Rethinking the aircraft design process using a cabin-centric development approach

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Abstract

The design of passenger aircraft is inevitably linked to the design of the cabin. However, the cabin design typically takes place late in the aircraft development process. Therefore, it is subject to constraints from earlier design phases and the integration of new cabin systems and technologies is impeded. To enhance innovations among cabin design and passenger experience, a cabin-centric design approach is proposed, which makes cabin design a starting point of the overall aircraft design process. This study explores how the combination of knowledge-based engineering (KBE) and parametric-associative modeling can support cabin-centric aircraft design workflows. An extensible workflow was developed, which allows to generate fuselage geometry models based on novel 3D cabin designs.

Keywords

Aicraft, cabin design, KBE, parametric-associative design

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1. Motivation

The design of passenger aircraft is inevitably linked to the design of the cabin. Being among the few options for differentiation in a highly competitive market, cabin design is one of the main factors for commercial success [1]. As the main interface between an airline and passenger, the cabin environment contributes massively to the overall flight experience. The passenger experience is improved by a well-designed cabin, turning travel from a necessity to an enjoyable experience. A thoroughly planned cabin layout can facilitate more efficient passenger movement and enhance in-flight services. Innovative features such as standing zones, recreational spaces or gastronomical areas can be integrated, which may be particularly beneficial on long-haul flights. While passenger comfort is cruicial, it must be compliant with safety standards set by aviation authorities, such as Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) [2,3]. Seat strength, material flammability, emergency exit location for evacuation, and equipment use are just a few of the numerous factors that need to be covered. Moreover, operational aircraft service is also impacted by cabin design. Effectively planned cabins can shorten turnaround times and expedite boarding through optimal seat layout [4], placement of the monuments, and effective storage solutions – as passengers often feel challenged locating suitable space for their carry-on luggage during the boarding process. A distinctive and ergonomically optimized cabin design enables an airline to develop a unique product that differentiates it from the competitiors. For instance, some airlines are recognized for their luxurious and airy cabin interiors [5]. Additionally, the adaptability of cabin design is important, as it shall respond to changing market trends and passenger preferences [6].

However, the cabin design typically takes place late in the aircraft development process. Fuselage shape is determined in the beginning of the design process and that defines available space and shape for cabin design [7]. Weight and balance parameters, critical for aircraft performance and aerodynamics, are established during the initial design phases. The maximum payload capacity of an aircraft is also limited by its structural strength. Therefore, to be able to manage the complexitiy and uncertainty in this early development stages, cabin is abstracted to mass points. This simplification facilitates preliminary weight estimation and subsequent calculations of the center of gravity. The outcome of the preliminary design provides the input data for detailed design phase of the cabin. Consequently, the detailed design of the cabin must adhere to the pre-established structural sizing. Significant modifications to the fundamental cabin design would necessitate a "preliminary redesign" process, which traditionally involves substantial manual effort [8]. Therefore, cabin design is subject to constraints from earlier design phases and the integration of new cabin systems and technologies is impeded.

In order to facilitate more innovative cabin designs and to enable substantial passenger experience improvements, cabin-centric design approaches need to be developed, which make cabin design a starting point of the overall aircraft design process. Currently, interdependencies related to the cabin are not considered during the initial process stages, which restricts opportunities for customization and full exploitation of innovation potential. The objective is to pursue a user-centric approach by prioritizing the passenger needs, involving them in the development process at an early stage, and shaping the product to meet their requirements from the beginning. However, the current process barely addresses this, leading to significant costs and time-consuming modifications, further slowing down any customization. The industry could produce more specialized and effective aircraft designs by putting the needs of passengers first and incorporating them early into the development process. This strategy may lower expenses and development time while simultaneously increasing operational efficiency and passenger satisfaction.

2. State of the art

2.1 Aircraft design process

Traditionally, aicraft design is a complex, multidisciplinary process, that depends on manual workflows and requires coordination of different departments [9]. The design must guarantee the aircraft's reliability throughout its operational lifespan, as well as its ability to withstand a variety of stresses and loads, accommodate necessary payloads, and maintain a lightweight structure. Furthermore, the design must satisfy economic, safety and performance standards. The process of designing an airplane is usually broken down into the following steps:

- Conceptual design
- Preliminary design
- Detailed design

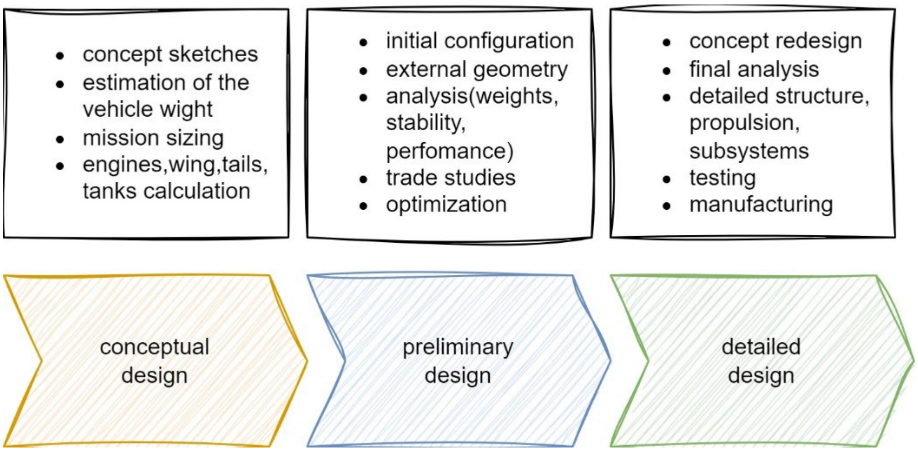

Figure 1: Typical aircraft design process [10]

Figure 1 shows the sequential stages involved in the conventional aircraft design process. Initially, the mission parameters and specifications of the aircraft are established, including factors such as operational range, cruising velocity, payload capacity, and compliance with environmental regulations. Starting with a basic layout of the plane, the designers come up with the first designs and configurations. In this phase general configuration is selected, such as fuselage shape, type of the wings or propulsion system. Resulting designs are subsequently evaluated for feasibility depending on aerodynamic properties, structural integrity and economic efficiency. This evaluation phase typically spans 9-12 months for a mid-size airliner. During the preliminary design phase, a more comprehensive analysis is conducted to refine the initial design concepts. This includes detailed assessments such as aerodynamic analysis, structural analysis, and systems integration. Scaled aicraft models may undergo testing in the wind tunnels to asses and estimate the aerodynamic performance. Contrary to the conceptual design phase, where engineers generally belong to a single team, specialists from multiple disciplines enter the process during the preliminary design. During this phase the approach strongly relies on systems engineering techniques. The preliminary design phase may extend for one year or longer, engaging teams comprising hundreds of engineers operating within a multidisciplinary setup. Once promising aircraft characteristics are identified, the detailed design phase begins. The duration of this development phase typically extends over two to three years. The configuration is frozen early in the detailed design phase, as modifications at this stage require substantial effort and resources [9,11].

Figure 2 shows typical cabin representations at different development stages. Although the cabin is not detailed during the conceptual design phase, it remains a critical component of the aircraft's weight and balance analysis. Assumptions for the essential cabin characteristics allow for determining the aircraft's center of gravity and enable the evaluation of compliance with stability and performance limits.

In the following preliminary design phase, the cabin is represented through space allocations, which involves defining general dimensions and organization of the cabin. This procedure is implemented to establish a basic layout that fulfills the functional requirements and takes constraints into account. Thus, passenger seat areas are established and the allocation for crew members as well as service areas are defined. The cabin layout is integrated in the overall aircraft design. This process necessitates coordination with other primary components, including the fuselage, wings, and propulsion systems. The cabin's space allocations are then iteratively refined and optimized. The models are continuously adjusted based on analysis and feedback from other disciplines.

Figure 2: Cabin representations at different development stages, from left to right: conceptual, preliminary and detailed design phase (modified from [12]).

During the detailed design phase, the cabin is finalized with highly detailed (high fidelity) models. Detailed geometry models for manufacturing and ergonomics analysis are created. The design of local features is now strictly constrained, only allowing for minimal flexibility.

2.2 Computational aircraft design frameworks

Numerous computational framewoks for aircraft design have been developed as a result of the necessity to efficiently investigate airframe design spaces, predominantly following classical methodologies.

One of the earliest developments is PrADO (Preliminary Aicraft Design and Optimization program) [13]. It assists in the design and optimization of aircraft, covering both conceptual and preliminary design phases. PrADO is developed in FORTRAN and contains various analysis modules for tasks such as aerodynamic analysis and structural mass estimation. The program is known for its versatility in handling both conventional and unconventional aircraft designs. Even though the cabin contributing factors are included within typical top-level aircraft requirements (TLARs), only rudimentary cabin layouts are considered.

Munjulury et al. explored the possibilities of extending a design tool named “RAPID” to derive low-fidelity cabin models from the outer mold line. Their extension supports conceptual and preliminary design phases with CAD model generation. Various modules such as the cockpit model, windshield, fairings, winglets, and cabin interior layout can be examined. The cabin layout is configured using a spreadsheet with validation rules, which ensures compliance with certification specifications and comfort standards for large airplanes (CS-25) [14,15].

The work from Motzer demonstrates how highly detailed geometric models of the cabin can be generated in CATIA using a graph-based design language, facilitated by additional software. These models are utilized for routing wires and pipes for electrical and ventilation systems. However, Motzer views cabin design activities as strictly subsequent to the preliminary and structural design processes [16].

The tool "CabLab" by Gobbin starts the design process with a cabin definition and allows to derive structure dimensions, limited to 2D geometry models [17].

A common program for cabin design in the industry is the commercial software "Pacelab ACE". It provides an environment that supports various aspects of aircraft development, including cabin layout and configuration management. For cabin design, Pacelab ACE offers tools for fine-grained configuration of seating arrangements, galleys, lavatories, and other interior elements, taking safety regulations into account [18].

The tool MICADO (Multidisciplinary Integrated Conceptual Aircraft Design and Optimization environment) is an academic development focused on the preliminary design and optimization of aircraft. The cabin interior is considered but no further description of the fidelity level and flexibility of the cabin models is provided [19].

While there are various sophisticated examples for automating some aspects of the aircraft design process, none of them start with a detailed cabin design and allow to create complete aircraft models based on that.

In the following, a possible setup of a cabin-centric aircraft design workflow is explored, which allows for an investigation of interdependencies of different disciplines and which can be implemented efficiently.

Research question:

How could a cabin-centric aircraft design workflow look like in detail? How could it be implemented efficiently to allow for the participation of all systems experts and an early connection of all disciplines to explore interdependencies?

3. Concept and implementation

As a basis for efficient execution of design activities, knowledge-based engineering (KBE) is an established practice. KBE represents an approach to accelerate engineering and coordination activities through automation of manual and repetitive design tasks [20]. A definition of automatically executable design rules allows for an efficient creation of designs and models. Commonly, the generation of adaptable yet detailed geometry models has been a challenging task within mainly code-based KBE rule development environments. An integration of parametric-associative design approaches [21] can alleviate that problem and render the automatic generation of high-fidelity geometry models feasible, as shown in a previous study [22]. Parameterizable CAD models can now flexibly be integrated in form of special knowledge rules and the underlying CAD models can dynamically be parameterized during rule execution. The study at hand now investigates how KBE and its combination with parametric-associative modeling can support cabin-centric aircraft design workflows.

As indicated in the Chapter 2, traditional aircraft design starts with designing an outer fuselage shape and focuses primarily on optimizing aerodynamics, propulsion, and structural integrity. The newly developed workflow establishes detailed cabin design during the conceptual or preliminary design phases.

Within this study, in order to explore the potential of a knowledge-based engineering framework in facilitating a cabin-centric design workflow, a conceptual model was developed. The cabin is considered the starting point of the aircraft design process. After definition of the cabin model, it allows for to generate fuselage geometry based on given 3D cabin designs, which is shown in Figure 4. The concept was evaluated on an unconventional cabin design and allows for a generation of different fuselage shapes.

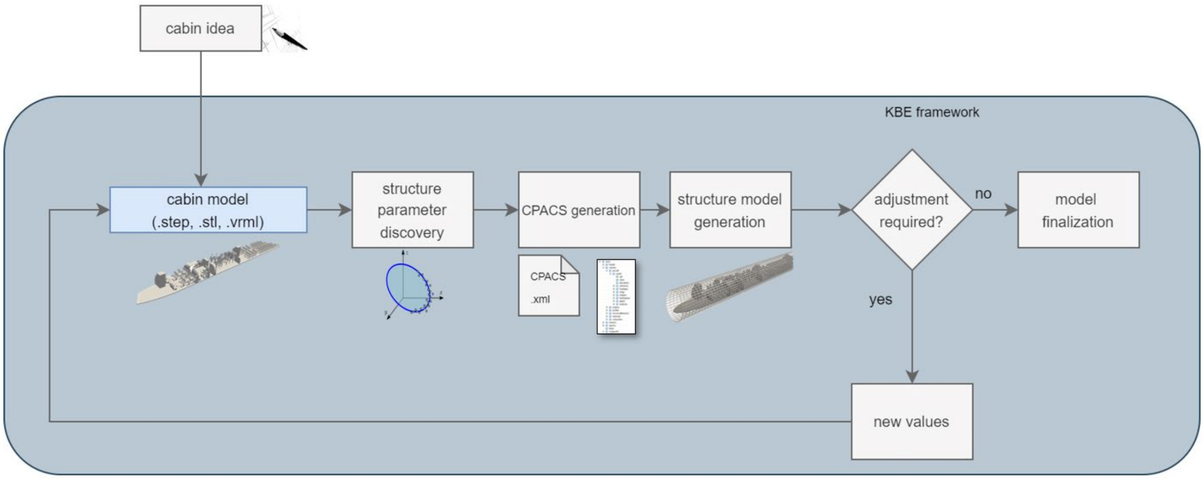

Figure 4: Concept of a cabin-centric design workflow

The DLR-developed, Python-based KBE framework *Fuselage Geometry Assembler* (FUGA) was used to implement corresponding knowledge rules [23]. FUGA is a recent implementation of a KBE-System, designed for the automated creation of structural and cabin models across different aircraft designs. As as the central product data model serves the Common Parametric Aircraft Configuration Schema (CPACS), utilizing a structured, XML-based description language specifically designed for aircraft, including airplanes and helicopters [24]. By dynamically generating various models in FUGA using CPACS as the central data source, consistency is maintained across the models employed for different analyses. The dynamic generation of geometry models is achieved using Open Cascade Technology (OCCT) [25,26]. By specifying the necessary input information for knowledge rules, dependencies between these rules can be established, enabling the creation of complex knowledge graphs. A recent implementation of integrating parameterized CAD-models allows for creating of high-fidelity geometry, such as cabin and fuselage models [22].

As input, a parameterized cabin layout or an imported model in common .step or .stl formats can be utilized. Based on a given 3D geometry cabin model, the shape of the fuselage is derived by segment-wise projection and determination of area-minimal hull curve function parameters. The derived parameters are used for automatic parameterization and placement of parameterizable fuselage structure models.

Upon completion of the aircraft model structure, a feedback loop can be initiated to assess the design's performance and suitability. The feedback obtained through a variety of analyses, such as computational simulations, stress tests or aerodynamics evaluation, is then analyzed to determine if the current aircraft model structure meets the intended performance criteria and safety standards. If adjustments are required, the structural model is refined iteratively. After each iteration, the updated model is re-evaluated using the same feedback mechanisms to assess the impact of the changes. If the model satisfies all criteria, the optimization loop is exited, and the aircraft model is finalized. The derived outer shape is described in CPACS, which then provides input parameters for the generation of 3D fuselage models. Complex part models e.g. for frames and stringers are automatically generated using parametric-associative base models developed with the CAD software FreeCAD.

Figure 5 shows a possible futuristic cabin design developed at DLR which includes tables, standing seat area and unusual, train-like seat placement. The configuration dimension of this layout is comparable to an Airbus A320 aircraft cabin, featuring a six-abreast seating arrangement in economy class with a single aisle.

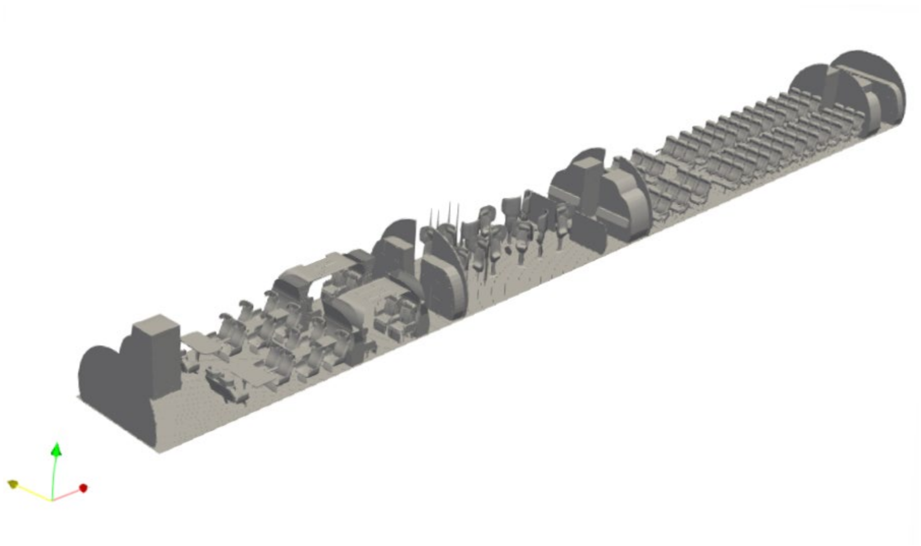

Figure 5: Example of a novel cabin design developed at DLR

To demonstrate the adaptability of the approach, the layout was altered as illustrated in the Figure 6 - modifications include the addition of side seats around the tables, an extra row of standing seats, and supplementary seats extending the configuration to an eigth-abreast arrangement.

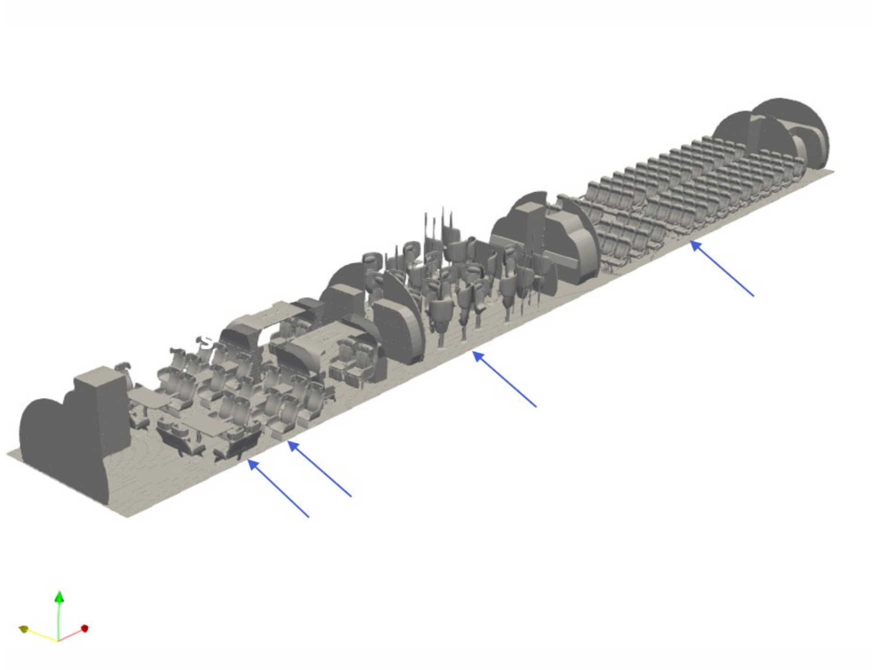

Figure 6: Modified novel cabin design

Figure 7 illustrates the aircraft model that was automatically generated by the described method. Frames, stringers and outer shape were generated around the geometry of the cabin. The resulting CAD models can be exported in different standard exchange formats, such as .step, .stl, or .vrml, facilitating their use in subsequent processes, including finite element method (FEM) or aerodynamic analyses.

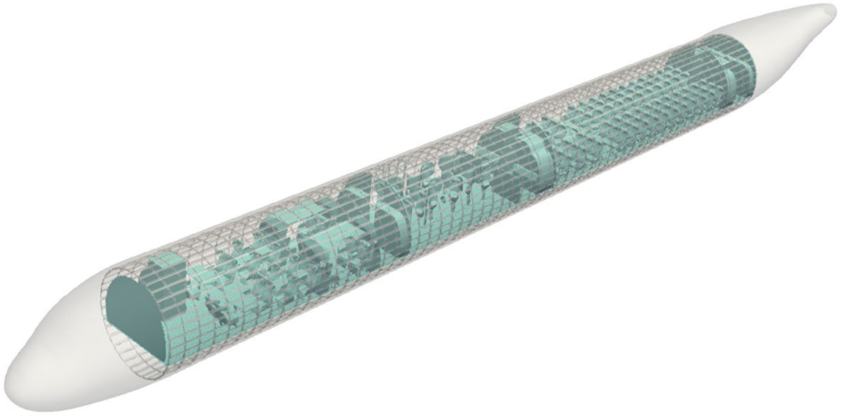

Figure 7: Dynamically generated structural model for a novel cabin design

As shown in figure 8, changes of the cabin model are reflected by corresponding changes of the generated surrounding structure.

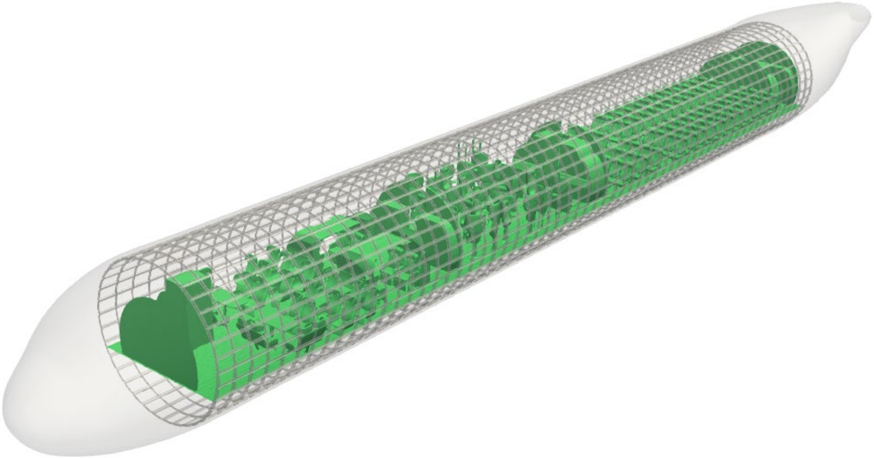

Figure 8: Dynamically generated structural model for a modified novel cabin design

Figure 9 illustrates the accuracy level in the generated structural model which was achieved based on parametric associative base models.

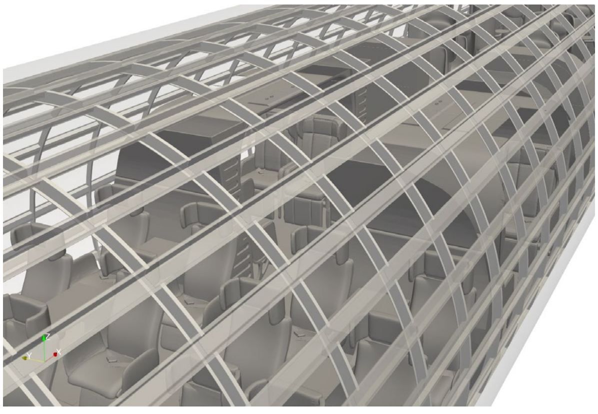

Figure 9: Highly detailed structural and cabin design models

4. Conclusion and outlook

In this study, a cabin-centric, knowledge-based aircraft design approach was developed and validated with unconventional cabin design concepts. The defined knowledge rules allow for an automated creation of realistic fuselage models solely from given 3D cabin designs.

This way, the creation of complete early-phase aircraft designs based on new cabin concepts could be significantly accelerated. At the same time, the increased fidelity level allows for an early identification of potential problems and a realistic assessment of novel concepts.

Further work is required to automatically evaluate the generated fuselage models and to check for optimization potentials – e.g. concerning aerodynamic properties – as shown in Figure 10. The DLR-developed “OpenAD” (Open Aircraft Design) software can be employed to enhance the aircraft's overall design. This program is specifically designed to develop external shapes that are aerodynamically efficient and to optimize wings and propulsion systems [27].

Subsequently, necessary fuselage adjustments need to propagate back to the cabin model to enable an iterative, global optimization of the aircraft [28]. This also requires parameterizable cabin models as well as corresponding cabin evaluation functions.

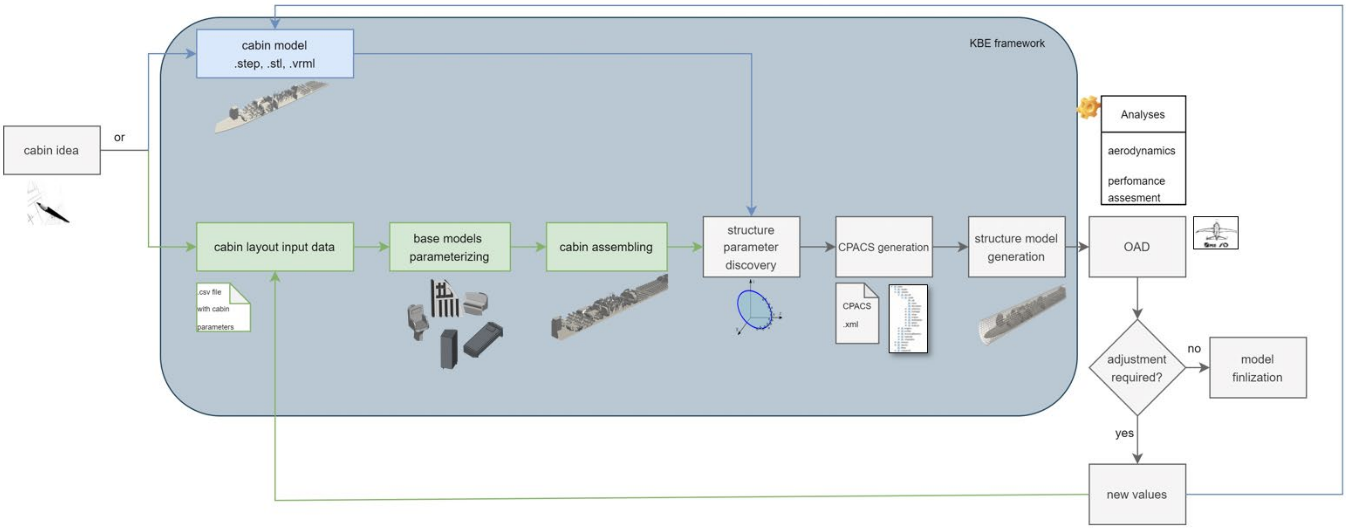

Figure 10: Outlook for the concept of a cabin-centric design workflow with parameterizable cabin layout

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