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# VIRTUAL RECONFIGURATION AND ASSESSMENT OF AIRCRAFT CABINS USING MODEL-BASED SYSTEMS ENGINEERING

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## Abstract

In order to create a detailed digital cabin, virtual models are combined with the geometric data of physical cabin components. This digital cabin can be used to analyse maintenance times, find optimization potential or test the integration of new technologies (e.g. hydrogen powered systems). This requires different levels of detail of the virtual cabin model as well as an automated data (e.g. 3D models, parameters) transfer infrastructure between them. However, this model structure is challenged by the complexity of the system to be mapped due to subsystems and interconnections. In addition, it requires an integration and preparation of the transmitted data (3D models, process data). This paper presents a method that addresses these challenges and introduces an architecture for building a virtual cabin for reconfiguration and analysis of new cabin variants. Model-based systems engineering is used to create a digital model of the aircraft cabin and its systems. The model is used for an automated reconfiguration of the cabin and consists of formalized knowledge and requirements. In addition, a 3D scan process is applied that digitizes the physical cabin subcomponents (e.g. riser duct) to increase the level of detail and to consider uncertainties. Subsequently, all data and models are visualized in a virtual reality environment in which users can interact with it and make direct changes to the layout. These changes are automatically transferred to the conceptual cabin design process for an automated reconfiguration and examination of the layout regarding the requirements. As a result, a baseline architecture for the digital cabin has been created, which enables fast system reconfigurability, traceability of changes, identification of interdependencies, and investigation of new cabin variations (retrofit).

**Keywords:** Virtual Reality; Data Management; 3D Scanning; Aircraft Cabin, Systems Engineering

## 1. Introduction

A virtual model of the aircraft cabin enables the investigation of cabin variants, the integration of new system technologies (liquid hydrogen powered systems) and the analysis of installation processes. However, different levels of fidelity and abstraction of the cabin are required for the respective conceptual design disciplines. In addition, the model structure to be mapped is challenged by the complexity of the systems and subsystems as well as their interactions within the cabin. This paper presents a method that addresses these challenges and introduces an architecture for building a virtual cabin for reconfiguration and analysis of new cabin variants. Model-based systems engineering (MBSE) is used to create a digital model of the aircraft cabin and its systems. The model is used, amongst others, for an automated reconfiguration of the cabin and consists of formalized knowledge and requirements. In order to retrieve more levels of detail from reality and to supplement the conceptual design process with high-resolution models alongside idealized 3D models, a 3D scanning process is used to digitize physical subcomponents of the cabin and to create 3D geometric models. The scanned components are purchased parts (e.g. riser duct, seat) that do not need to be parameterized during the conceptual design process. As a result, uncertainties from the production process or textures for the realistic visualization are considered. Depending on the conceptual design discipline, the different abstraction levels of the cabin can then be derived for thermal analyses, finite element method (FEM) models, subject tests or installation analyses. Finally, these data (e.g. process data, requirements) and models (e.g. 3D models) are merged in a virtual reality (VR) environment. Here, the user has the opportunity to interact with the virtual cabin and to visualize the results of the conceptual design process. Moreover, layout changes can be made directly in the virtual cabin. The new position of the cabin components is automatically saved and transferred to the conceptual design process to check the new layout according to the requirements and to transfer the result back to the VR. By that, the virtual cabin reflects and evaluates its current state as well as predicts future behaviour [1]. All in all, this architecture enables traceability of coupling effects, fast system reconfigurability and the optimisation of the aircraft cabin.

In the next section, the state-of-the-art and a literature review about virtual design, prototyping and model-based approaches are given. Section 3 presents the methodology for system architecture and configuration of virtual environment for reconfiguration and testing. In section 4, two different use cases are presented using the developed approach. The idea of the methodology is discussed in detail in section 5. Finally, conclusions and an outlook are drawn in section 6.

## 2. State-of-the-art

The need for reconfigurable models and the simultaneous evaluation of new product variants is high. Due to the growing complexity of products such as the aircraft, the understanding of interactions and dependencies within the system becomes more difficult. The understanding of changes due to the integration of new system components or technologies into already existing infrastructures and the verification of the effects on the overall system have to be supported with the help of dedicated methods. At the same time, in addition to the functional properties, other factors must also be taken into account in the evaluation of new variants. These are, above all, customer wishes that have an influence on the aesthetics, performance, ergonomics or costs in the context of customizing [2].

One approach to overcome this challenges is the interdisciplinary approach of model-based systems engineering. This holistic approach supports the different phases of system development, from specification definition through system design, implementation and testing with the aim of replacing the document-centric approach through the end-to-end use of digital models [3, 4]. International research projects such as AGILE have already demonstrated how MBSE can be used to build architectural frameworks to identify stakeholders, gather their needs, and develop system requirements [5]. Some studies have already investigated the modeling of product variants with the help of the modeling language SysML (Systems Modeling Language): Bilic et al. [6] investigated variability modeling in SysML for engine behavior for Volvo, Weilkiens and Diekmann [7] used variant modeling to separate different installation contexts for a system as well as Meacham et al. [8] who used product variants modeling to ensure compliance for e-Health applications. However, no standard has yet been established for variant modeling. The challenges are mainly the traceability of features between the multiple models, the management of dependencies and the separation of variants from the common part. Another approach that addresses variant modeling and reconfiguration is virtual prototyping (VP). This approach has become established for the integration of product variants and customer requirements in the development process. Through the application of computer-generated, virtual system prototypes, product development time and costs could be reduced. Already Tseng et al. [2] showed by combining virtual prototyping with manufacturing simulation techniques how a design environment can be created to enable mass customization for product families. The further development of VP and rapid prototyping through the use of VR technologies enables a boost in effectiveness and planning in early visualization and functional testing. Thanks to the intuitive approach of VR, objects can be manipulated in terms of their position and shape based on CAD models, supporting the analysis of geometries, functionalities and customer request aspects such as aesthetics or ergonomics. Typical applications of industrial VR systems are therefore interactive design reviews, assembly investigations or photorealistic product presentations [9]. Furthermore, real-time development and evaluation promotes collaborative and global teamwork [10, 11]. Nevertheless, the representation of CAD geometries in a VR environment is a challenge due to the complexity of the geometry and thus the high number of polygons. In addition, a platform is needed that handles both geometric data and enhanced product information [10]. This requires, that dependencies between elements across domains and structures have to be considered, enabling a data and information traceability.

In order to accomplish the described challenges, data interoperability between CAD and MBSE is needed for testing variants and reconfiguration. In this paper, an innovative methodology is presented, that links the respective partial models such as functional, requirement and geometry models with 3D CAD models in a virtual reality environment enabling a continous exchange of information and data consistency. By using VR, the experts involved in the development process can participate directly in the evaluation process or reconfigure the model. To meet the computational and immersion requirements, the polygons of the scanned 3D geometries used are reduced by a re-meshing process. As a use case, the conceptual design of the aircraft cabin and its systems is studied to examine the method.

## 3. Methodology

In the following, the methodology for establishing a digital aircraft cabin is presented. Creating a digital cabin requires three parts, the physical product, the virtual product and the connection between the physical and the virtual product. These parts are shown in Figure 1. On the left side is the physical cabin. Here, it is a quarter section of an A319 aircraft fuselage. On the right side is the digital cabin model. This model is visualized in a virtual reality (VR) environment. Here, VR is used as an environmental platform to display the digital cabin and allows real-time inputs for cabin reconfiguration by humans. To enable these two models to communicate with each other and to obtain a digital representation of the physical subcomponent model of the cabin, a digital connection must be created. This connection is composed of three elements: digitization of physical components, development of models and processing of data.

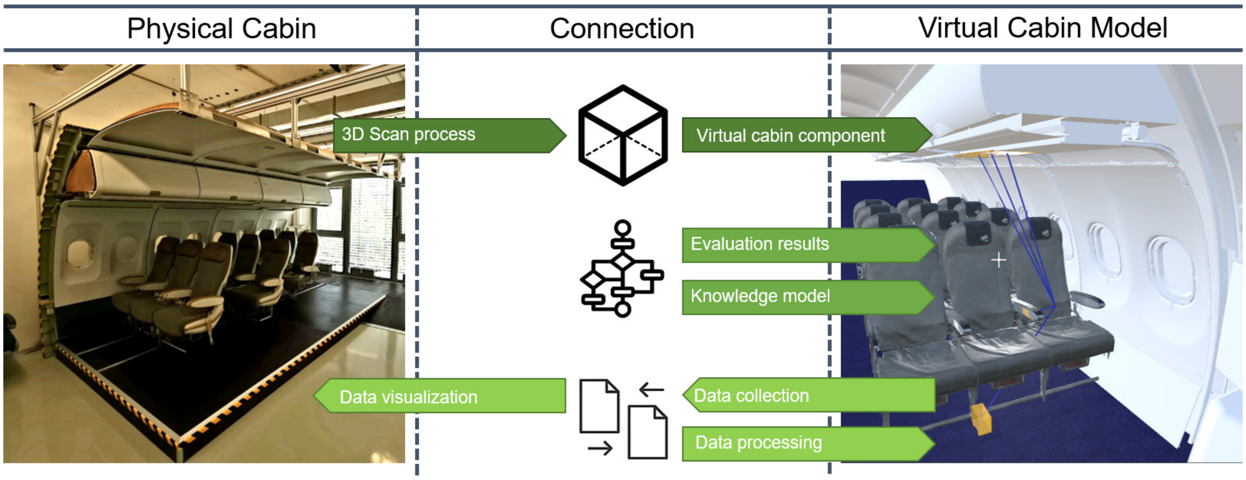


Figure 1 – Main parts of the digital aircraft cabin.

### 3.1 Digitization of physical components

The first element is the digitization of the physical components. This involves a 3D scanning process that captures the physical objects using a structured light method and then converts them into virtual 3D geometric components using a methodical process [12]. This process is shown in Figure 2, using a seat row as an example. First, the physical object is prepared for the recording. Therefore, it is taken out of its environment and placed in the room, so that it can be viewed from all sides. Smaller objects can be placed on a rotation table, which can partially atomize and accelerate the scanning process. In addition, reference points must be distributed on the object to track its orientation and movement relative to the 3D sensor and superimpose the recordings from the top and bottom side to obtain a closed model. Now the 3D scanner captures the physical object, recording a finite number of numerical measurement points that describe the surface. Now the measurement points are connected by a triangulation, usually the Delaunay Triangulation [13], and a mesh is created. To obtain a surface, the areas between the lines of the mesh are filled. Finally, the polygon mesh is post-processed and colorized. This includes closing any holes that accrue in the mesh and reducing the number of points and thus triangles, which reduces the memory size of the exported models. The coloring of the mesh is done using color information from the camera sensors. Each point gets a color value according to the RGB scheme and the areas in between are interpolated. This process creates virtual 3D components with an optimal sense of reality [12]. Here, only subcomponents and purchased parts of the cabin (e.g. seat or riser duct) with a fixed geometry are scanned. Parameterization of these 3D objects is therefore not necessary and not supported by the existing procedure. However, primary parameters (e.g. dimension and weight) of the cabin components can be derived from the model. These parameters in turn can be used as input for the conceptual cabin design process to study the integration of new sub component parts into the cabin and their influence on the overall layout behavior. Subsequently, these objects are also used for the realistic visualization of the virtual cabin in order to perform further analyses of the cabin configuration (subject tests).

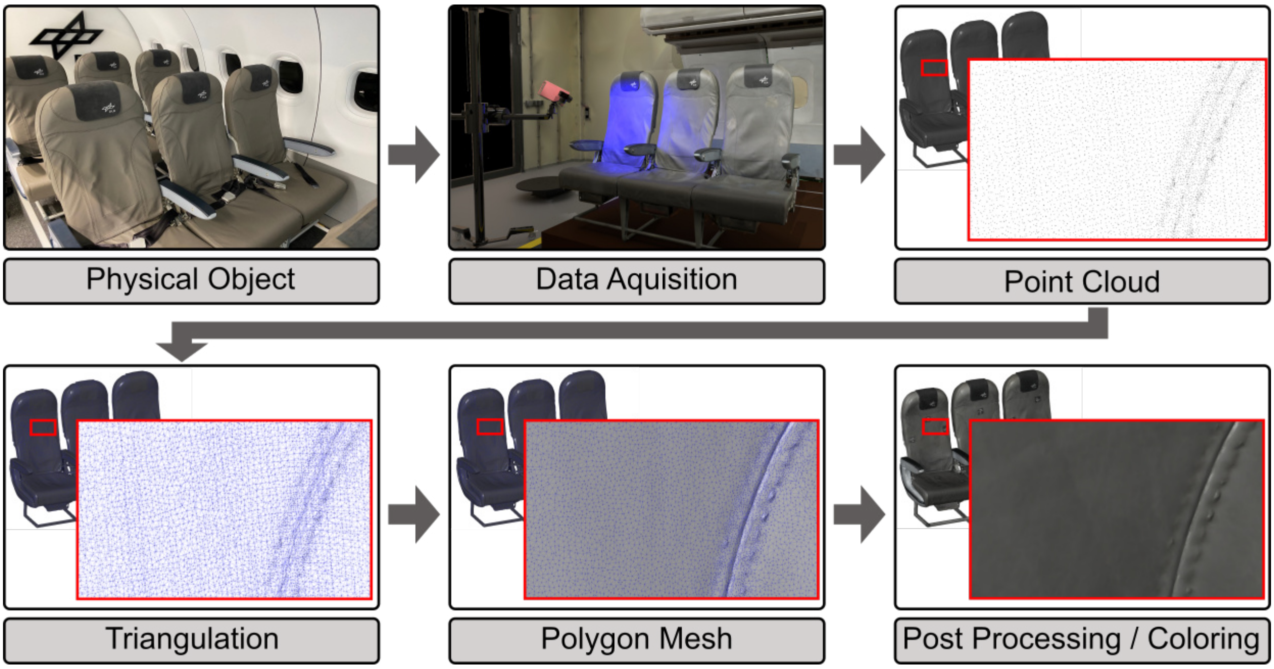


Figure 2 – Digitization process of physical components.

## 3.2 Knowledge model for cabin systems

The second element deals with the development of models that are required for the characterization of the individual cabin and system components as well as the linking with one another. To handle the complexity of the cabin and its system, models are built using a model-based approach. The model-based design approach ensures data consistency between the various models and establishes an infrastructure that complements the vision of a digital thread. The structure and linking of the models is shown in Figure 3. Initially, the system architecture of the cabin and its systems is designed. This starts with the modeling of the top level aircraft requirements (TLARs). These reflect the most important requirements and needs of the stakeholders (e.g. number of passengers to be transported). In parallel, if required, further conceptual design parameters are imported, which are necessary for the architecture modeling. With these parameters, the logical (hierarchical structure, ontology) and functional (functional groups and their activities) system architecture can be designed. By linking the individual system objects with the collected requirements, their compliance can ultimately be checked and traced. The system architecture is modeled using SysML in the MBSE platform Cameo Systems Modeler.

For the system layout, the result of the system architecture is used as input. With the models, all objects of the desired architecture are instantiated in SysML, according to the stored requirements. For instance, a cabin with 180 passengers will generate 180 individual reading lights. However, these ob-

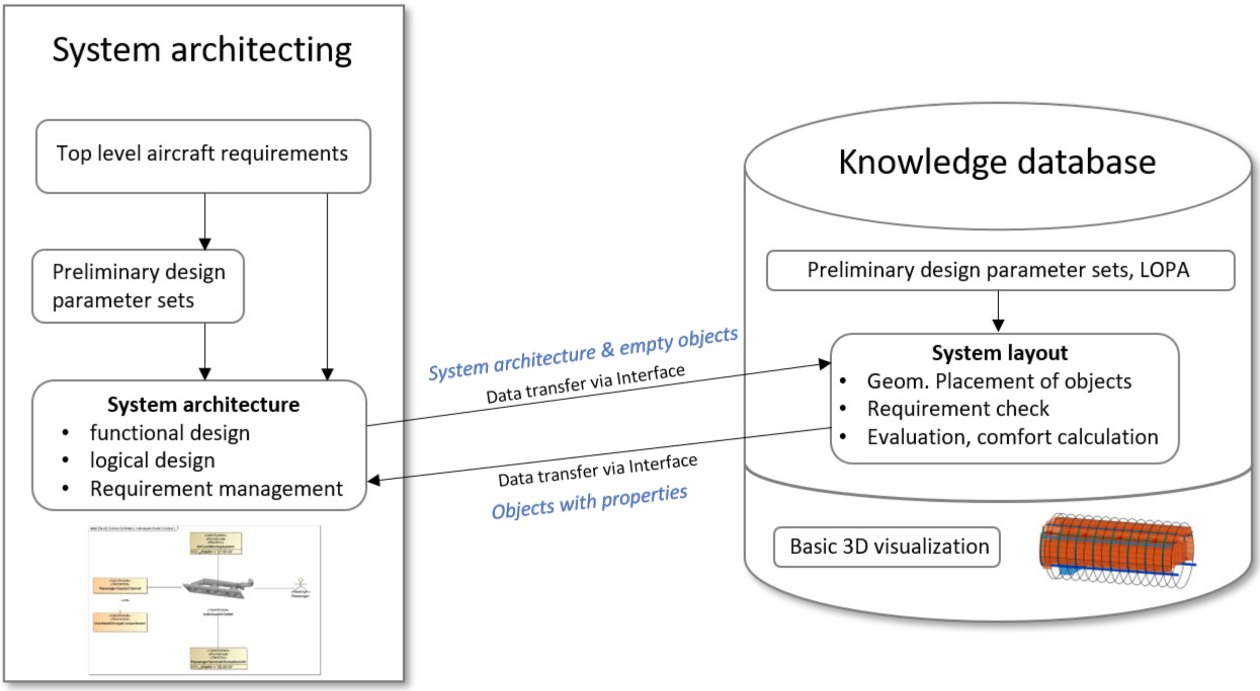
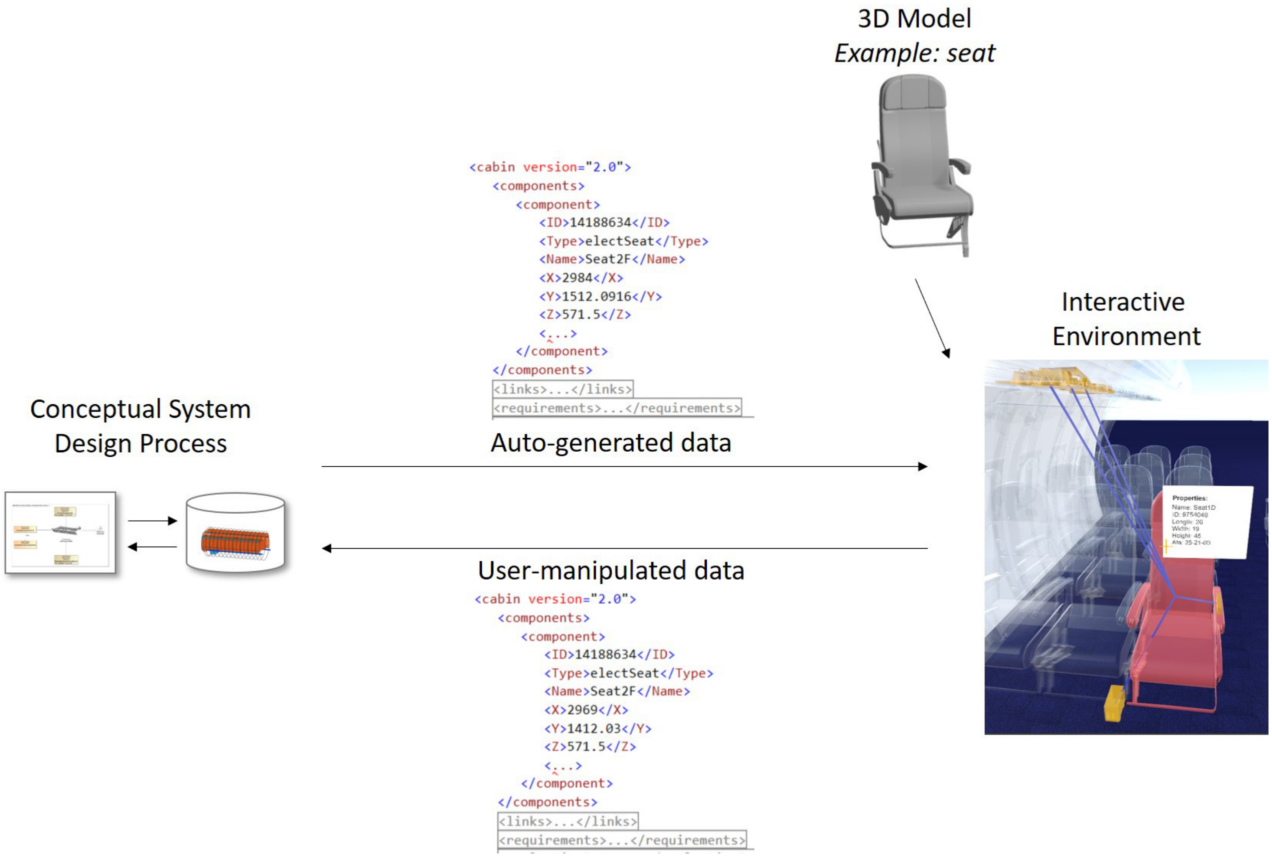


Figure 3 – Structure of the knowledge models and connection of them via interfaces.

jects still lack many property values at this stage. Therefore, a data interface to the knowledge base in Matlab is used to transfer the system architecture in the form of the empty objects. These are then expanded and filled with information and values in the system layout process. Formalized knowledge (e.g. requirements, parameters, properties, dependencies) is used in the form of variables and equations to automatically generate the cabin and feed the previously instantiated objects with information [14]. The design rules are based on additional data from preliminary design parameter sets, see [15], or the Layout of Passenger Accommodations (LOPA) as well as on safety requirements from the Certification Specification for Large Aeroplanes (CS-25). Then, using these rules, the objects are placed within the cabin design space. Subsequently, the evaluation takes place. This is on the one hand the verification of requirements (e.g. free area of emergency exits) and on the other hand the passenger comfort evaluation of the concept. For a first impression, the automated cabin system design can be visualized with simple basic geometries in Matlab. Finally, objects in the architecture model in SysML are supplemented with the generated property values from Matlab in order to use them for further analyses. The entire procedure is also called the conceptual cabin system design process.

## 3.3 Data processing

The third element deals with the processing of data. On one hand, this involves transferring the data generated in the conceptual cabin system design process to the virtual cabin model and subsequently displaying it there. To archive this, a structured XML data format is defined that includes all cabin components, links between them and associated requirements. Every element is given a unique ID to reference it across the whole process. Within the XML file, geometrical and functional properties are stored systematically e. g. the position of a cabin component in X, Y and Z-coordinates. Combined with the previously generated 3D-models these properties are used to generate the interactive virtual cabin model. Within this environment the user is able to experience the results of the system design process, display properties and functional connections. Additionally, the user is able to make changes to the layout of the cabin components by moving them with controllers. These changes in turn must be linked back to the conceptual design process which can be archived by altering for instance the position properties (x, y, z) within the XML file. The renewed data file can be transferred back to the system design process and used there to analyze and validate the changes made by the user with the implemented validation functions. The results of this process can then again be transferred back for visualization in the virtual environment and so on. The data exchange is shown graphically in Figure 4.



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    <component>
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      <Type>electSeat</Type>
      <Name>Seat2F</Name>
      <X>2984</X>
      <Y>1512.0916</Y>
      <Z>571.5</Z>
      <...>
    </component>
  </components>
  <links>...</links>
  <requirements>...</requirements>
```

```
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  <components>
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      <Y>1412.03</Y>
      <Z>571.5</Z>
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  </components>
  <links>...</links>
  <requirements>...</requirements>
```

Properties:
Name: Seat1D
ID: 9754040
Length: 26
Width: 19
Height: 45
Ata: 25-21-00

Figure 4 – Data exchange of property values between the conceptual system design process and the interactive environment.

Finally, the results of this iterative process can be brought back to the physical world e. g. by building a physical cabin mockup based on the acquired data. Another promising approach is the use of augmented reality (AR) systems to visualize the altered system layout data and the results of the evaluation and validation within an existing mockup.

## 4. Cabin reconfiguration and assessment use cases

In passenger aircraft in particular, the demands on the cabin system are very high, as a large number of subsystems interact and have to be aligned with each other. Not only do safety requirements such as the supply of oxygen masks or comfort requirements, including air conditioning, seat pitch and lighting, play a role, but also the smooth operation of the crew members' activities. Two examples of how these requirements can be tested in a virtual environment are presented in the following using the model-based approach.

### 4.1 Introduction into cabin assessment and VR setup

The following two studies were carried out in the virtual reality lab. Figure 5 shows the setup of the test environment. This consists of three base stations (lighthouses), a VR headset and two controllers. In this experiment, the HTC Vive Pro Eye was used. The live view of the user in the VR environment is displayed on a monitor. The cabin concept is shown in a 1:1 scale virtual mock up. This allows the user a realistic impression of the concept and lifelike investigations, such as serving operations in the aisle e.g. serving drinks and food. The runtime and development environment Unity version 2018.4.27f1 is used as the environment platform for the virtual cabin.
In the following, two use cases are presented as proof-of-concept to demonstrate assessment and reconfiguration with the developed methodological approach. The first one deals with the evaluation

of one aspect of passenger comfort: individual air ventilation. The second one deals with the implementation of a crew process and simulation of the travel path of a cabin trolley. In both cases, the fuselage structure of an Airbus A320 is used as a baseline. For a better representation only the first part of a cabin section (4 rows of seats+exits+galley) is shown.

Figure 5 – Setup of the virtual reality laboratory for testing and assessing cabin concepts.

## 4.2 Use case 1: Evaluation of individual air conditioning

One aspect of aircraft cabin comfort assessment is the provision of additional ventilation for the passenger. For this purpose, individual air outlets are available to the passenger. These are located below the overhead storage compartment (OHSC) in the passenger supply channel (PSC). The desired individual ventilation can be set manually by means of a rotary mechanism. Studies have shown that an airflow velocity in the range of 0.15 m/s to 0.25 m/s is perceived as pleasant [16]. Speeds above this are perceived as too strong and below as too weak [16]. Factors influencing the provision of airflow velocity are thus the distance between the outlet nozzle and the passenger seat, as well as the size of the outlet nozzle and the available flow velocity of the ventilation arriving at the air outlet from the air distribution system of the aircraft. Figure 6 shows the visualization of evaluation results in the virtual cabin model for the individual ventilation for each seat and passenger. The flowing air is represented in the form of a cone. Depending on the distance from the passenger‘s head position to the air outlet nozzle, the cone is colored differently. The color green indicates a pleasant airflow speed range of 0.15 m/s – 0.25 m/s, while the color yellow indicates insufficient ventilation and the color red indicates excessive ventilation. The reference case in the upper pictures shows a single-aisle configuration with a 3x3 seat arrangement. The upper right image shows a front view with the center positioning of the air outlets in the PSC. The use of a standard arrangement of the air outlets in the center below the overhead storage compartment shows that pleasant air ventilation is achieved in the reference area for the middle seat, while only weak ventilation reaches the passenger at the window and aisle seats. In order to improve the ventilation for the passenger and at the same time to investigate a new seating concept, the cabin is now reconfigured manually in virtual reality by a user. Thereby, the user operates with the controller and places the air outlets as well as the seats in the cabin in a new configuration. As inspiration, the seating arrangement of the premium business class of Lufthansa [17] is investigated, where a feeling of more privacy should be given to the passenger by offsetting the seats. In addition, this design concept supports the separation of passengers while taking into account the spread of Covid-19 (cf. zig-zag seating by [18]). The new layout of the passenger seats is visualized in the lower pictures of Figure 6. The middle seat has been moved back by about half a length. In addition, the position of the air outlets has been changed, as can be seen in the front view in the lower right image. These adjustments have improved the passengers' perception of ventilation for the aisle and window seats. Through the connection to the embedded evaluation functions, the user gets feedback on his reconfigured design directly in the virtual environment.

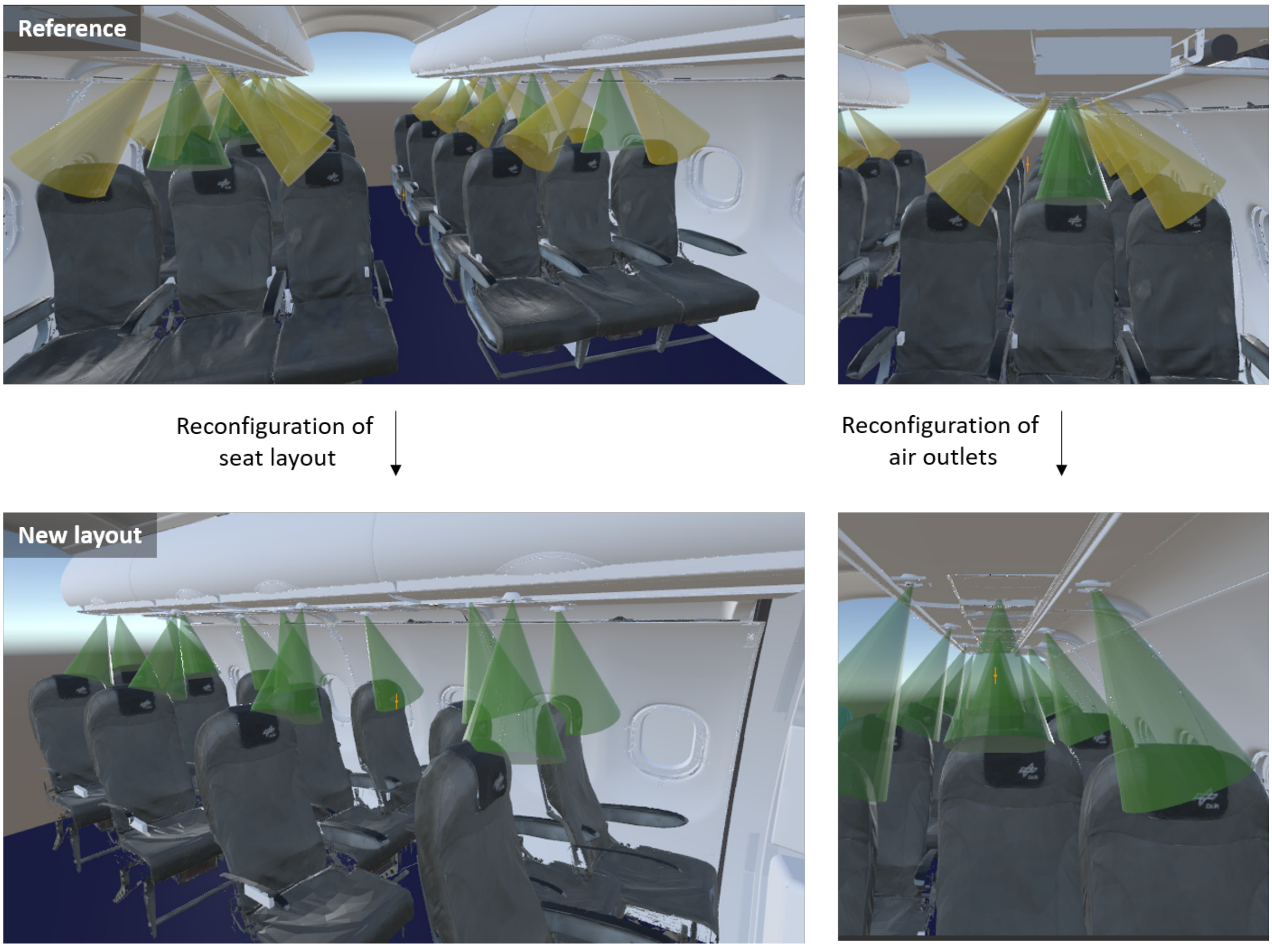


Figure 6 – Visualization of the assessment results for individual air ventilation in the virtual cabin model for different seat and air outlet positions.

### 4.3 Use case 2: evaluation of crew services

As part of this work, a real-time evaluation of cabin crew operation was performed using the example of serving passengers with a trolley. This process is displayed in a virtual environment created using the Unity game engine. In an airplane, the galleys are usually separated from the seating area by a wall, so there is only limited space available for maneuvering the trolley. The trolley must first be pulled completely out of the galley before it can be turned. With a standard trolley, the movement is relatively simple. However, full-size trolleys are often used on airplanes to speed up the catering process. These trolleys must be pulled further from the kitchen counter before rotation is possible. In this case, there is much less room to maneuver when moving the trolley. Figure 7 shows this contrast. To check the aisle width in the cabin, the movement of a trolley from the galley to the end of the aisle is visualized in the virtual environment by means of an animation that can be started via a main menu in VR. This menu can be selected via the button on the side of the right controller, as long as no cabin object has been selected beforehand. Selecting the "Aisle Optimation Animation" field switches to a separate menu. In this menu two fields "Standard Trolley" and "Fullsize Trolley" can be selected, which stand for the respective trolley sizes. After selecting one of the two fields, the variable activatedTrolleyMovement, which was initially deactivated, is activated for the respective trolley and

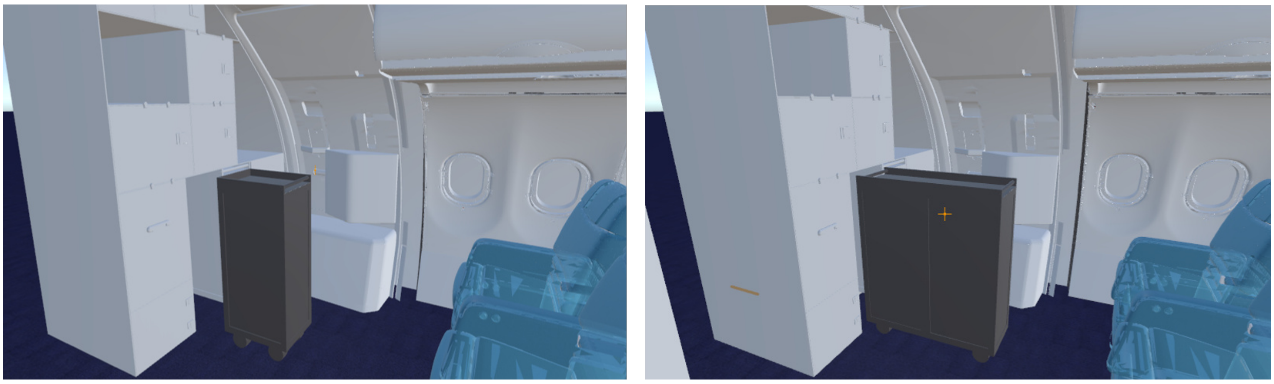
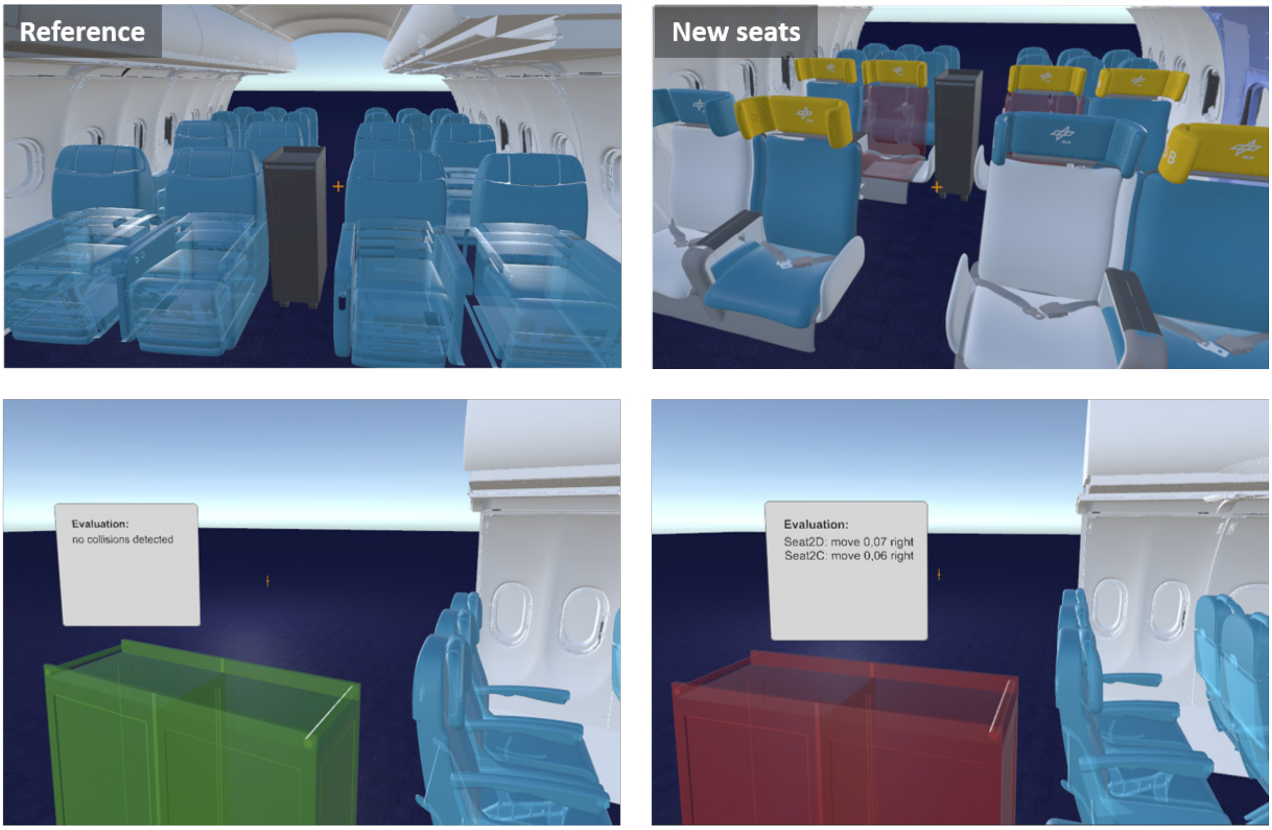


Figure 7 – Comparison of different sizes of trolleys in the galley.

the animation of the selected trolley model is started. In the following, the animation is tested on two cabin concepts to verify the method and design. The cabins both have two-class seating, with a difference in the business class seats. The two variants are:

1 Standard business and economy seats (reference),

2 New design for business seats, which promise more comfort by allowing the width to be varied (user group: pregnant women, overweight people, traveling with babies).



Evaluation:
no collisions detected

Evaluation:
Seat2D: move 0,07 right
Seat2C: move 0,06 right

a) No collision detected

b) Collision detected

Figure 8 – Case studies of the crew service evaluation.

Here, the first two rows consist of business class seats with a 2-2 arrangement and rows three and four each have 6 economy class seats with a 3-3 arrangement. In the first cabin concept (Figure 8a), the business class has today's standard seats. Thus, the trolley should be able to move along between the seats without any problems. The figures show the movement of the trolley in the aisle (top) and the corresponding evaluation at the end of the animation (bottom). The trolley is at the level of the first row at that point. It can be clearly seen that there is enough space to the left and right of the trolley up to the seats and that the aisle seats 1C and 1D are not colored red. Behind the fourth row, the trolley stops and turns green because there was no collision. This feedback is also given in the info panel. In the second cabin concept (Figure 8b), the business class consists of width-expandable seats. These provide more comfort. In the first row of seats the armrests are fully retracted, showing the maximum aisle width. In the second row, the armrests are extended and the aisle is narrower. At this point, the box collider meets the seats, which can be seen accordingly from the red discoloration of the seats in the upper illustration. However, the necessary buffer distance is not maintained, which is why a collision occurs. In the evaluation overview (lower figure), the names of the colliding seats, 2C and 2D, can be seen. To correct this, the two seats should each be moved at least 0.07 m, 2C to the right and 2D to the left, so that there is sufficient aisle width.

## 5. Discussion

In recent years, virtual 3D mockups and environments have continued to enter the preliminary design process. Through the joint advancement of MBSE coupled with CAD methods, passenger-related requirements for comfort [19] or the assembly of the systems [20], for example, can be checked at an early stage. The resulting changes or optimization potentials thus increase overall product quality and reduce the development process by reducing changes later in the development process. Especially for the evaluation of cabins and their systems, the physical characteristics of the cabin (e.g. seat appearance) have a decisive influence on the passenger's sense of well-being and thus on the passenger's comfort. By coupling a model-based functional system architecture design with a geometric and conceptual design modeling of the system components presented in this paper, different cabin system configurations can be checked for functional characteristics, physical appearance and spatial perception already in the preliminary design. In addition, interaction with the virtual mock up allows direct interpretation of the evaluation results (see 4.2 ) and promotes understanding about system couplings. The examples presented here show only some of the possibilities offered by coupling to a virtual environment platform. In addition, the different levels of abstraction of the 3D representation of the cabin elements can also be used as a basis for further investigations in the field of acoustics (FE analysis) or design.

In the next step, the system architecture created can be used for further analyses. For example, the assembly of the cabin into the aircraft fuselage structure can be investigated, thereby adding another factor to the evaluation of cabin concepts. The architecture and ontology required for this is already available and can be connected using XML or the Cameo Systems Modeler and Matlab interfaces. In addition, the data infrastructure shown also offers the possibility of transferring the results from the virtual design to the physical world. Devices such as the Hololens 2 are suitable for this purpose in order to create an augmented reality. Figure 9 shows exemplarily how a representation of the data from the preliminary conceptual design process can look like. This figure shows the live view while the user is wearing the Hololens 2 glasses. The user is standing in a physical mockup and is able to see the results virtually via the AR device. Here, the results of the virtual calculation are superimposed on the geometry of the real physical cabin elements and displayed appropriately. In this example, the air outlet flow cones are visualized. By coupling the virtual mockup and conceptual design process with the physical model, assessments can now be performed simultaneously on both models and exchanged with each other. The digital end-to-end approach enables a better understanding of system changes and thus shortens development times.

Nevertheless, there are limitations to the approach. The 3D scan with the coupled processing method reduces the file size of the 3D models to enable a realistic but at the same time less computationally intensive representation of the cabin components. However, not all components are suitable for the scanning process. Black or reflective surfaces are difficult or even impossible to scan. Therefore, the 3D models have to be supplemented with some self-constructed models. In addition, only a few system groups such as the air distribution system and the digital as well as the electrical supply of the passenger service functions have been modeled so far. In the next step, the systems will be expanded to include other cabin-related subsystems and methods to reduze the memory size of the

Figure 9 – Example of data transfer and visualization of assessment results using Hololens 2.

scan objects, like color mapping and normal mapping, will be investigated. Also, in the simulation of crew processes, only single-aisle configurations have been studied so far. Next, these must be extended to concepts with two aisles and the possibility for asymmetrical seating arrangements so that interruptions in the non-parallel aisle can also be taken into account.

## 6. Conclusion and outlook

In this paper, it was shown how the model-based approach in combination with virtual reality can be used to reconfigure and evaluate cabins and systems already in the preliminary design stage. The aim of the method is to take a holistic approach to design and evaluate interdisciplinary systems by linking physical attributes with functional properties. This was demonstrated using the example of the aircraft cabin and its systems. The demonstrated method consits of three parts. First, the digitization of physical cabin elements using a structured light method to enable the most realistic representation of the cabin for investigations in immersive environments. Second, the modeling of the system architecture and geometric placement of the cabin objects. Here, the SysML-model for the functional and logical architecture design was coupled with a geometric-placement- and requirements-verification-model in Matlab. Third, an XML structure was created for consistent data transfer between the cabin design results from the models and the virtual environment platform. Finally, two use cases were used to show firstly how comfort evaluations/analysis can be performed by live design changes and secondly how the virtual cabin can be used for crew process evaluation.

The use cases presented in this paper serve as a proof-of-concept and show the possibilities of connecting model-based system design to a virtual development platform to collect specific aspects of cabin system investigation. An end-to-end digital thread was created where the effects and interactions caused by changes to individual system components can be traced and directly re-evaluated. In the next step, connection options to the manufacturing processes will be studied and the cabin design will be supplemented in the preliminary design with further system groups and technology integrations, such as the integration of liquid hydrogen systems.

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## 8. Copyright Statement

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