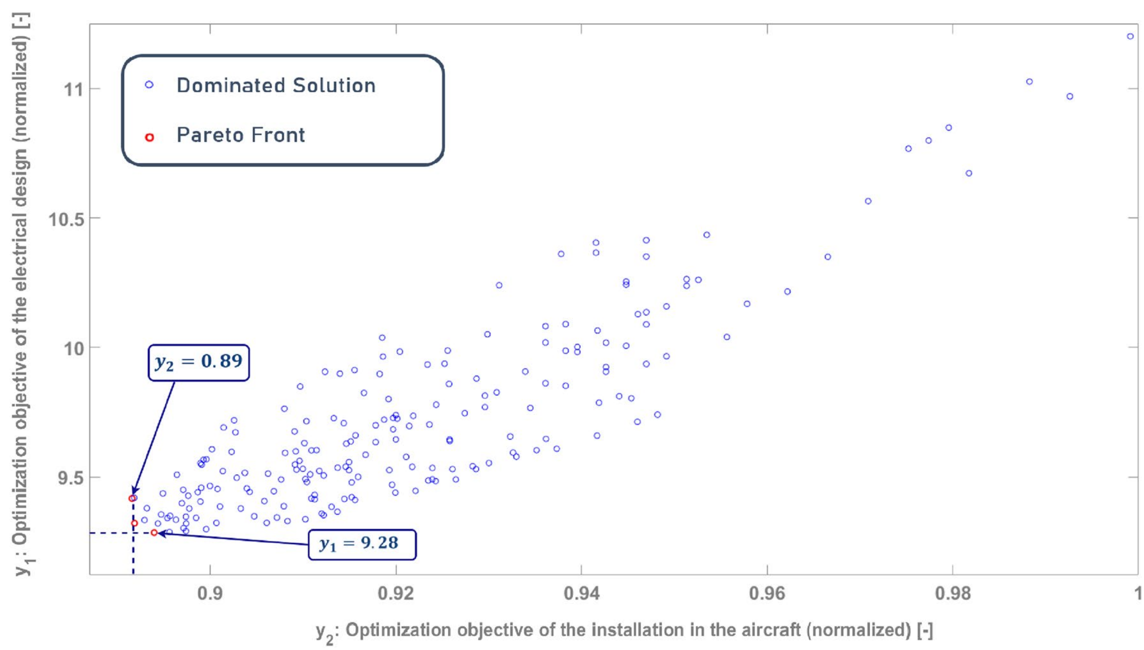

Fig. 9 Results of the MOO for the configuration with 8 SPDBs and 2 galleys

components, the results of the input variables are visualized in VR. For example, for the second configuration, the interfaces between the SPDBs and the PSUs are represented. Figure 10 represents the interfaces leading to the optimal installation objective, while Fig. 11 represents the interfaces leading to the optimal electrical design objective. Here, the interface between the SPDBs (red) and the corresponding power supplies (green) is represented by blue lines. An exact representation with the cables was not realized at this point.

The results for the installation objective show another effect of the cabin configuration on the interfaces. In the first configuration, the front SPDBs have longer cable

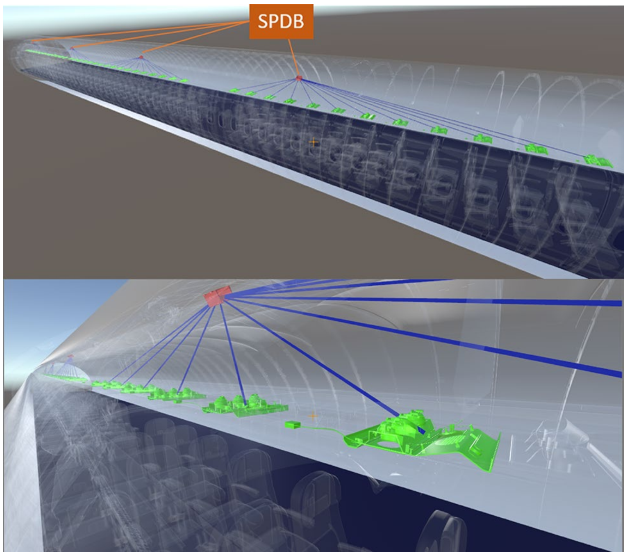

Fig. 10 Interfaces for optimum electrical design objective (configuration: 8 SPDBs)

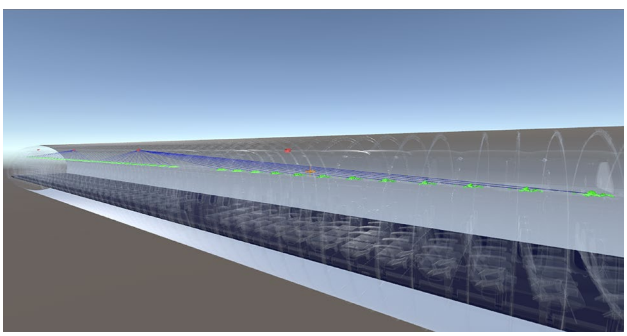

Fig. 11 Interfaces for optimum electrical design objective (configuration: 8 SPDBs + 2 galleys)

connections in the optimal case than those in the rear of the cabin. This is due to the fact that there are fewer seats in the first than economy classes, and thus larger connection areas are required for optimal power distribution. In the second configuration, the front and rear SPDBs are not connected to the PSUs at all. The reason for this is that they supply the galleys, so in the optimal case of the electrical layout, all PSUs are supplied by the center SPDBs. In addition to the visualization and analysis of the results, the staging of the component connection in VR allows the verification of the optimization results. A future extension of the visualization of the results in VR and an accurate representation of the cables offers the potential to verify the selected placement. This can be used to verify if the selected placement of the PSUs do not interfere with other cabin elements (e.g., if the cables have installation space).

Finally, the component parameters that lead to the best values of the objective parameters are fed back into the system architecture. The goal is to simulate the system instances with the parameter values and enable automated verification of the architecture instance against the requirements. For example, the parameters of the optimal electrical design of the second configuration are used to instantiate the system architecture. Figure 12 represents the association of these parameters with the constraints and requirements in the system model. These relationships allow automated verification of the architectural instance, as shown in Fig. 13.

The automated verification shows that the general conditions and the corresponding requirements for the interface areas (see Eq. 6) are met. However, it also shows that the electrical requirement for the maximum number of power supplies connected to the SPDB is not satisfied. Thus, tracing the optimization results back to the architectural context helps to detect non-valid architectural configurations. Linking the requirements to the system architecture and the MOO model allows a quick and early investigation of the candidate solutions from the point of view of the different disciplines, as well as the verification of these architectural solutions in the overall system context.

6 Benefits and limitations of model-based design and optimization framework

As stated in Sect. 3, the primary goal of this research is to define methods for extending the model-based analysis and design process with disciplinary optimization models and parameters. The application of the suggested methodology in the context of cabin system design and optimization aims to assess the suitability of the methodology in achieving the research objectives. The interdisciplinary analysis of system parameters is achieved through a domain-neutral model using SysML, providing a common platform for all engineers involved. Disciplinary parameters are interconnected using the same interfacing method between the SysML model in Cameo and the optimization model in Matlab. Consequently, no additional effort is required to adapt the interface between the architectural and optimization models. This link facilitates the synchronization of updated values, granting direct access to the system parameters. This arrangement offers the advantage of enabling all associated models to access current values and automatically synchronize dependent parameters. The link also serves to provide feedback from the optimization solution to the architecture for further verification. The “satisfy” relationship in the architecture model enables the integrator, responsible for specifying system requirements, to review the outcomes of domain experts working on optimization challenges. Both parties can operate within their domain-specific models and

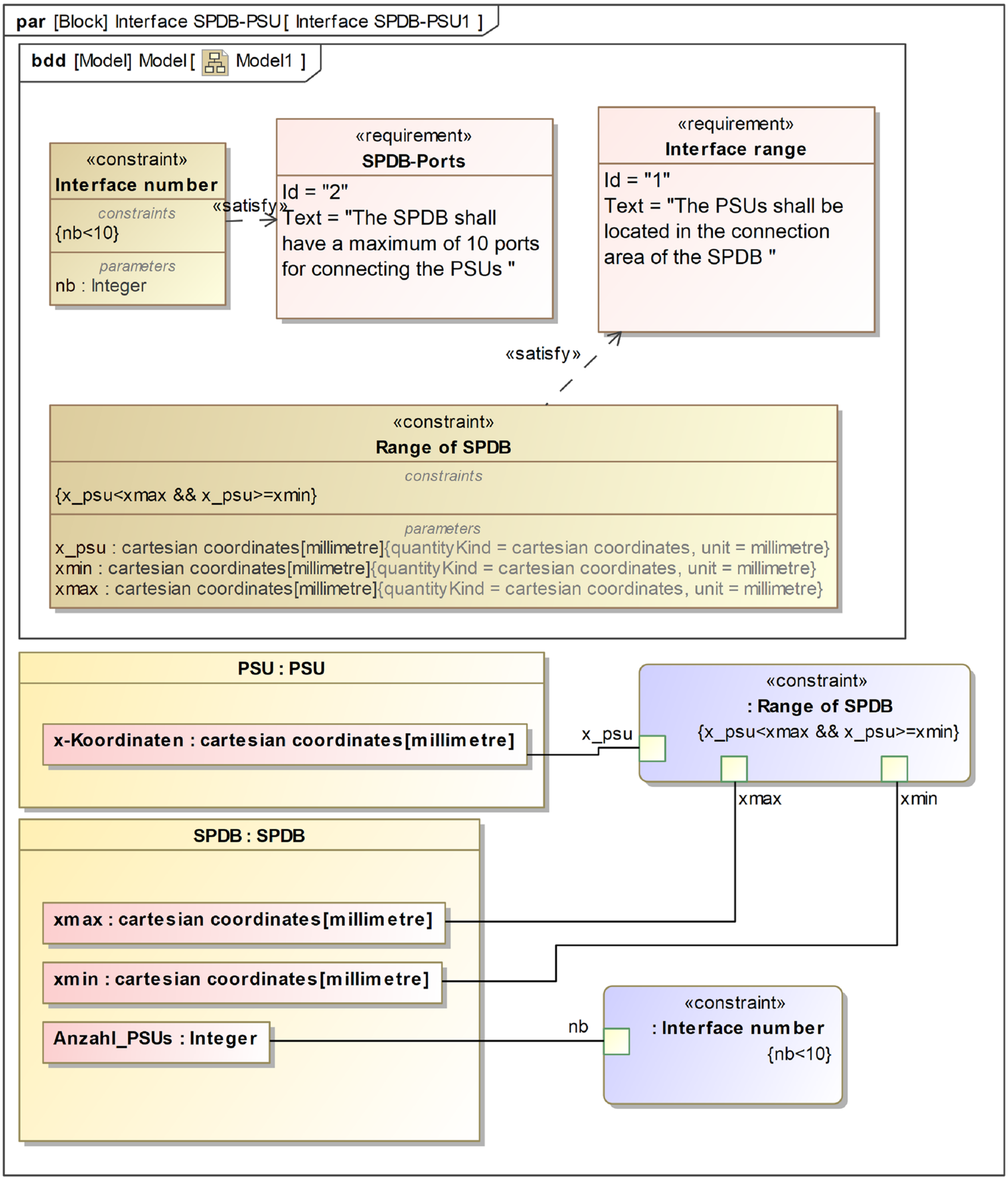

Fig. 12 Linking of the optimization parameters with the constraints and the requirements in the system model

tools while remaining connected through the system architecture. However, this approach does exhibit limitations in the subsequent analysis. Given that only individual values are updated in SysML, it becomes impractical to merge different solutions and conduct trade-off studies within the architecture model.

As demonstrated in this study, the inclusion of galleys alongside the PSUs resulted in significantly altered interfaces between the power supply components (SPDBs) and the power consumers (PSUs). This highlights the system architecture's sensitivity to cabin configuration changes. Additionally, integrating supplementary optimization objectives and variable input parameters into a trade-off analysis offers a comprehensive perspective on how various system and module parameters impact multiple design objectives. Evaluating these interactive effects among diverse aircraft parameters during the early design stages proves immensely advantageous. It facilitates the

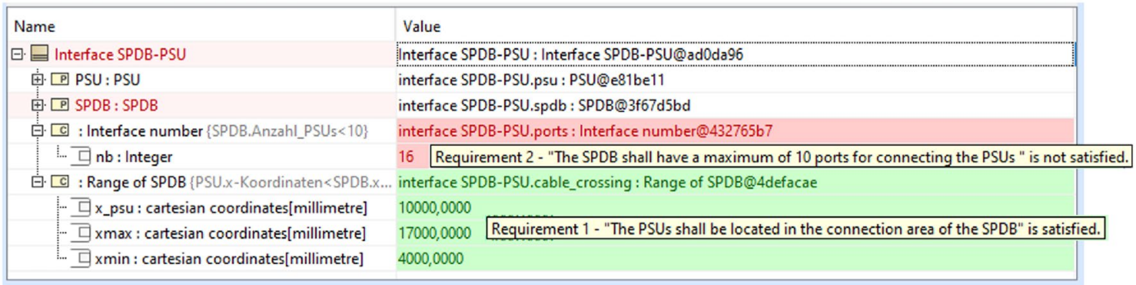

Fig. 13 Automated verification of optimization results in the system architecture

assessment of how modifications to a single aircraft system affect external systems and allows for the consideration of the aircraft's global impact. This approach minimizes the need for unnecessary and costly changes in the aircraft design during later developmental phases.

The presented use case considers two disciplines and their corresponding parameters. In practice, aircraft design involves numerous disciplines, increasing the complexity that currently restricts the methodology's applicability. Peer-to-peer communication between the architecture and optimization model is feasible due to the constrained analysis parameters. However, if the optimization process involves additional analysis tools such as Finite Element Method (FEM), Structural Analysis, Electrical Simulation, Aerodynamics, etc., the implementation of tool interfaces becomes intricate and time-consuming. While parameter synchronization suffices for the current use case, it might be insufficient when integrating numerous tools, necessitating a more sophisticated data linking approach. Moreover, the Cameo tool offers integration with Matlab for value exchange, which might not be the case for other specialized tools. Consequently, a globally standardized data exchange method becomes essential to facilitate communication between all tools.

Therefore, concerning the research question, the methodology offers a way to incorporate results from disciplinary analysis and optimization into the system architecture. This enhances the understanding of multidisciplinary systems and, through comprehensive system evaluation, provides an early grasp of interdependencies and sensitivities within the aircraft systems as a whole. Nonetheless, it exhibits certain constraints regarding tool interfacing, particularly in scenarios involving advanced optimizations that encompass diverse models and analysis tools. These limitations are slated for expansion through the implementation of improved and standardized approaches for data linking and exchange.

7 Summary and outlook

In this work, a framework for model-based design and optimization of system architectures in the aircraft cabin was developed, taking into account different development disciplines. It complements the DLR end-to-end approach for the digital development process and extends the already developed methodology for functional analysis and integration of the system architecture. Using the use case in the cabin context, the framework was able to illustrate the advantages of digitally linking different model parameters in a consistent manner. The application of the discipline-neutral language SysML in modeling the system architecture enabled the identification of multidisciplinary system parameters and synergistic interfaces in the system. Subsequently, these parameters were transferred through the interface to the optimization model and used to perform multi-objective optimization. By examining two different architectural configurations and normalizing the optimization objectives, it was possible to perform sensitivity analyses and evaluate the effect of the configuration parameters on the optimization objectives. By transferring the results to VR, optimal solution configurations could be visualized and analyzed in the entire cabin context. Feeding the optimization results back to the system architecture enabled automated verification of the optimal architecture instances against the linked requirements.

The framework provides the ability to realize data continuity from aircraft preliminary design in CPACS, through system architecture, to detailed design and optimization. The application use case outlines how decision-making at the system architecture level can be supported from disciplinary parameters and optimization models. Thus, early analysis of interactive system aspects between different development disciplines is possible and avoids costly changes later on. By considering functional properties of the cabin and cabin systems in the design and optimization models, these can be added to the classical disciplines such as aircraft structure and aerodynamics, which are represented by the CPACS-based approach for multi-fidelity and consistent multidisciplinary analyses (cf. [3]). The next challenge is to link the detailed cabin parameters to higher-level MDO frameworks that consider a broader range of discipline parameters and objectives in multidisciplinary optimization.

Digitally tying the analysis and optimization models to the abstract system architecture in SysML and using the CPACS aircraft description schema as a common central data model enabled data consistency and traceability of generated information throughout the development process. To enable the vision of a comprehensive Digital Thread throughout the product lifecycle, the proposed framework will be extended in further work. Especially in production, the digitization of the system architecture and the connection of production planning to the product design is very beneficial. It can enable rapid reorganization of resources, reconfiguration of production or assembly tasks, and agile response to last-minute reconfiguration, late provisioning of resources, or technology upgrades. In addition, the future challenge is to connect the model-based system architecture to real assembly and production facilities to exploit feedback data from the adaptive and robotic assembly execution taking place in DLR for process planning and optimization.

Funding Open Access funding enabled and organized by Projekt DEAL. No funding was received for conducting this study.

Data availability The data that support the findings of this study are available from the corresponding author, Y. Ghanjaoui, upon reasonable request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

References

1. DLR: Aeronautic research at DLR: programme and strategy (2020). https://www.dlr.de/en/research-and-transfer/aeronautics/programme-and-strategy. [Visited 12.05.2023]
2. BMWK: Aviation strategy of the federal German government. Technical report (2016). https://www.bmwk.de/Redaktion/EN/Publikationen/aviation-strategy-federal-german-government.html. [Visited 12.05.2023]
3. Hesse, C., Walther, J.-N., Allebrodt, P., Wandel, M.: Integration of multi-physics analysis into the cabin design process using virtual reality. AIAA AVIATION 2021 FORUM (2021). https://doi.org/10.2514/6.2021-2776
4. Walther, J.-N., Hesse, C., Biedermann, J., Nagel, B.: High fidelity digital cabin mock-up based on preliminary aircraft design data for virtual reality applications and beyond. AIAA AVIATION 2021 FORUM (2021). https://doi.org/10.2514/6.2021-2775
5. Walther, J.-N., Hesse, C., Biedermann, J., Nagel, B.: Extensible aircraft fuselage model generation for a multidisciplinary, multi-fidelity context. In: 33RD Congress of the International Council of the Aeronautical Sciences Stockholm, Sweden (2022)
6. Fuchs, M., Beckert, F., Biedermann, J., Nagel, B.: Experience of conceptual designs and system interactions for the aircraft cabin in virtual reality. AIAA AVIATION 2021 FORUM (2021). https://doi.org/10.2514/6.2021-2773
7. Fuchs, M., Beckert, F., Rauscher, F., Goetz, C., Biedermann, J., Nagel, B.: Virtual reconfiguration and assessment of aircraft cabins using model-based systems engineering. In: 33RD Congress of the International Council of the Aeronautical Sciences Stockholm, Sweden (2022)
8. Li, Z., Wang, G., Lu, J., Broo, D.G., Kiritsis, D., Yan, Y.: Bibliometric analysis of model-based systems engineering: past, current, and future. IEEE Trans. Eng. Manag. (2022). https://doi.org/10.1109/TEM.2022.3186637
9. Shortell, T.M.: INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, 4th edn. Wiley, San Diego (2015)
10. Weilkiens, T.: Systems Engineering with SysML/UML—Modeling, Analysis, Design. Morgan Kaufmann, Burlington (2007)
11. Friedenthal, S., Moore, A., Steiner, R. (eds.): A Practical Guide to SysML: The Systems Modeling Language, 3rd edn. The MK/OMG Press/Morgan Kaufmann, Boston (2015)
12. Alt, O.: Modellbasierte Systementwicklung Mit SysML. Carl Hanser Verlag, München (2012)
13. Chen, H.: Multidisciplinary design optimization (MDO). Encycl. Ocean Eng. (2021). https://doi.org/10.1007/978-981-10-6963-5_65-1
14. Sadrehaghighi, I.: Aircraft Multi-Disciplinary Optimization (MDO). Series CFD Open (2022). https://doi.org/10.13140/RG.2.2.24725.76003
15. Bussemaker, J., Boggero, L., Ciampa, P.D.: From system architecting to system design and optimization: a link between MBSE and MDAO. In: 32nd Annual INCOSE International Symposium (2022). https://doi.org/10.5281/zenodo.6820575
16. Fuchs, M., Beckert, F., Biedermann, J., Nagel, B.: A collaborative knowledge-based method for the interactive development of cabin systems in virtual reality. Comput. Ind. **136**, 103590 (2022). https://doi.org/10.1016/j.compind.2021.103590
17. Fuchs, M., Ghanjaoui, Y., Abulawi, J., Biedermann, J., Nagel, B.: Enhancement of the virtual design platform for modeling a functional system architecture of complex cabin systems. CEAS Aeronaut. J. (2022). https://doi.org/10.1007/s13272-022-00608-z
18. Ghanjaoui, Y.: A model-based methodology for the integration of a system architecture in a digital aircraft design process. Master's

thesis, HAW Hamburg- Department of Automotive and Aeronautical Engineering at Faculty of Engineering and Computer Science (2021)
19. Lamm, J.G., Weilkiens, T.: Functional architectures in SysML. In: Maurer, M., Schulze, S.-O. (eds.) Tag des Systems Engineering 2010, pp. 109–118. Carl Hanser Verlag, München (2010)
20. Rauscher, F., Biedermann, J., Allebrodt, P., Pätzold, C., Meller, F., Nagel, B.: Permanent aktualisierte 3D-Realgeometrie des ISTAR im Digitalem Zwilling. Deutscher Luft- und Raumfahrtkongress 2022 (2022)
21. Nya, B., Brombach, J., Schröter, T., Schulz, D.: Weight evaluation of cabin power architecture on smaller civil aircraft. In: 3rd International Workshop on Aircraft System Technologies AST 2011, Hamburg (2011)
22. Prasad, R.: Fundamentals of Electrical Engineering. PHI Learning Pvt. Ltd., Delhi (2014)
23. OSLC: About the OSLC open project (2021). https://open-services.net/about/. [Visited 11.05.2023]
24. SeatGuru: Lufthansa seat maps airbus A320 layout 1. https://www.seatguru.com/airlines/Lufthansa/Lufthansa_Airbus_A320-200_NEK.php. [Visited 06.02.2023]
25. Tian, Y., Cheng, R., Zhang, X., Jin, Y.: PlatEMO: a MATLAB platform for evolutionary multi-objective optimization [educational forum]. IEEE Comput. Intell. Mag. **12**(4), 73–87 (2017). https://doi.org/10.1109/MCI.2017.2742868