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FORMALIZED KNOWLEDGE MANAGEMENT FOR THE AIRCRAFT CABIN DESIGN PROCESS

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Abstract

The design process of an aircraft cabin as well as the cabin systems are driven by design rules and certification requirements. These are necessary to ensure a secure air travel. Furthermore, the cabin should provide a comfortable area for the passengers and a pleasant working environment for the cabin crew. To improve the flight experience and to generate new use cases for the airlines, new technologies and innovations are required. However, the cabin itself is a complex system, which is subdivided into many subsystems (System of Systems). In addition, the interactions of the different systems may not be directly apparent for the partners involved. For that reason, this paper demonstrates a framework for the methodical design of an aircraft cabin and its systems. Therefore, a Central Data Model is established where the design knowledge, the requirements and the connections of the systems are formalized. The parameters are then used to automatically design the cabin systems. Subsequently, the data created in the model is linked with the 3D-geometries of the components and visualized using a virtual reality (VR) environment. Control elements make it possible to highlight relevant systems and their interdependences to get a more intuitive and enhanced overview for integrating new technologies or to evaluate the cabin design.

Keywords: Formalized knowledge; System of Systems; Aircraft Cabin; Systems Engineering

1. Introduction

Today's cabins and system architectures are an optimized evolution over decades. New technologies and innovations are required to improve the flight experience and to generate new use cases of the cabin for the airlines. The need for individual efficient solutions is increasing. At the same time, development times are shortened. Current cabin studies with higher levels of integration are part of a long development cycle with extensive design and testing efforts to validate solutions and assess user acceptance. Changes or adaptations at an advanced stage of development lead to extensive effort or delays in the overall product schedule. The challenge of the engineering process is to reduce development time for new systems including integration, dimensioning, evaluation and optimization.

For the cabin design process this means developing new configurations for the cabin and integrating new technologies in a much higher pace. However, the cabin is subdivided into several subsystems, called System of Systems, and represents a complex holistic system. In addition, the interactions of the different systems may not be directly apparent for the partners involved. These links are important for future customized concepts and the reconfiguration of cabin and fuselage modules. Moreover, the design process of an aircraft cabin as well as the cabin systems are driven by design rules and certification requirements. These are necessary to ensure a secure air travel. Furthermore, the cabin should provide a comfortable area for the passengers and a pleasant working environment for the cabin crew. A digital platform is needed, which can identify these cross-system functionalities and opportunities in an early design stage to increase efficiency more rapidly to enable a simple (re)configuration as a System of Systems. This enables an evaluation of various cabin configurations including different technology bricks on a conceptional design level, e.g. fuel cells and power supply systems for the electrics.

In order to accelerate innovations and manage the complexity, the use of a model-based systems engineering (MBSE) process has been established. MBSE is a methodology of the interdisciplinary approach of systems engineering (SE) for the development and realization of complex technical systems [1]. Here, the system information is based on models and not exclusively on textual information and thus places a cross-disciplinary system model at the center of development [1]. The potential lies in the reusability, better documentation and clearer product structure through linked models [2]. Complex relationships can be made analyzable and navigable, creating a better understanding of the system [2]. Information dissemination is important and vital to enable teams to act both independently in their domain (multidisciplinary) and in a larger network (interdisciplinary) [3].

The model-based approach has already been adopted in the engineering field. In product data management, additional information such as dimensions and general notes can already be accessed intuitively within a CAD assembly through the three-dimensional representation of a product [3]. Page Risueño and Nagel [4] in turn developed a knowledge-based engineering (KBE) model that integrates production processes (cost and performance estimation) into the design process of aircrafts. Pawletta et al. [5] pursued a holistic approach to variant modelling of system configurations with ontology-supported modelling. The above review shows that modelling requirements and systems as well formalizing the knowledge can be very difficult. Most studies only consider the parameterisation of requirements but not the coupling with rules and subsequent 3D model generation for a virtual connection with an interactive model.

For the early design stage, this paper present methods and a design process based on a MBSE and KBE approach to configurate a virtual model of a cabin. The focus is on knowledge management as a part of MBSE. In this way, models can be generated automatically with parameterised requirements and properties of the cabin components. In the future, this basic concept will serve as a baseline for further analyses to evaluate the cabin concepts. So, a Central Data Model is established where the design knowledge, the requirements and the connections of the systems are formalized. The data is then linked with the 3D-geometries of the components and visualized using a virtual reality environment. Control elements in the virtual environment make it possible to highlight relevant systems and their interdependences to get a more intuitive and enhanced overview. Moreover, the stored knowledge in the central model can be used to investigate new cabin concepts and the installation of different technologies. In addition, identifying the links provides potential indications for improvements and enhancements within the cabin. As a result, new technologies and innovations can be integrated in an optimized way. Due to the use of a Central Data Model, a comprehensive but understandable and vivid overview of all interactions and dependencies is given.

The aim of this paper is to demonstrate a fundamental framework for the design and later evaluation of future cabin system concepts. Chapter 2 begins with an introduction and explanation of the process steps of the methodical design process for the cabin and its systems. In chapter 3, knowledge modelling for system design is explained in more detail using an exemplary system. Finally, in chapter 4 the results of an exemplary system design are demonstrated in a virtual environment and an outlook on the further procedure is given. A conclusion is given in chapter 5.

2. The design process of the aircraft cabin and its systems

Over the last years collaborative design methods for the aircraft cabin and its systems were developed and applied within the German Aerospace Center (DLR). Different sources of knowledge were used as input for these methods in order to be able to design the respective systems. In this section, the individual process steps and the transfer of data are explained in more detail.

As shown in Figure 1 five steps characterize the collaborative design process of the cabin and its systems. Starting with the preliminary aircraft design, where first mass estimations and aircraft geometries are calculated based on the input parameters. Here, the input parameters are the top level aircraft requirements (TLARs) like design range, maximum payload, or seat class layout of the cabin [6]. Afterwards, the results of the preliminary design estimation are exchanged by the central data format CPACS[1][7]. This schema is used for exchanging geometric as well as analysis result data. Thus, for the current study it serves as a connector between preliminary aircraft design and cabin design.

Using the preliminary design, the fuselage structure of the aircraft is designed in the second step [8]. The modelled fuselage structure includes all relevant components such as frames, stringers, floor structure assemblies, and outer skin. In addition, further assembly models or monuments of the cabin such as seats and sidewall panels are designed in this step. During the design, the specifications from the certification regulation (CS-25) [9] are considered.

Process step three addresses the cabin system design. CPACS also serves here as an input format for the transmission of essential data. First, boundary conditions for the design of the cabin and its systems are extracted from the CPACS file. Examples are the position of the frames, the cabin diameter and the number of passengers. This information is used to design the respective cabin components and cabin systems. The methodology used here is based on an individual central data model which is aligned with CPACS and is built on the knowledge of three data sources. First, the architecture and breakdown into subsystems is defined by the Air Transport Association (ATA) chapters [10]. These can already be used to derive connections. Second, the design rules for the placement of cabin components and the interactions during the design process are derived by experts. The collected and structured know-how will make the design process more efficient by integrating process knowledge based on the expertise. Third, the system design requirements are formulated based on the information of the CS-25 and can be applied during the design process or subsequently checked for compliance. With the help of a visualisation function, the final cabin can be visualised for the first time in 3D with simple geometric shapes. This completes the design of the cabin and its systems.

For further analyses and evaluation, the cabin including the fuselage structure is modelled as a 3D model in process step four [11,12]. An Extensible Markup Language (XML)-file serves as an interface for the transfer of all generated data to the 3D modelling and rendering environment Blender [13]. There, a 3D object corresponding to the geometric dimensions is automatically assigned to each cabin object via python code. Depending on the level of detail, either simple 3D geometries, such as blocks, or more complex geometries can be used. For high-quality renderings or the most realistic possible representation in a virtual environment, 3D scanned objects are recommended [14].

After the entire cabin has been virtualised, it can be automatically transferred to a virtual environment in the final process step. Here it is possible to experience the result of the design in a virtual inspection and to interact with the cabin. For example, the dependencies of systems or their properties can be displayed. In this way, the first draft of the cabin can be evaluated.

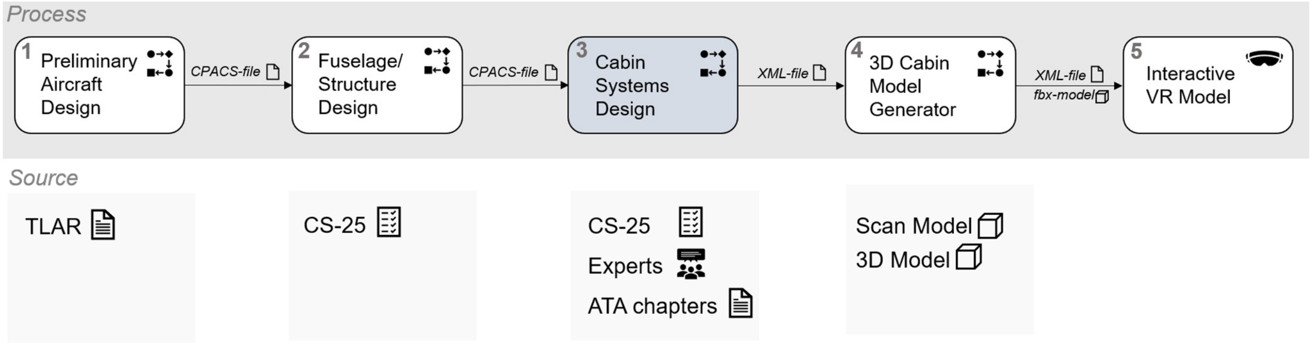

Figure 1 – The individual aircraft cabin design process steps and their sources of knowledge.

In this paper, the methodology used for process step three is described in more detail. The method is based on the object-oriented approach [11]. As a framework, the software Matlab [15] is used. During the design process, all cabin and system components are represented by object classes and their instances are defined by a unique identification number (ID). The properties of the individual

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[1] Common Parametric Aircraft Configuration Schema

components can be stored in these objects as well. The initialization and placement of the components is done with the help of rules and considering the given requirements. In the process, any dependencies that occur between the system components are stored as well. These can be accessed in the further process and used, for example, for the representation of system chains. In the Following, the structure of the knowledge management is shown in more detail using the air distribution system as an example.

3. Knowledge modelling for system design

This section presents the cabin and system design using the example of the cabin air distribution system. First, the main functions are briefly summarized. The knowledge modelling in terms of design criteria requirements, architecture, properties and fuselage integration is then also detailed here.

The main functions of the air conditioning system are to keep the air in the pressurized fuselage compartments at the correct pressure, temperature, and freshness [16]. The air conditioning system consists of the sub-systems distribution, pressurization control, air cooling, and temperature control. The complexity of this system offers a good insight into the different methods for modelling knowledge and dependencies. There are requirements that need to be considered, there are interdependencies with other cabin components and there are different use cases with changing stakeholders. When designing the system, various criteria must therefore be considered, which are shown in Figure 2. First, the requirements are defined. These either specify system boundaries, e.g. handle area, or define the number or arrangement of a system component. Then the layout of the system is specified with which the architecture can be built. This determines which components and how many of them are needed. The properties of the components also play a role. Both the functional and the geometric properties are stored and used for the design. Once it has been determined how the system is to be constructed and which components are needed, they are placed geometrically within the cabin, considering the requirements. This completes the design and integration of the cabin systems. How these criteria are managed and applied as formalized knowledge is explained in more detail in the following sections.

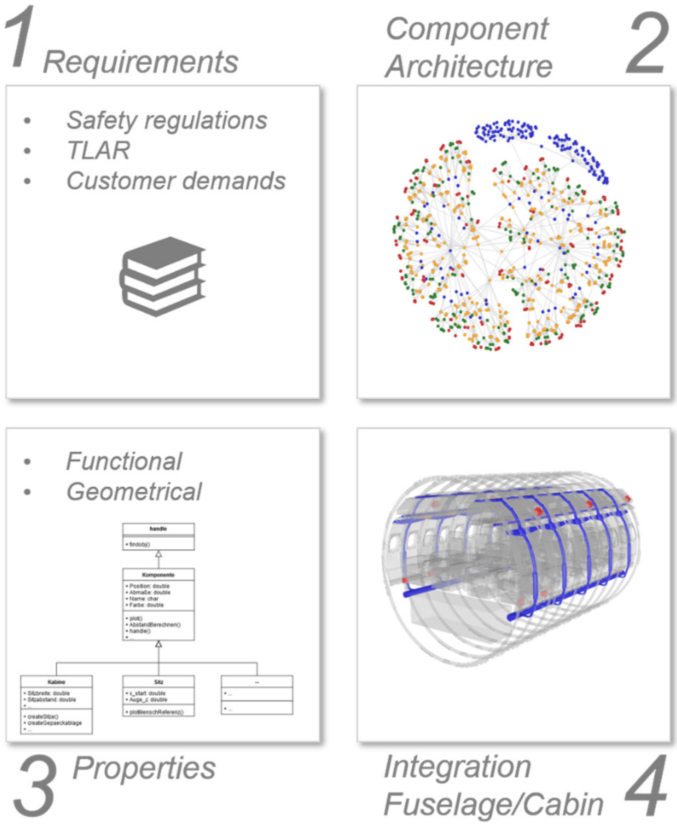

Figure 2 – Design criteria for the air conditioning system.

3.1 Requirements

The requirements of the air conditioning system are a major driver for the design process. A distinction is made between three types: safety regulations, top level aircraft requirements and customer demands. The safety regulations guarantee the minimum requirements for all systems and functions in normal cases as well as in the event of a fault. As a result, they represent a mandatory requirement and are recorded in the Certification Specification for Large Aeroplanes (CS-25) for the certification of an aircraft [9]. The top level aircraft requirements are derived from the use case and are a set of overall specifications for the design of the aircraft so that it can fulfil the main objectives like the safe transport of passengers over a specified travel distance. Moreover, they are the basis from which are derived the level 1 requirements that define, at system and subsystem level, how to achieve the desired performance. The last requirement type is the customers' demands. Depending on the airline's requirements, special requests can be made e.g. for the airflow speed in the cabin.

For the design process, these requirements are stored as rules, e.g. in the form of an equation or as a limit value. These can either be applied directly during the design process or the final design can be checked for compliance. As an example, the customer`s requirement for the individual passenger airflow is shown. With the individual air outlet as part of the passenger service functions, the passenger has the possibility to switch on his or her own ventilation on demand. Airflow speeds between 0.15 m/s and 0.25 m/s are found to be comfortable [17]. By modelling the air as a free air jet [18], where the flow exits through a nozzle into an environment without wall refraction, the maximum distance between passenger and nozzle for a comfortable ventilation can be calculated. Equation 1 shows the relation between the diameter of the nozzle d_0, the distance x, and the exit velocity of the air v_0 at the nozzle. With this equation, the targets can be calculated and satisfied.

$$v(x) = v_0 * \frac{d_0}{0.32 * x} \tag{1}$$

The target is to find the distance x between the seated passenger and the nozzle at which the desired airflow speed can be achieved. Rearranging equation 1 and inserting the airflow speeds range $v(x)$ (0.15 m/s – 0.25 m/s) results in a distance range for the placement of the individual air outlets. This range is considered in the geometric positioning of the individual air outlets in the cabin.

3.2 Component architecture

Another criterion is the layout or architecture of the system. The implementation of air conditioning in the cabin depends on requirement parameters such as the number of passengers. The various arrangements lead to variable component compositions. Today`s standard is an even distribution of riser ducts in each sidewall and supply ducts below the floor. Nevertheless, Airbus is investigating new concepts for cabin design [19]. A modular cabin design is being applied, which allows a modular construction for faster installation and also influences the design of the air conditioning components. By grouping assemblies into modules, these can be mounted in a pre-assembly stage and then connected via a few interfaces in the aircraft fuselage. Moreover, there are different ventilation principles like the ceiling-based cabin displacement ventilation [20]. However, the state-of-the-art variant for an Airbus A320 is used in the following.

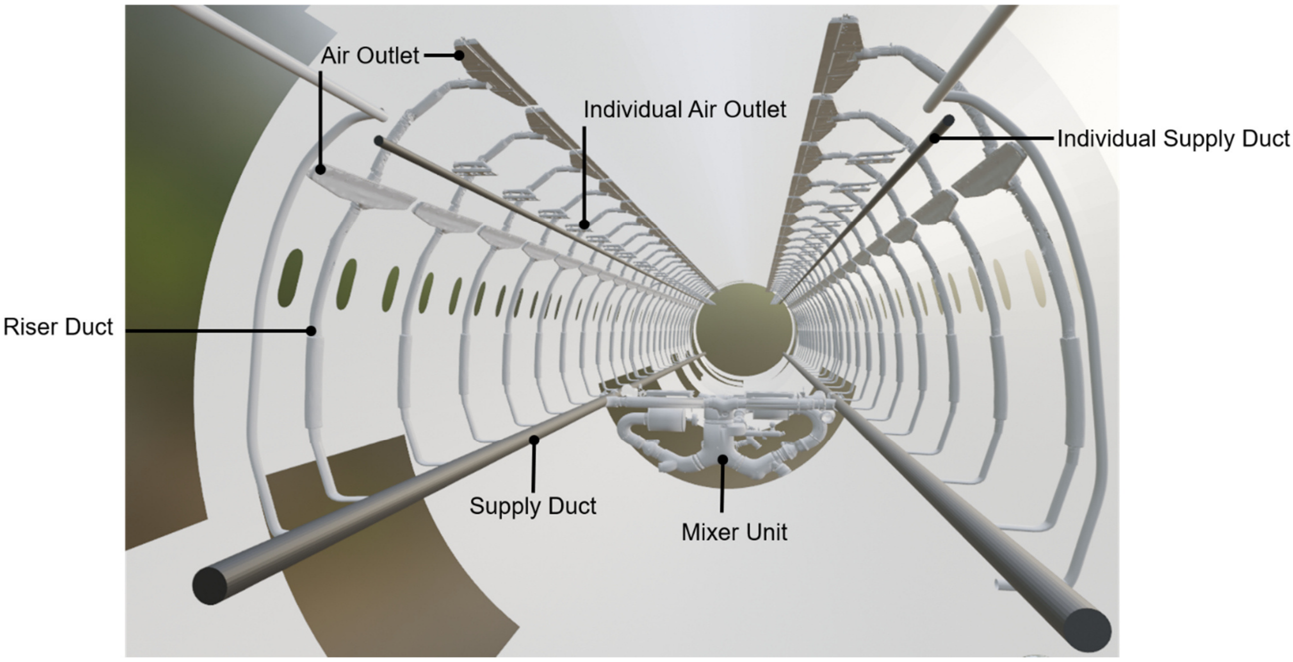

Figure 3 – Rendering of the distribution system in the passenger cabin for a A320 layout (Blender).

Figure 3 shows the components of the distribution system to deliver conditioned air to the pressurized fuselage. It consists of the mixing unit, in which the air for the cabin is mixed, and the supply ducts to distribute the air along the entire length of the cabin. Connected riser ducts bring the air to the air outlets. These are located firstly at the top of the sidewalls and secondly above the overhead storage compartments to provide circular air distribution in the cabin. In addition, two individual supply air lines are connected to the main supply air lines via a further riser duct. This gives the passenger the option of individually operating the additional ventilation at the seat using the individual air outlets.

3.3 Properties

The properties of the individual components and their interaction are decisive for the design of the overall system. A distinction is made between two types: functional properties and geometrical properties. The functional properties include, for example, the supply of a mass flow or the air flow temperature. Equation 2 shows the calculation of the total mass flow q_m for the air to be provided in the cabin. This is calculated from a selected flow factor f, the cabin pressure Pc, the cabin temperature Tc, and the normal volumetric flow at sea level q_n. This property is assigned to the mixer unit, as it must normally provide the mass flow. The target is to calculate the total mass flow q_m in order to use it for the calculation of the pipe diameters for the supply ducts.

$$q_m = \frac{f * q_n * Pc}{2.87 * Tc} \tag{2}$$

The second property type comprises geometric properties. These include the component dimensions or the position. Other properties that cannot be directly assigned to any group are the identification number, the name, or the affiliation to the ATA-chapters. The latter is used for referencing the system components to the standard commercial aircraft documentation [10] and the classification in a system group. All properties are stored in the objects. Figure 4 shows a section of the class diagram for the aircraft components. Blocks represent the classes including their attributes (properties) with their data type. Inheritances are shown with an arrow. According to the unified modelling language (UML) convention, the arrow starts from the respective child class and points to the parent class. In this example, all instantiated objects of the airOutlet class inherit all basic attributes of the cabinObject and Component classes. In addition, the attributes for a geometric description are inherited from the geometryObject class. Furthermore, the airOutlet class has its own properties, for example the value of the air mass flow. Also, there is a relationship (aggregation) between the objects of the airOutlet class and the riserDuct class. This means that the air outlets are existentially dependent on the riser ducts. In this way, the dependencies and connections between the cabin objects are considered in the design process.

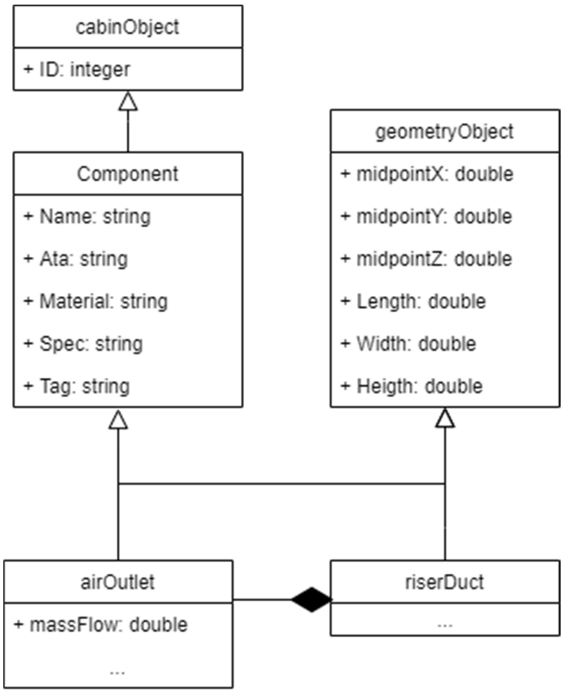

Figure 4 – Section of the class structure of the design algorithm.

3.4 Integration into fuselage and the cabin

Finally, it must be able to integrate the system into the predefined fuselage structure and thus be installed in the cabin. Changes to the structure or the system itself lead to mutual adjustments. This creates dependencies that go beyond the system boundary. Therefore, the relationships between the individual system components need to be defined and considered in the layout process. In this way, the available installation space can be checked when placing the system. As an example, the placement of the individual air outlet is examined in more detail. Figure 5 shows a block definition diagram of the Systems Modeling Language (SysML) as a system context definition diagram. Here, the black envelope depicts the system context boundaries and the solid lines between the cabin modules, external cabin systems, and modules signify interactions between them.

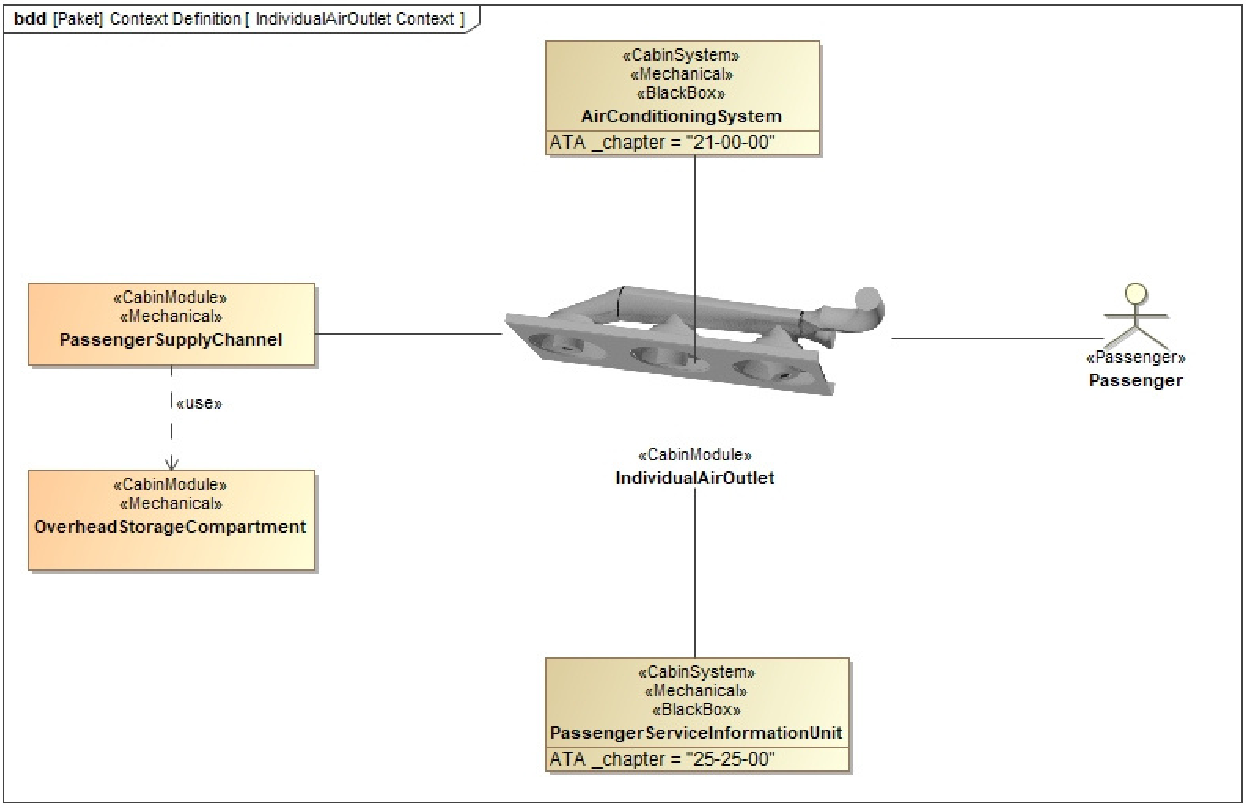

Figure 5 – Context definition of the individual air outlet in the cabin.

Here, the passenger regulates the individual ventilation through the air outlet. Air is supplied by the mechanical connection to the air conditioning system. There is another mechanical connection to the passenger supply channel (PSC), as the individual air outlet is mounted in it. The PSC, in turn, is dependent on the placement of the overhead storage compartment and thus has a dependency relationship with it (dashed arrow). Last, the cabin module individual air outlet also has an interface with the passenger service information unit, as these are arranged together as passenger service functions in the cabin. By classifying the cabin modules in a system context, the interdependencies can be seen and considered in the cabin design process. The diagram is made with the collaborative Model-Based Systems Engineering environment Cameo Systems Modeler^{TM} [21].

4. Results and Outlook

This section presents the automatically created cabin model in a virtual environment. The various functions to interact with the cabin concept are presented exemplary in the air distribution system components. In addition, an outlook in further proceeding the cabin model to investigate the design is given.

The results from process step three (Fig. 1) can be automatically transferred to the 3D cabin model generator for the creation of a realistic cabin model. The result of the cabin and system design can then be explored in a virtual environment in process step five. Therefore, the geometric model of the aircraft cabin is automatically loaded in Unity [22] to be processed and to create the virtual scenario. Unity is a platform for creating and running interactive real-time 3D content that supports realistic modelling of actual environments and multifunctional interactions with an object. Figure 6 shows a front cut-out section of an A320 cabin layout with business and economy class. The front view shows the cabin modules such as seats and overhead storage compartments as well as other elements of the lining (sidewall, ceiling, dado panel). In addition, the frames are also shown as part of the fuselage structure. Natural lighting and different textures depending on the object group were added for a more detailed representation.

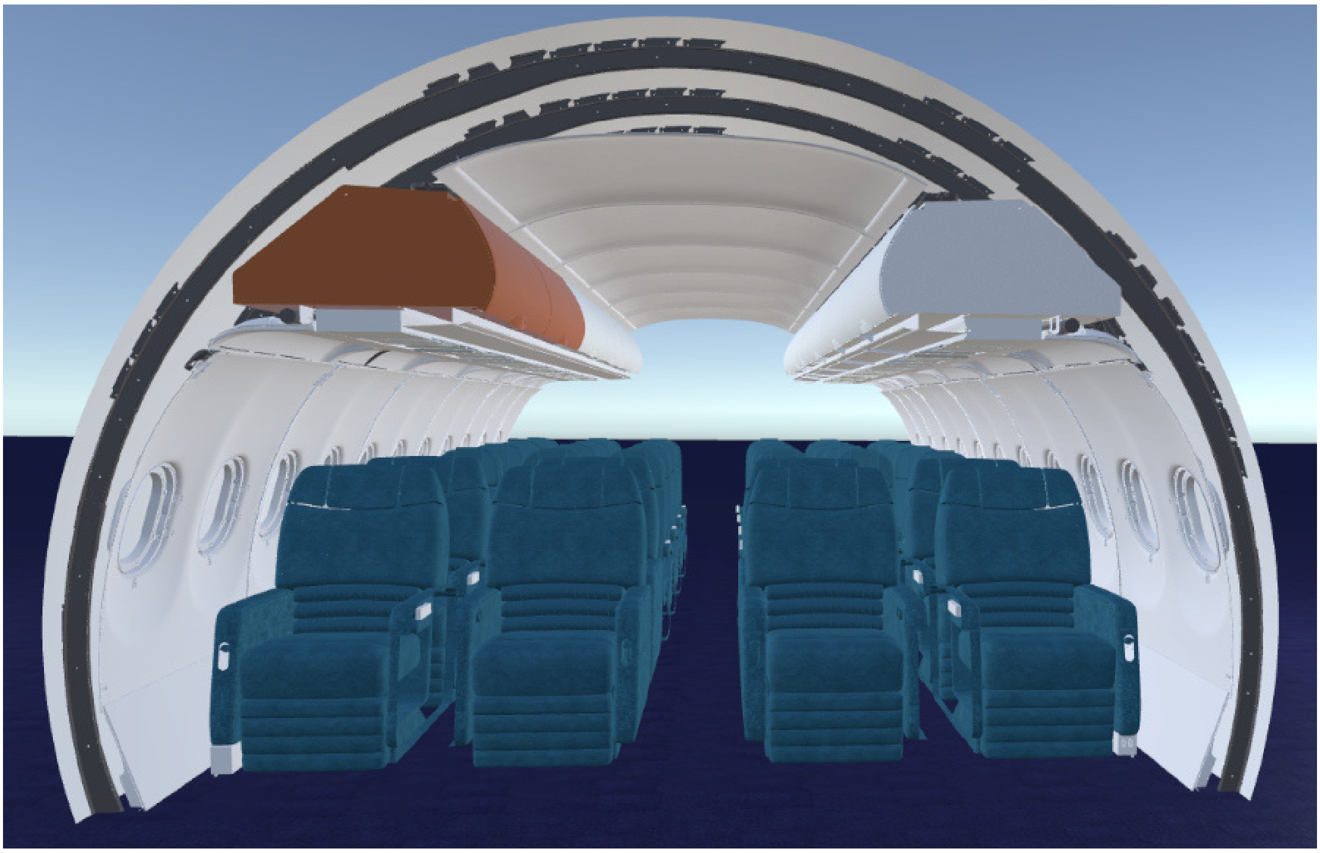

Figure 6 – The automatically created cabin concept in a virtual environment (Unity).

In this cabin design, the user can now move freely with the help of VR equipment [23] and explore the methodically generated cabin model. Different functions are available to the user. Three of them are illustrated in Figure 7 using the example of the individual air outlet. First, the user has the possibility to highlight and select objects (highlighted in red) in the cabin, which he wants to examine more closely, with the help of a laser pointer on the controller. Secondly, there is a function to display the properties of each cabin component. Here, a built-in algorithm accesses the data generated and stored in the object during the design process. Then, the results are displayed in an appearing info panel (grey rectangle window). For the individual air outlet, these are the ID, the name, the geometric dimensions and the ATA chapter affiliation. Thirdly, the associated system group can be displayed for each object. For the example shown here, the air conditioning system group is highlighted with the color yellow while all other components change to a transparent mode. This makes it easier to see the system structure and the placement of the individual components.

In the next step, further functions for the interaction with the virtual cabin will be implemented so that it can be used for the evaluation of new concepts. Currently, more complex and new solutions for cabin and system design have to be validated through costly studies, assessments and user acceptance tests. This will lead to longer development times in the future. The acceptance of new technologies and standards needs to be assessed in early design phases and in advance of product launch and production planning. Virtual reality as a technology can be used in this process for an overall concept evaluation. This technology supports the initial evaluation of a concept or the user acceptance tests, as the virtual cabin mock-up can be created automatically and more cost-effectively than physical mock-ups.

Properties:
ID: 71379558
Name: IndividualAirOutlet2RH
Length: 6 inch
Width: 10.2 inch
Height: 2.95 inch
Ata: 21-24-19

Figure 7 – User view: visualization of the individual air outlet’s properties (upper picture) and the air conditioning system (lower picture).

Virtual Reality technology is about to enable more than the previous realistic, purely visual impressions. The virtual aircraft cabin experience enables an extremely realistic subjective assessment of a cabin design from a passenger’s point of view to support next-generation human-centered design through improved user acceptance tests. Therefore, further functions will be implemented. For example, the distance measurement between the current position of the test person and an object. This can be used, for example, in accessibility assessment. The test person can sit virtually in the cabin seat and determine the distance to the control elements (such as the individual air outlet). Furthermore, a grab function is implemented. This allows the generated layout to be changed in virtual reality. Using a grab function, individual objects can be picked up and repositioned. The new architecture can be fed back into the design process and checked for compliance with the requirements. Another scope is the involvement of more human senses in the immersive VR environment like audio by integrating simulation results. During the design process, a 3D CAD model of the cabin is created using the integrated geometric model generator. This 3D model of the cabin can also be used for multidisciplinary analysis and assessment of the concept (e.g. finite element method) [24, 25]. In this way, the cabin can be analyzed acoustically and the results subsequently transferred to the virtual environment. The user can then test the speech intelligibility in the cabin during loudspeaker announcements. All these functions favor the virtual testing of new cabin configurations and designs. The basis for this is already given by the method presented here and the design process of the cabin and its systems.

5. Conclusion

The paper has shown an approach for formalizing knowledge as a part of MBSE for the automated design of the cabin and its systems. The aim of this work is to develop a basic concept in which an interactive cabin model can be developed based on parameters, which can then be used in the future for further analyses and validation. Therefore, the requirements, the functional properties, and the geometric properties of the system components were parameterised in order to automatically build architectures and models. The dependencies and interactions between the cabin components were also considered. An object-oriented approach was chosen as a framework to instantiate the cabin objects and to store their properties. Using an object-oriented structure will lead to reusable models and a better understanding of the architecture.

Subsequently, the data generated in the design process could be forwarded for a visualisation of the cabin. The data can be further processed through an XML and CPACS interface. The data is used to generate a high-resolution 3D model of the cabin and its systems, which is then transferred to a virtual environment. Here, the user has several functions to interact with the cabin model. For example, the properties of each cabin component can be displayed or system groups can be highlighted. This helps the user to explore the cabin concept and to better understand the interdependencies between the systems. The data for this is taken from the previously generated models and parameters.

With this work, a fundamental framework has been created and demonstrated that can be used to generate an interactive model based on parameters. This can be further processed in the next step and used for analyses (e.g. acoustic simulation). In the next step, further functions will be implemented in the virtual environment and the interfaces to the VR platform will be expanded with the aim of providing a virtual test facility for new cabin concepts.

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