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Integrated Tool for Cabin and Fuselage Modeling in Future Aircraft Research

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Abstract
This paper describes an integrated tool for cabin and fuselage modeling. It enables more detailed analysis in a conceptual aircraft design environment. The motivation is to capture component level innovations and soft changes and integrate them into future conceptual designs. Analysis of cabin layout concepts, new cabin materials or new system technology require sophisticated modeling in order to identify their potential in future aircraft designs. The described tool enables the incorporation of innovations and new concepts in this sector. The inclusion of the tool in a distributed design environment with usage of a common file format (CPACS) allows an efficient analysis of new technologies.

1 INTRODUCTION

Aircraft design incorporates all activities from initial layout sketches up to detailed manufacturing drawings. The viability of new aircraft concepts is analyzed in conceptual and preliminary design. In this stage simple design methods are used for the estimation of aircraft performance and comparison to reference types. At this stage the benefit of a new technology needs to be identified in order to receive a go-ahead. The benefit can be defined differently: classically it can be a reduced aircraft mass or fuel burn advantage. More sophisticated methods include life cycle cost and estimate the benefit in terms of increased net-present value [17].

The successful assessment of any technology requires accurate modeling. If the beneficial characteristics cannot be modeled in early design stages, the benefit cannot be analyzed. A simple example is a technology that reduces the mass of a component, for example a lighter passenger seat. The reduced mass of the passenger seats can be translated into lower fuel burn and less charges. Many new technologies have less obvious advantages as they may increase the overall aircraft mass, but reduce secondary energy consumption during flight.

The cabin includes many different components that may offer potential for mass or power savings, for example in monuments, linings and overhead bins. Some cabin design decisions involve different disciplines: larger overhead bins may reduce the turnaround time through accelerated carry-on stowage during the boarding process. The added mass of such bins is compensated by quicker and less costly turnarounds. Analysis of such design decisions requires a much more detailed modeling of the cabin in conceptual design.

1.1 Motivation

The motivation for the described tool is to include as many design decisions as practicably possible into aircraft preliminary design. At the same time the creation of a cabin needs to be simple and highly automated, with the possibility of creating a large number of different designs within a short time frame. The output needs to be used as input for other tools within a distributed design environment and as basis for more advanced models. For that purpose the key characteristics need to be stored in the common file format CPACS (Common Parametric Aircraft Configuration Schema) [6] [7]. Cabin and fuselage design often enjoys rather rudimentary attention in academic-level preliminary aircraft design. Thus, many innovations emerging from industry cannot be analyzed in a conceptual aircraft environment. Further, current aircraft are used by operators with very diverse business models. The business model is reflected in the cabin layout, average load factor and average stage length. For a holistic analysis of a technology in a preliminary design environment the particularities of different airline business models need to be captured. A further intention is the close connection of cabin and fuselage design, in both directions. That is, designing the fuselage “inside-out” by defining a cabin, or receiving a cabin from a given fuselage external shape.

1.2 State of the Art

Cabin and fuselage design is usually the starting point of an aircraft design process. Many parameters in cabin design are determined by regulations such as certification standards (number of exits), comfort standards based on human engineering (seat pitch, number of lavatories) and knowledge-based solutions based on experience (monument location). Design textbooks commonly used for aircraft design do mention standards for cabin layout [9] [10]. More recent design guidance can only be found through expert consultation or observation of current designs.

Design frameworks used in academia and research are largely based on these textbooks and common design practices. In most frameworks the cabin design is the starting point for the design. The detail level is restricted. Most masses are determined with regression formulas, sometimes based on outdated databases.

Detailed cabin design can be accomplished using established solutions such as Pacelab Cabin [11]. However, Pacelab Cabin is less well suited as design solution in a conceptual aircraft environment. It does not support a fully automatic cabin layout.

2 BASIC CABIN DESIGN PROCESS

The basic cabin design process creates the cabin and the surrounding fuselage. It has several different work modes, one is shown in figure 1. Many design decisions can only be partly automated, such as the choice of a suitable cross section or the best door arrangement. The design process is iterative and allows to quickly generate a basic cabin layout from basic set of input parameters. The design can then be refined by defining an increasing number of parameters. The structure of the tool allows to define details such as the galley locations and cargo hold limits. However, a basic cabin and fuselage model can be created with no more than a defined number of passengers.

The iteration can be automated. Due to quick processing time of less than 10 seconds for a single aisle and less than 30 for large widebody, the iteration can be performed with the user in the loop. If few parameters are defined, the missing parameters are generated using knowledge-based design rules derived from existing aircraft. These can be overruled by the user by defining parameters. For example, start and end of the cabin are derived from the length of the fuselage. They can be overruled, but are limited to the physically acceptable limit. This allows to closely model existing aircraft down to the positions of the individual frames.

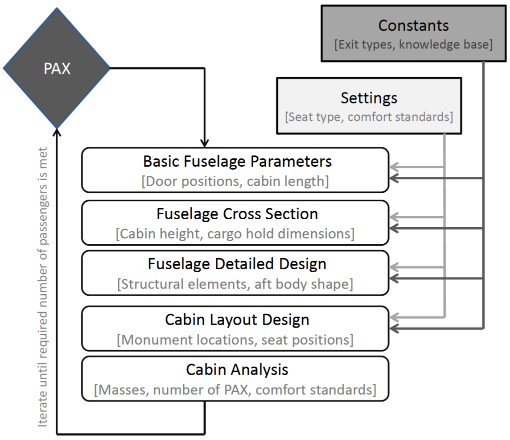
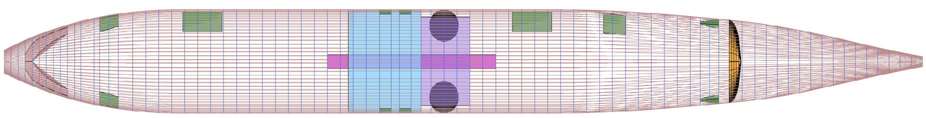
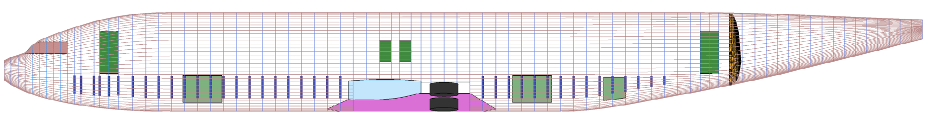


Figure 1: Process chart of the basic cabin and fuselage design.

If the design is started with a target passenger capacity, the most suitable seat abreast configuration is chosen from a statistic. The fuselage diameter is set accordingly. Emergency exits are placed along the fuselage. The tool creates a fuselage contour and derives the location and size of many structural components. The fuselage contour further allows to determine the cabin in the non-constant section of the fuselage. Several parameters allow the user to adapt the rear and front fuselage if he wishes to do so. Figure 2 shows the preliminary arrangement of structural elements of the fuselage.



(a) Top View



(b) Side View

Figure 2: General structural arrangement of the fuselage. Note the doors and the center section with wing box and keel beam.

The frame-wise cabin contour is used for the creation of a cabin layout. Actual tapering of the fuselage is considered for monument and seat placement. This may lead to unusual solutions at the forward and rear end of the cabin. In figure 3 a 150-seat twin aisle is shown, a very unusual cabin with large proportions being in the non-constant section. The monument locations are based on knowledge patterns and often leave room for improvement. However, thanks to a number of internal check procedures the process demonstrates a high stability.

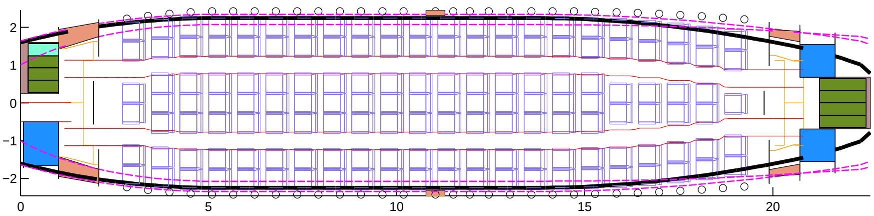
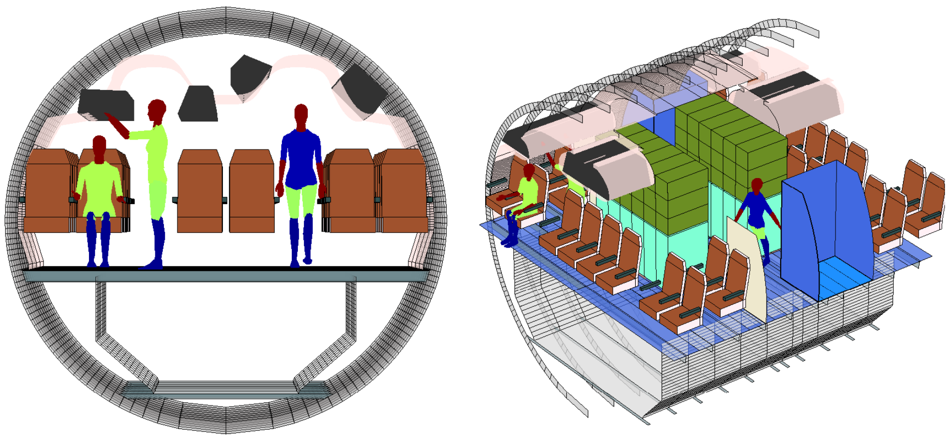


Figure 3: Layout of Passenger Accommodation (LOPA) of a 150-seat twin aisle.

Besides the seat and monument locations the tool also develops a preliminary lining contour. This is necessary for determination of the lining mass and estimation of the volume for carry-on luggage. The lining contours use a number of basic parameters and adapt to the cabin. Although the lining contour only approximates actual designs, it offers a better understanding of the overhead bin situation and also delivers a more appealing visual impression of the cabin. The data allows a 3D-representation of the cabin as shown in figure 4.



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(a) Front View

(b) Monuments

Figure 4: 3D view of cross section with overhead bins, seats and monuments. Note that left cross section has pivoting overhead bins.

The cargo hold is also determined in size and shape. If possible the contour is adapted to match current container types. Boundaries of the cargo hold are set in accordance to modern standards and leave room for the placement of systems like the environmental control system and avionics. The arrangement of containers is shown in figure 5.

3 INTEGRATION INTO AIRCRAFT DESIGN

In the aircraft design process the wings, tail surfaces and engines are matched to a defined mission range and other performance requirements. The fuselage general layout does not change

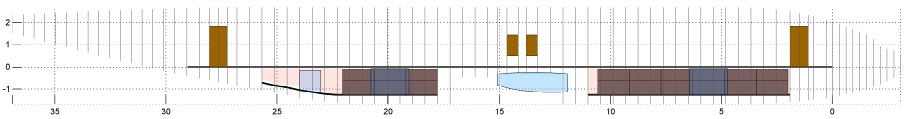


Figure 5: Cargo hold arrangement with unit load devices (ULD). Note bulk cargo compartment in the rear fuselage.

during the design process. The cabin and fuselage design delivers geometric parameters and masses for the subsequent design process. Fuselage mass estimation is done with a semi-empirical approach initially developed by NASA [3]. It is enhanced by calculation component-specific masses for the floor structure, bulkheads, center fuselage and doors using different methods and sometimes unitary masses. All methods are calibrated with current technology aircraft. The method is comparable to that used in industry applications [4]. The calculation of component masses allows the usage of technology factors for certain components and delivers the fuselage mass in a better dependence to design decisions. In figure 6 the used method is compared to two established mass estimation methods, namely the LTH method and the Howe method [1] [2].

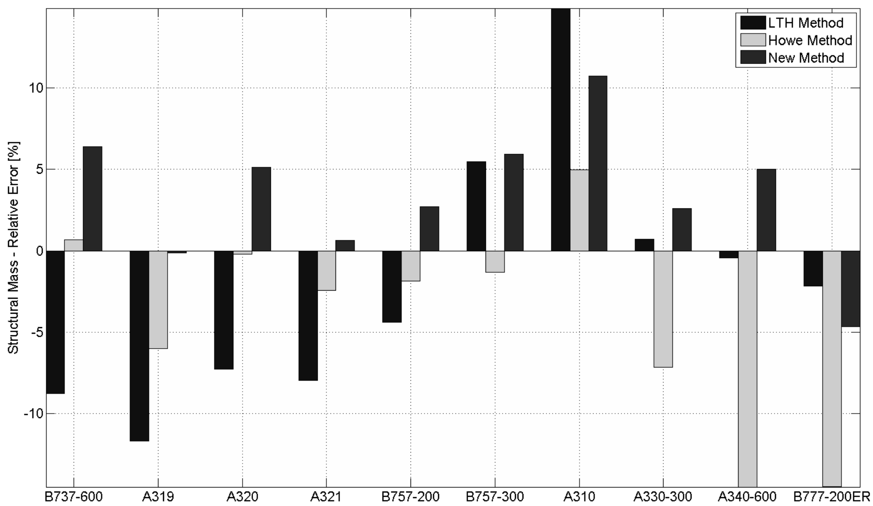


Figure 6: Comparison of different fuselage mass estimation methods. Shown is the relative deviation from the actual mass. The used method in the tool is called “New Method”, LTH and Howe Method refer to statistical methods.

Besides the structural mass, secondary masses are equally important as they contribute roughly the same mass to overall empty mass. These secondary masses are furnishings like the overhead bins, trim panels, cargo hold lining and cabin installations. Also included are the Operator’s Items with galleys and seats being the main contributors. These masses are strongly influenced by airline cabin layout. The tool uses a variety of methods for mass estimation. Most are of statistical nature, while some components can be determined using specific masses and component size. The detailed 3-dimensional cabin layout delivers enough data for an advanced estimation, for example by calculating the total surface of the cabin lining. The masses are further influenced by the cabin layout. In figure 7 the masses are shown for five different designs with 240 passengers each. As can be seen, the different number of aisles and changing fuselage length results in a substantial difference in fuselage secondary masses. Influential factors are cross section parameters such as the size of the overhead bins, but also the length of the cargo hold.

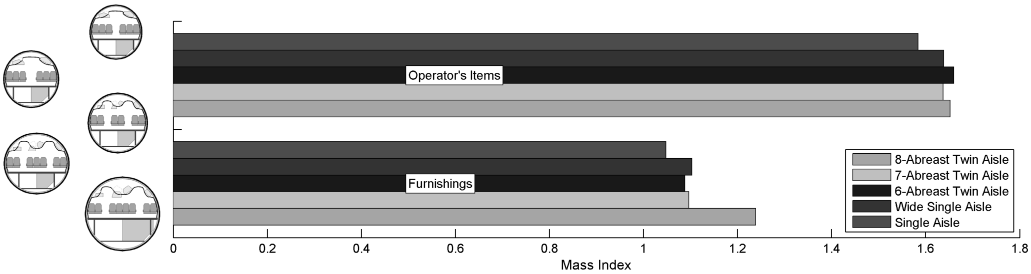
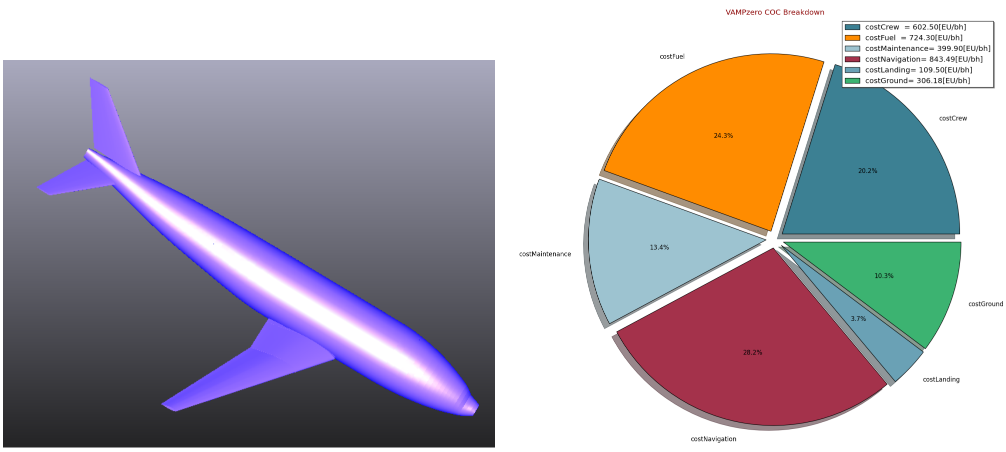


Figure 7: Fuselage secondary masses for different fuselage cross sections.

Aircraft design is performed either with VAMPzero as simple and fast conceptual design tool or a more sophisticated aircraft design framework [8] [5]. VAMPzero can be nested directly inside a loop, while usage of the framework requires establishing a design project in the integration environment RCE. The data is transferred using the CPACS data standard. CPACS is a file in XML format. CPACS is used by an increasing number of tools. It contains many parameters including masses and complete external contours. The TIGL-viewer can be used to visualize the design in a simple fashion. In figure 3 the TIGL-viewer representation of the output is shown to the left, while the result after usage of VAMPzero is shown to the right. The CPACS file extracted from VAMPzero contains preliminary masses for all components, flight performance and cost figures.



(a) Aircraft View

(b) Cash Operating Cost

Figure 8: Result of sizing with VAMPzero. VAMPzero estimates all necessary components and delivers masses and cost of a reference mission, allowing the direct assessment of fuselage design decisions.

4 ADVANCED ANALYSIS FEATURES

Cabin and fuselage design and optimization is the field of many engineering disciplines. Structural analysis is performed to estimate structural mass and crash behavior. CFD simulations are run for the estimation of cabin airflow. Operational analysis of airport processes is performed for turnaround time estimation. One objective of the tool is to provide a common model to these advanced applications. Figure 9 shows the available interfaces. A number of tools from other entities are connected via the CPACS data format. It allows a storage of most of the cabin design information relevant to other tools. Vice versa, CPACS fuselage geometry can be used in the tool for cabin generation.

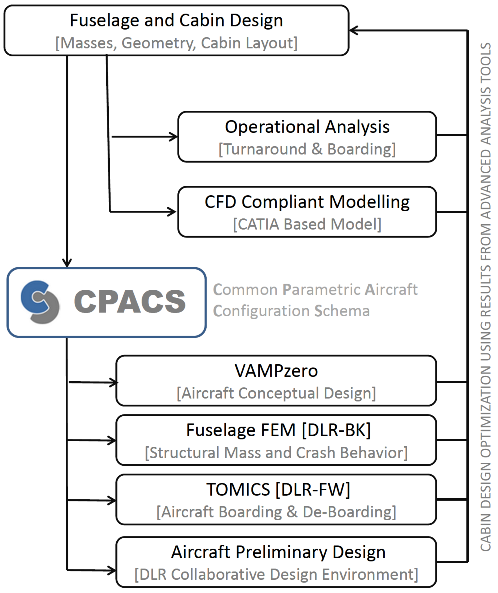
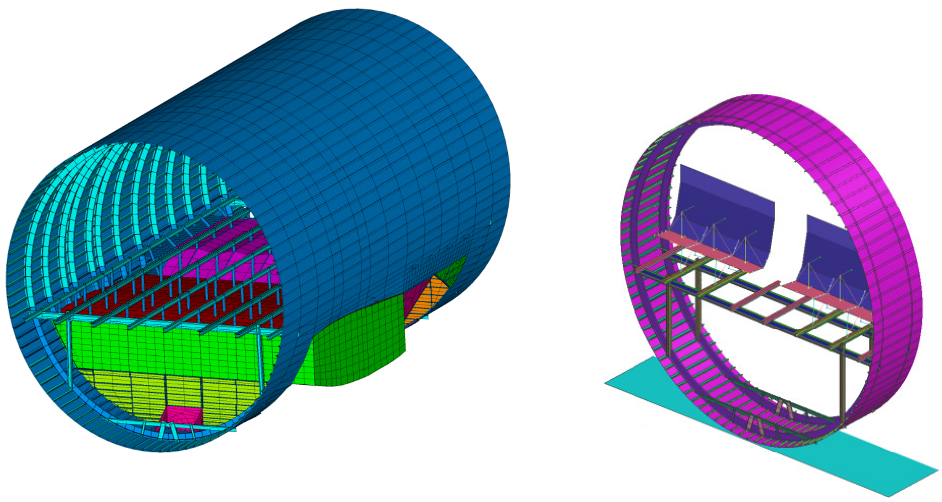


Figure 9: Advanced analysis options emerging from fuselage and cabin design.

Finite element modeling allows a deeper investigation of the fuselage structural properties. Via the CPACS data format such methods can be fed. Both the general structural layout and the secondary masses are imported into the finite element model. This application is in development at the DLR institute for Structures and Design. An intended application in near future is mass analysis. A center fuselage finite element model can be seen in figure 10. An established application is crash analysis. The fuselage model delivers the basic geometry for the crash simulation. A number of inputs have to be added as they are not generated in the preliminary design process [12]. Of course, a high fidelity crash analysis is beyond the scope of preliminary aircraft design. However, future configurations may require a closer investigation of this issue before work can be continued. The ability of the tool to closely resemble existing designs allows to extent the input delivered to advanced analysis methods.

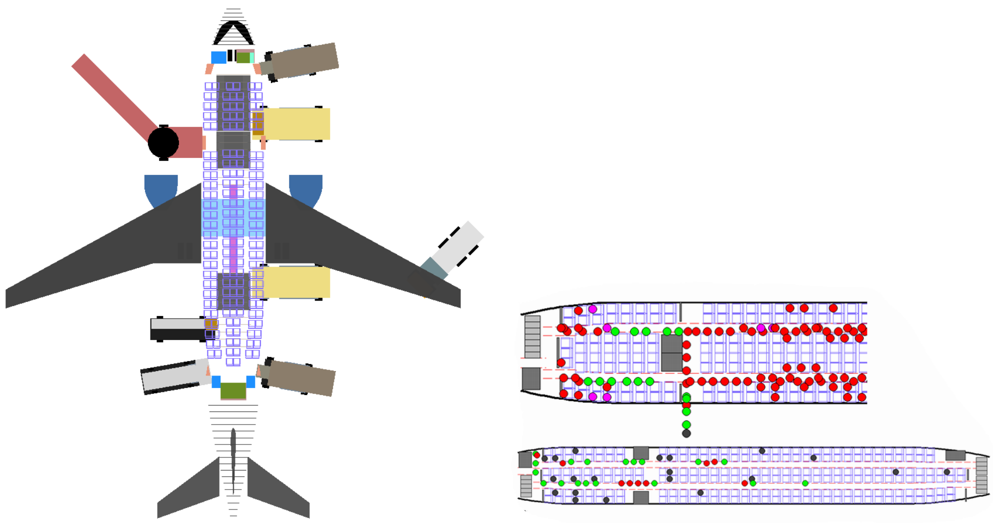
Airport compatibility is a major driver for fuselage layout. Easy unobstructed access to all doors needs to be granted. Further, the design of the cabin can have strong influence on the passenger boarding and de-boarding time, thus the turnaround time in general [13] [14]. The data generated during the cabin design can be used both for a local boarding simulation and the more sophisticated passenger flow simulation TOMICS. The latter is again connected via CPACS. With a wing area and plan form returned from VAMPzero, the position of turnaround vehicles can be analyzed and door locations can be adjusted if necessary. An example is shown in figure 11 for a rather short aircraft with door in front of the wing. A boarding simulation screen shot is shown to the right. The boarding simulation includes the size of the overhead



(a) Top View (b) Side View

Figure 10: Examples for finite-element analysis of the fuselage using CPACS as basic input. Especially the crash simulation does require a substantial amount of additional design information, and can only partly be fed by the fuselage design tool.

bins into the estimation of carry-on stowage times, hence makes use of the 3D cabin geometry.



(a) Vehicle Accessibility (b) Boarding Simulation

Figure 11: Turnaround analysis. Left the vehicle accessibility can be assessed. Right a boarding simulation is performed using the geometrical data of the cabin.

The analysis of cabin air flow is a very specialized application and less important for preliminary aircraft design. The tool allows to create a CATIA model using CATIA Visual Basic Script. The model is designed to be “watertight”. That is, the model can be used in a meshing tool and generate an input for a CFD simulation. Although successful CFD simulation requires much more than just a watertight model, the modeling is one of the more time-consuming process steps. A possible tool chain was described in [15]. In figure 12 two screen shots of the resulting CAD-model are shown.

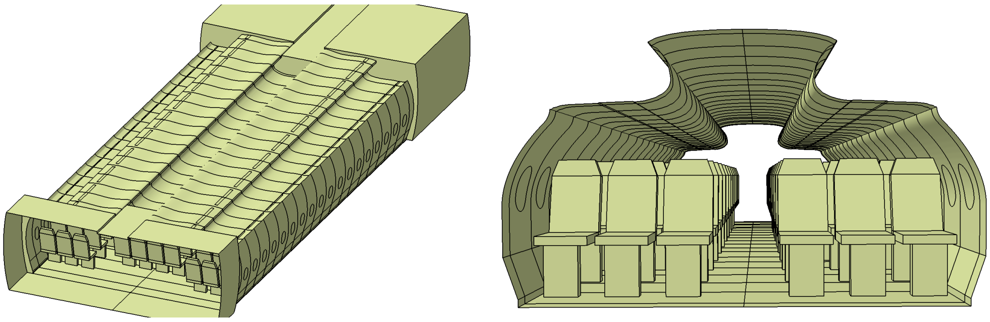
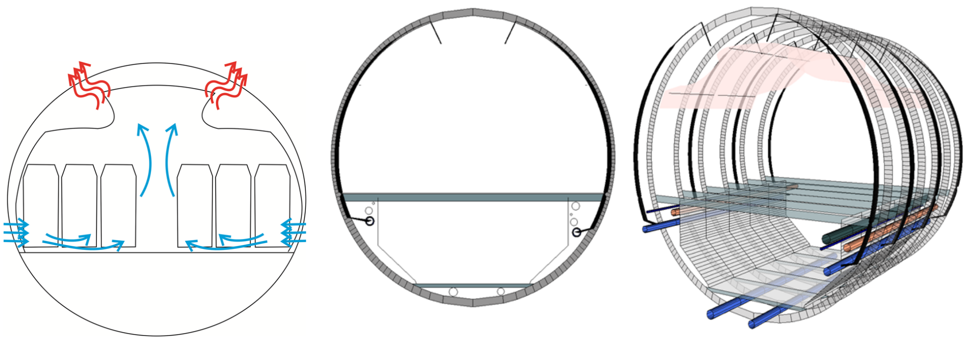


Figure 12: Screenshot of CATIA model for meshing. The geometry is watertight and allows direct meshing with little additional effort. Pictured is a part of an A380 cabin on the left, and a single aisle cabin on the right.

A future application will involve the integration of environmental control system components into the fuselage model. Displacement ventilation offers benefits in terms of passenger comfort and energy consumption [18]. The tool will be used for the analysis of changing system layout. Primary objective is the identification of potential mass benefits and integration challenges . In figure 13 the general concept is provided. Next to it is an example how the tool can be used for the analysis of ducting of various systems. The system uses a algorithm for collision avoidance and allows to consider different temperature zones and component locations [16].



(a) Ventilation Concept

(b) Duct Location

Figure 13: Concept of displacement ventilation and system ducting in fuselage section.

5 CONCLUSION AND OUTLOOK

The paper described an integrated tool for cabin and fuselage design in conceptual and preliminary aircraft design. Primary objective is the assessment of cabin design decisions early in the process. The tool enables usage of higher fidelity methods out of a preliminary design project. The usage of the data standards CPACS eases connection to other tools. It further enables the integration of the tool into a distributed design environment. Further development is planned, for example integration of cabin system aspects.

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