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Knowledge-based engineering methods for hydrogen tank and system integration in aircraft fuselage design

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Abstract

Integrating new technologies such as liquid hydrogen as an energy carrier is a key step toward climate-neutral and sustainable aviation. Current research mainly focuses on integrating cryogenic hydrogen tanks in the rear fuselage section. This paper presents an extended knowledge-based engineering (KBE) framework that enables the automated modelling and assessment of hydrogen tank integration concepts in preliminary aircraft design. The framework integrates several stages of the preliminary aircraft design process. Starting with *openAD*, a design synthesizer for determining the aircraft outer mold line and tank positions, followed by the *Fuselage Geometry Assembler* for generating structural, cabin, and cargo geometries as well as the *Systems Architecting Assistant* and *GeneSys* for system sizing and integration. Data exchange between these tools is realized through an *XML*-interface, and geometric consistency is ensured using the Open Cascade Technology library. Parametric data exchange with simulation environments is supported via CAD-exchange formats and the *Common Parametric Aircraft Configuration Schema*. The newly developed methods enhance an existing KBE-based fuselage design system with experimental tank mounts, crash structures, and hydrogen distribution systems. These additions enable a consistent and fully automated generation of structural and system models at the required fidelity level for future disciplinary analyses. The proposed method is demonstrated in a preliminary design study of two liquid-hydrogen-powered aircraft configurations, highlighting the improved automation, consistency, and integration capabilities of the extended KBE framework.

Keywords Knowledge-based engineering · Fuselage structure · System integration · Liquid hydrogen · CPACS

1 Introduction

Climate change and its social, technical and economical challenges have a huge impact on the aeronautical sector. In order to fulfil the rising demands for sustainable and climate neutral aviation in the future, new ultra efficient aircraft configurations including innovative technologies are required. To evaluate the potential of various aircraft concepts in combination with several new technologies, digital methods for modelling and simulating on aircraft level including all relevant aircraft properties are needed. Getting a precise assessment of new approaches and reducing the development time to the entry into service for future aircraft requires a digital thread connecting the first conceptual drafts, structure, cabin and system design as well as the final product. This digital thread allows to integrate manufacturing, operation and the whole circular economy in the early stages of the aircraft design process.

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New climate neutral propulsion technologies are a key factor for the success of future aviation. Liquid hydrogen powered aircraft with cryogenic tanks integrated in the fuselage show immense potential for a variety of possible mission profiles in different studies for overall aircraft design (OAD) [1–3]. Integrating novel hydrogen technologies in aviation without existing reference aircraft or empirical values opens up a broad range of design choices. The influence of all these different choices on the overall system has to be evaluated, to obtain the best overall design. Therefore, the expertise and cooperation of many disciplines and their respective experts are key for a successful overall aircraft design process. Especially the integration of cryogenic tanks and connected hydrogen distribution system poses many open questions and technical challenges. Hence, experts for cryogenic materials and hydrogen processing need to be included in future aircraft design processes.

This paper presents a new approach for knowledge-based design and modelling of the rear fuselage section of a liquid hydrogen powered aircraft. The presented methods allow to quickly obtain consistent multi-fidelity models for disciplinary analysis, simulation and optimization. Thus, disciplinary experts are involved in the early stages of the aircraft design process, which helps to improve the integration of components in the overall systems and to utilize possible synergies during the development. The following section section 2 explains the overall aircraft design process and the knowledge-based engineering methods used in the preliminary aircraft design process. Afterwards, the newly developed extensions of the knowledge-based engineering methods for liquid hydrogen tanks and their distribution systems installed in the rear fuselage section are presented in section 3. Finally, the extended methods are used in section 4 to analyse and compare two promising research concepts for hydrogen powered short/medium range aircraft.

2 Knowledge-based engineering methods in preliminary aircraft design

This section explains the already established methods for preliminary aircraft design until the overall system design level, which are the foundation for new extended methods developed to model the rear fuselage described in the following section. Starting with the overall aircraft design based on the top-level aircraft requirements, described in section 2.1, an initial design for the aircraft structure and cabin is generated with the methods presented in section 2.2. Finally, section 2.3 presents a system design process to obtain a preliminary layout of aircraft systems based on the structural and cabin information.

2.1 Overall aircraft design methodology

During the preliminary overall aircraft design, the outer mold line of the aircraft as well as the estimated masses and performance properties for the aircraft including its structure and on-board systems (OBS) are calculated to fulfil the top-level aircraft requirements and mission profiles. This can be done using a design synthesizer, based on statistical data and handbook methods such as *MICADO* [4], and by incorporating simple physics-based calculations such as *Tango* [5], the *Initiator* [6] or *FAST-OAD-GA* [7]. Iterative calculations of mass, range, and aerodynamic properties are performed until a converged aircraft design is obtained. For this work, the overall aircraft design was performed using the *openAD* framework [8], which relies on publicly available handbook methods and supporting analytical functions. The results are saved in the *XML*-based *Common Parametric Aircraft Configuration Schema* (*CPACS*) [9, 10]. *CPACS* is an established exchange format for preliminary aircraft design, which is focused on describing the outer mold line and mission trajectories of aircraft as well as structural [11] and cabin information [12] in a unambiguous way. Using the *CPACS* format, physics-based models can be incorporated into higher-fidelity design loops within *openAD*, allowing iterative refinement of aerodynamic, structural, and propulsion characteristics while maintaining consistency across all subsystems.

2.2 Rule-based modelling of structure and cabin layout

The early stages of aircraft design require not only sizing and aerodynamic estimations but also an initial definition of fuselage structure and cabin layout to enable multidisciplinary analyses and assess the feasibility of system and component integration. knowledge-based engineering (KBE) tools have emerged as an effective means to automate and standardize these processes, providing consistent, traceable, and multi-fidelity models while reducing manual modelling effort. Overall aircraft design information, as described in the pevious subsection, are imported via a central data interface into the KBE applications. Modular and integrated software frameworks such as the *Design and Engineering Engine* (*DEE*) link the overall aircraft design capabilities of the *Initiator* with the *Multi Model Generator* (*MMG*), which provides aircraft designers with a parametric modelling environment [6]. Conventional and novel unorthodox aircraft configurations can be modelled using combinations of high level primitives, representing fuselage, wing and engine components, to derive dedicated geometry and analysis models for various disciplinary analysis tools. The *Conceptual Aircraft Design Laboratory* (*CADLab*) framework enables a seamless integration of CAD data into the preliminary aircraft design process with *Tango* using a central *XML* database. Within the framework, the *Robust aircraft parametric interactive design* (*RAPID*) approach employs knowledge patterns to automatically generate fully parametric geometric models in the commercial CAD system *CATIA* [5].

In this work, the preliminary *CPACS* design data, described in section 2.1, serve as the input for the Python-based *Fuselage Geometry Assembler* (*FUGA*), which generates an initial structural and cabin layout. The tool implements an approach based on knowledge-based engineering methods, formalized techniques, rules, and computational strategies used within the KBE methodology, to generate consistent multi-fidelity models for disciplinary analyses in the preliminary aircraft design domain. This approach combines two different concepts during the model generation. The first concept, hereafter referred to as knowledge-based design, uses design rules to augment an initial preliminary aircraft design data set with structure and cabin information requiring only a limited set of user input parameters. The second concept, hereafter referred to as knowledge-based modelling, builds multi-fidelity geometries based on the previously designed data to derive suitable simulation and visualization models for static fuselage design [13], cabin virtualization [14, 15] and dynamic vibro-acoustic analysis [16, 17]. A knowledge-based system, as described by La Rocca, requires three core components: a data storage including all required information to describe a product, a knowledge repository containing the knowledge rules on how to build a product and an inference engine, which determines the execution order of the knowledge rules from the repository.

The *CPACS*-format forms the core of the data storage implemented in the *FUGA* tool. Entries in the data storage can contain any *Python* object, allowing storage of CAD geometries based on the *Open Cascade* format (*OCC*) or visualization meshes based on the *Visualization Tool Kit* (*VTK*). All knowledge rules are implemented as *Python* classes inheriting from a common base class. A mandatory evaluation method returns an element of the data storage referenced by a unique label. Additionally, every class maintains a list of required input values, also referenced by their respective labels. A schematic class diagram, following the conventions of the *Unified Modeling Language* (*UML*), of the implemented knowledge rules is shown in Fig. 1. The *compute*-function requires the return value of all *compute*-functions of all classes with their *label*-attribute contained in the *requires*-list as *inputs* and can call class specific *supportingMethods* during its execution to help structuring and make the overall system more modular.

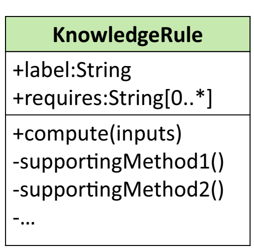


Fig. 1 *UML* class diagram of a knowledge rule implemented in *FUGA*

The inference engine builds a graph-based network connecting all knowledge rules based on their own labels and required input values. The graph network is built with the *Python* package *NetworkX* [18], where the evaluation methods are represented as nodes with their label as outgoing and the list of required input values as incoming connections. The maximum connectivity graph (MCG) contains every knowledge rule in the knowledge repository. Based on the requested structural and cabin information by the user, the required end nodes and all prior nodes form the full problem graph (FPG). All initial nodes without incoming connections have to be filled by input parameters either given by the *CPACS* file from overall aircraft design or problem specific user inputs. If the full problem graph does not contain any cyclic dependencies, then the problem graph is a directed acyclical graph and Kahn's topological sort algorithm is able to generate the problem solution graph (PSG) independently from the number of nodes [19]. The problem solution graph describes an executable sequence for the knowledge rules to obtain all the requested results. Figure 2 shows an exemplary visualization of the three different types of graphs used in the *FUGA* inference engine. In this example, twelve rules labelled *A*–*L* are part of the knowledge repository. The MCG (top left) contains all rules as nodes with their directed connections, representing the complete set of possible dependencies. A user submits a query for the node value of rule *L*, highlighted in orange. The resulting FPG (top right) is derived from the MCG by isolating only those nodes and connections relevant to solving the specific problem defined by the user input. These relevant elements are shown in colour, whereas all others are shown as dashed grey nodes and edges. For a successful problem resolution, the user query must include the input values for all initial nodes–namely, rules *C* and *D*, marked in green. Finally, the PSG, shown in the bottom, contains all nodes of the FPG arranged in an executable sequence required to generate the return value of rule *L*.

An extract of the MCG of *FUGA* is shown by Fig. 3. The graph shows how geometric inputs from the overall aircraft design including fuselage profile curves and wing spars as well as design parameters such as bulkhead positions and the internally calculated exit layout contribute to determining the mainframe positions. These mainframe positions and a parametric frame pitch are then used to compute the remaining frame positions, which serve as key reference locations for subsequent fuselage design and structural layout tasks.

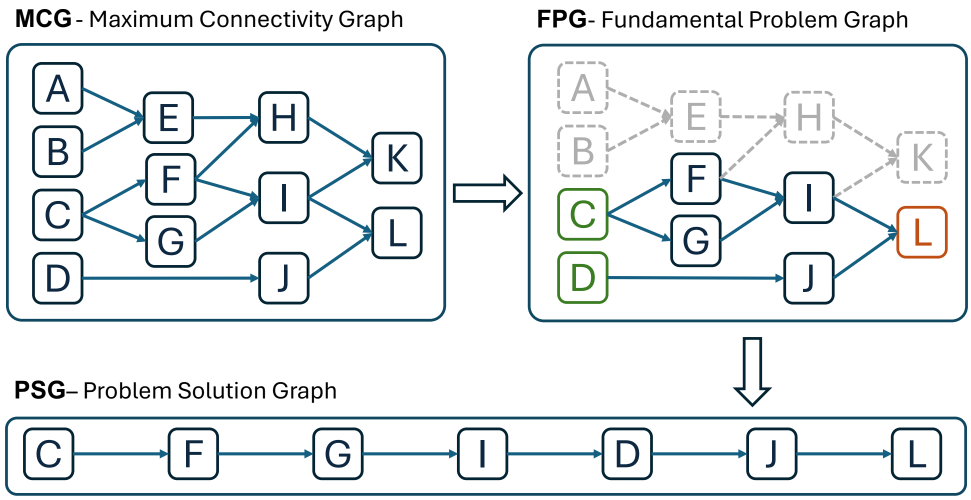


Fig. 2 Visualization of the MCG, FPG, and PSG in the *FUGA* inference engine, showing an exemplary rule sequence generation for the query of rule *L*

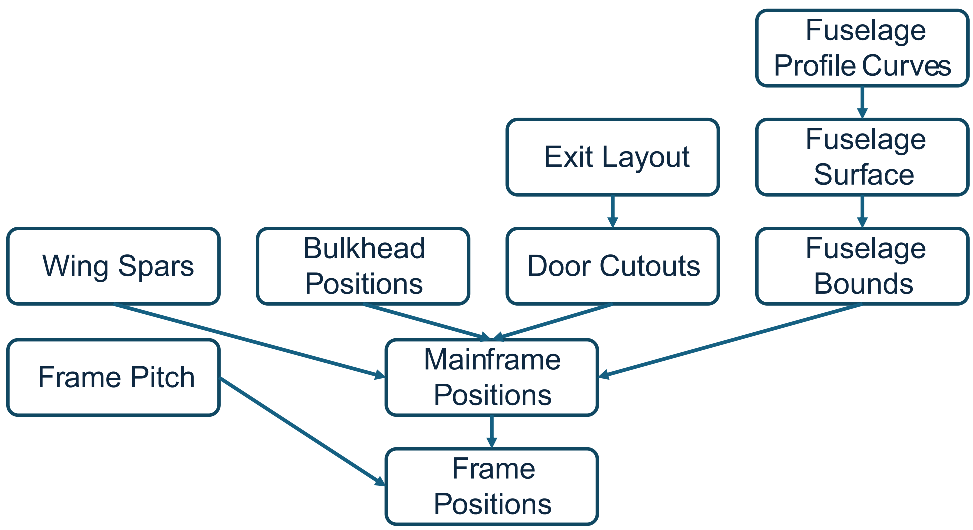


Fig. 3 Extract of the MCG of *FUGA* for the calculation of frame positions

An overview of the complete knowledge system implemented in *FUGA* is shown in Fig. 4. The figure illustrates the core principles of the three main components and the interconnections between them. The system architecture integrates the knowledge repository, the inference engine, and the data interface. The knowledge repository contains domain-specific rules and dependencies in the form of labelled *Python* classes. The inference engine processes user-defined queries by identifying relevant rules by their labels, generating and executing the rule sequence to derive the requested outputs. The data storage component manages all rule input and output values, providing access to *CPACS*-based data as well as meshed and volume-based geometries.

The results of the structural and cabin design process are exported in the *CPACS* format as far as they are supported by the schema definition.

2.3 Overall systems design

Overall Systems Design (OSD) is performed as part of aircraft conceptual design and typically includes different abstraction levels of aircraft, system, and component models [20]. Several approaches have been established in industry and academia to address this complex topic, such as the industry tool *Pacelab SysArc* [21] and the academic tool *ASTRID*, developed by the Politecnico di Torino [22]. The Institute of Aircraft Systems Engineering (FST) at Hamburg University of Technology (TUHH) has also developed its own approach for OSD, which is illustrated in Fig. 5. This OSD framework is categorized into the abstraction levels OAD, systems architecting, OSD, and Detailed Systems Design (DSD).

As part of OSD, concept studies are performed to evaluate the on-board system (OBS) design at relevant levels (e.g., architecture, geometry, design) [23–26]. Promising concepts are then further assessed through system behavior analysis based on transient simulation models. Since this is a

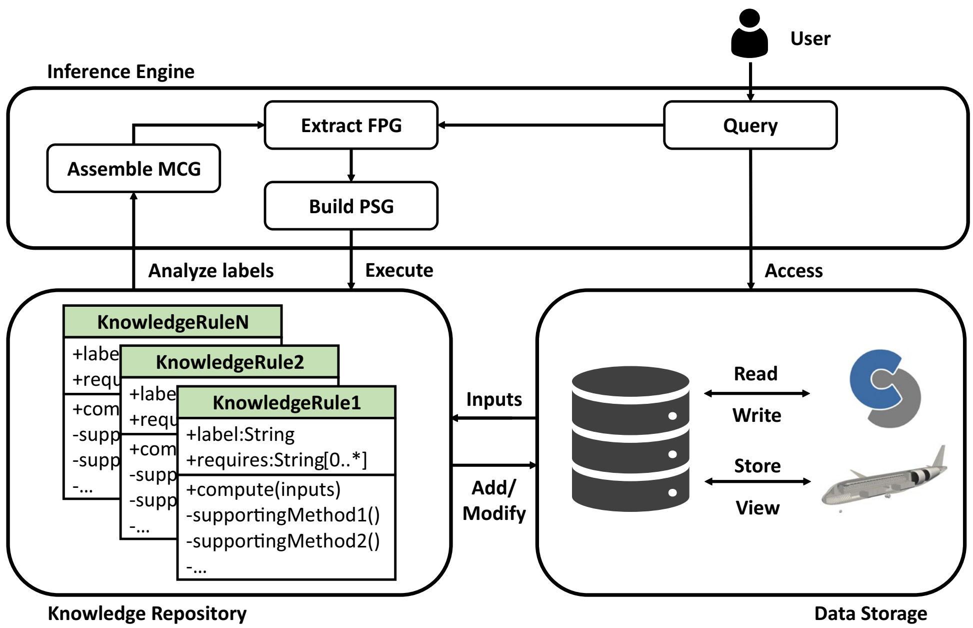


Fig. 4 Overview of the knowledge system implemented in *FUGA*

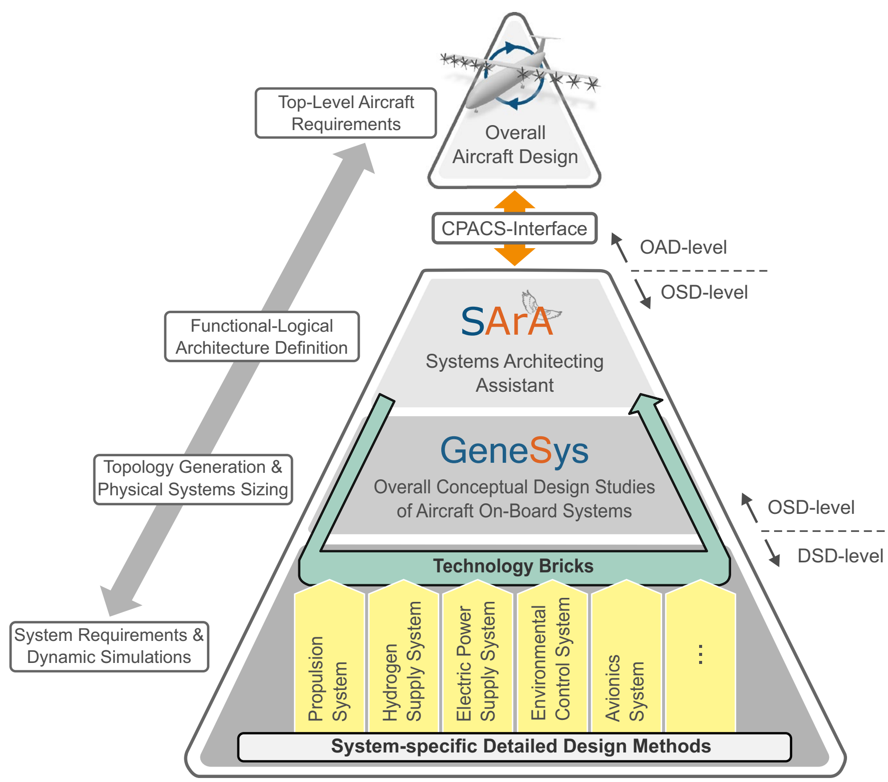


Fig. 5 Framework for overall systems design

time-consuming process, development time can be reduced by performing such rapid concept studies [23]. However, within the scope of this paper, the focus remains on OSD.

As a first step, OAD provides relevant parameters such as aircraft geometry, top-level aircraft requirements (TLARs), and a design mission trajectory [20]. The *CPACS* format is used as an interface [10, 27].

Subsequently, on system level, a functional-logical systems architecture is defined and evaluated using the in-house developed *Systems Architecting Assistant* (*SArA*) [20]. In *SArA*, technologies are selected and the evaluation is based on criteria such as safety, reliability, complexity, and risk [26].

Based on the defined systems architecture and the aircraft geometry from the *CPACS* file, an initial systems topology (the positioning of components and the routing of connections) is generated. The positioning of components follows a knowledge-based approach, while an automated routing method is used for the connections [28]. This method enables the definition of dedicated installation spaces for connections (e.g., cables, pipes) and the specification of boundary conditions for routing, such as segregation requirements, minimum distance constraints, and no-routing areas [28]. Defining no routing areas is particularly relevant for the hydrogen supply system, as hydrogen pipes must not be routed through installation spaces containing electrical equipment [29]. For performing the routing, the predefined routing network is translated into a graph, which can be manipulated to determine shortest paths while accounting for the boundary conditions mentioned above. In this context, cost functions are applied to the connections to virtually increase their length. For instance, when a cost is applied to a connection or to specific areas of the graph representing the routing network, the shortest path algorithm automatically selects an alternative route [28, 29].

With the generated systems topology, a parametric geometry description of the aircraft OBS is obtained. This description is used for the physical sizing of the OBS, using the *GeneSys* software framework, which is also being developed at FST [23, 24]. To design the power supply systems (e.g., electric or hydrogen power supply), a graph-based approach is applied, as shown in Fig. 6. The first step in this approach is to define the power requirements of all power-consuming systems. To this end, the load factor of each consumer system is specified. It is the fraction of, e.g., the nominal power or heat-flow demand that is required to guarantee functionality at the defined load case of the power supply system. If the load case includes inactive system components, for instance to account for a technical-failure scenario, a subgraph is created by discarding inactive nodes and their associated edges (c.f. grayed-out elements in Fig. 6). In a second step, the relevant system parameters are propagated from the consumer systems through the graph toward the power sources. As a result, the connections and power sources are sized while accounting for power losses in both the connections and components [23]. Finally, the initial parametric description of the OBS is updated with the calculated geometries of the components and connections.

3 Knowledge-based rear fuselage design and modelling of liquid hydrogen powered aircraft

This section presents new methods to enhance knowledge-based design and modelling of the rear fuselage section of liquid hydrogen powered aircraft. Furthermore, a new approach to integrate designed hydrogen distribution systems into the complete aircraft model including the structure and cabin is introduced. The structural connection of the hydrogen tanks to the primary aircraft structure as well as the layout of the hydrogen distribution systems is still in an early research and development stage. Therefore, a broad variety of possible variants and combinations of concepts needs to be generated and evaluated. Hence, a flexible tank design and three promising concepts of the structural tank mounts with an adjustable parametric design are developed and a knowledge-based design process for liquid hydrogen distribution systems on overall system design level as well as the integration of the designed systems in the *FUGA* knowledge system containing the whole aircraft data are described. The models are built with a high fidelity level so multidisciplinary simulation and optimization models can be derived to evaluate the tank and system integration in the overall aircraft concept. This includes *CPACS*-based geometries for static sizing of aircraft structures as described by Scherer et al. [11, 30] and CAD-geometries to generate tailored meshes for dynamic crashworthiness simulation as described by Schatrow et al. [31]. In the following the longitudinal axis is described as x-axis, the lateral axis as y-axis and the vertical axis as z-axis. The origin of the coordinate system is placed at the nose of the aircraft.

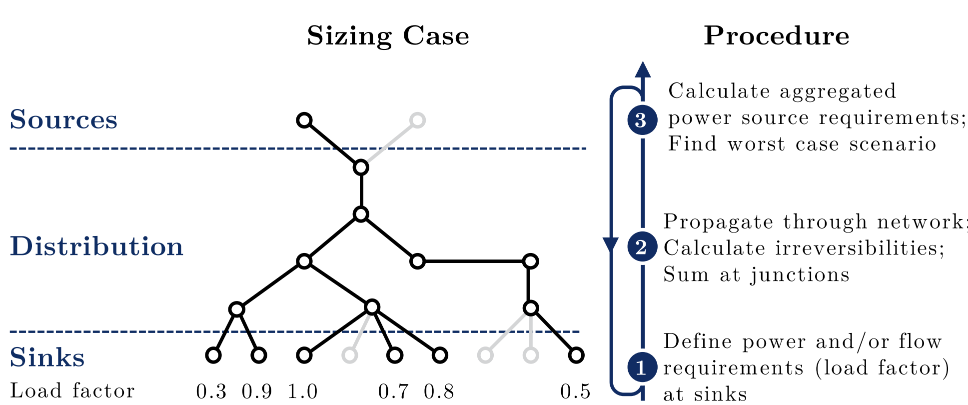


Fig. 6 Graph-based sizing procedure: Power requirements are numerically propagated from power sinks to power sources

3.1 Knowledge-based parametric tank design and geometric modelling

The knowledge repository of *FUGA*, as developed by Walther [32] and described in Sect. 2.2, is extended by a rule set for hydrogen tank design and modelling. If the overall aircraft design process already generated detailed geometric and positional tank information, these can be imported in the data storage via established CAD exchange formats, such as BREP or STEP. If such data is not available from the overall aircraft design or further investigations with alternative tank geometries are required, a simple tank design rule is added to the knowledge repository. The tank geometries presented by Silberhorn et al. [33], Burschyk et al. [2] and Verstaete et al. [34] are used as guidelines for the tank design. Since the primary focus of this work is the integration of liquid hydrogen tanks into the fuselage, the knowledge-based engineering process is restricted to modelling the outer hull of the tank, while the internal structure is left for future work.

Starting with a target tank volume V_{target} and a maximum allowed tank radius r_{max} the tank length l_{tank} is calculated. For the central part either a cylinder or cone is used depending on the user value of the opening angle ϕ_{con}. The top and bottom end of the tank on both circular surfaces of the cylinder or cone are modelled by combining a torus, representing a knuckle connecting the centre part with the end cap, and a sphere, representing the end cap assumed as a spherical calotte. The respective radii of the torus and sphere are directly calculated by two factors and the radius of the circular end surface. Furthermore, the thickness of the isolating layers t_{iso}, which is used as an offset in all directions inside the tank, to obtain the inner tank volume V_{in}, and a usable fraction for fuel v_{use} of the inner tank volume V_{in} are defined. Consequentially, the tank length l_{tank} and all depending values are calculated. The tank can be tilted by an installation angle α_{inst} respective to the horizontal *x*-*y*-plane of the aircraft. Finally, the tank is positioned by the coordinates of the centre of the front surface of its bounding box in the aircraft model.

Exemplary results of the simple tank design process are shown by Fig. 7. On the left side, a cylindrical tank and on the right side, a conical tank with an opening and installation angle of $\phi_{\mathrm{con}} = \alpha_{\mathrm{inst}} = 4°$ are pictured. The central axis of the tanks are shown in dark blue. The tank length l_{tank} and the maximal allowed tank radius r_{max} are visualized on the cylindrical tank. Whereas, the installation angle α_{inst} in which the central axis of the tank is tilted in respect to the orange horizontal plane of the aircraft is shown on the conical tank. The opening angle ϕ_{con} is pictured in between the conical surface and the light blue coloured line parallel to the central axis of the tank, which represents the cylindrical distance to the central axis with the radius r_{max} shown in white.

3.2 Design and modelling of hydrogen tank mounting concepts

Three new mounting concepts for hydrogen tanks in aircraft are presented. These concepts can either be used on their own or in combination to mount the tanks in the fuselage and attach them to the primary aircraft structure. Based on the tank positions and dimensions from the overall aircraft design or the previously presented simplified tank design process, new main frame positions before and after each hydrogen tank are calculated. Therefore, the knowledge rule on mainframe positions gets extended to calculate two additional positions, one in front and one after the tank, for each hydrogen tank defined in the data storage of the knowledge system. So, if no hydrogen tank is defined in the knowledge system, no additional position is calculated. The additional main frame positions are calculated from the starting x_{start}, and end position of the tanks x_{end} as well as an adjustable tank frame distance d_{frame}

$$x_{\mathrm{frame},1} = x_{\mathrm{start}} - d_{\mathrm{frame}}, \tag{1}$$

$$x_{\mathrm{frame},2} = x_{\mathrm{end}} + d_{\mathrm{frame}}. \tag{2}$$

3.2.1 Supporting mount

The supporting mount can be used as a static tank mount as well as a crash structure to bear dynamic crash loads in vertical direction. Therefore, the hydrogen tank is mounted on multiple crossbeams, which are supported by several

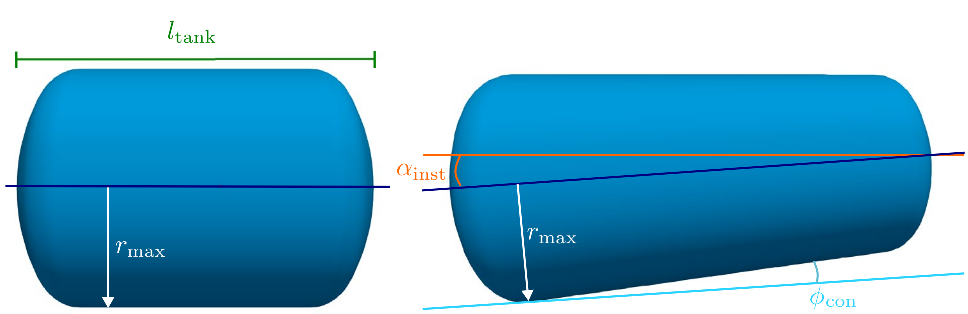


Fig. 7 Cylindrical and conical results obtained using the simplified tank design, with an opening and installation angle of $\phi_{\mathrm{con}} = \alpha_{\mathrm{inst}} = 4°$ applied for the conical tank, including a visualization of the corresponding design parameters

support struts. The crossbeams are placed in lateral direction on every frame position x_{frame} in between the tank start x_{start} and end position x_{end} minus an offset x_{off}. The *x*-positions x_{cross} of the crossbeams are given by

$$x_{\text{cross}} = x_{\text{frame}} \in [x_{\text{start}} + x_{\text{off}}, x_{\text{end}} - x_{\text{off}}]. \tag{3}$$

The position and shape of the crossbeams in the *y*, *z*-plane is defined by an intersection of a half plane and the outer shell of the hydrogen tanks. The half plane is limited in the *z*-direction by the boundary value z_{max}, which defines the last contact point between the tank and the crossbeam. To account for the bend of the rear fuselage section and a tank mounted with an installation angle β_{inst}, as described in the previous section, the boundary value z_{max} is interpolated linearly over the length of the tank between a start value z_{start} and an end value z_{end}

$$z_{\text{max}}(x) = z_{\text{start}} + (z_{\text{end}} - z_{\text{start}})\frac{x - x_{\text{start}}}{x_{\text{end}} - x_{\text{start}}}. \tag{4}$$

The sides of the crossbeams between the tank and the outer shell of the fuselage are straight lines with an increase defined by the derivatives at both ends of the intersection curve respective to the *y*, *z*-plane. The cross section of the crossbeams can have an arbitrary profile described by a referenced *StructuralElement* given in the *CPACS* format. This cross section is extruded perpendicular to the calculated beam line to build the three-dimensional model of the crossbeam.

Beneath the crossbeams an arbitrary number of support struts can be defined. The support struts can be solely static elements or compressible crash elements with designed deformation properties to bear the dynamic crash loads and absorb the resulting kinetic energy of the hydrogen tanks. The support struts are described by a *y*-position y_{support} on the crossbeam line and an installation angle α_{support} around the *x*-axis. From the starting point on the crossbeam line and the installation angle α_{support}, the intersection point of the vector in the direction of the strut line with the fuselage is calculated and the final strut line is obtained. The cross section of the support struts, which is equally described as a *StructuralElement*, is extruded along the support strut line.

A hydrogen tank on its supporting mount in the rear fuselage is shown in Fig. 8. The hydrogen tank is pictured transparently in blue, the crossbeams in dark red and four support struts per crossbeam in orange.

3.2.2 Polar mount

A polar mount connects the hydrogen tanks on one or two of its poles with the primary aircraft structure. The variant of the polar mount described in this subsection is based on the concept of Gallois et al. [35]. A horizontally aligned crossbeam is placed at the height of the pole z_{polar} and at the *x*-position of a main frame before or after the tank. For each tank, the existence and polar height z_{polar} are defined separately for both tank ends. The cross section of every crossbeam is given by the profile of a *StructuralElement*. In the centre of the crossbeam at the defined pole, a cylinder with the height h_{a}, matching the width of the crossbeam defined by its cross section, and the radius r_{a} is generated. This cylinder mounts a concentric cylinder with a smaller radius r_{i} connected to the tank. The smaller cylinder transfers the tank loads to the other parts of the polar mount and contains the installation space for cables and pipes required for the hydrogen supply, which are connected to the inner part of the hydrogen tank.

Starting from the centre of the polar mount reaching to the fuselage shell, an arbitrary amount of support strut is generated. Every support strut is completely defined by its installation angle α_{polar} around the *x*-axis and the profile of its cross section, given as a *StructuralElement*. Figure 9 shows a tank with a polar mount consisting of a dark red crossbeam and two support struts symmetrically placed in a 30° angel in respect to the *z*-axis.

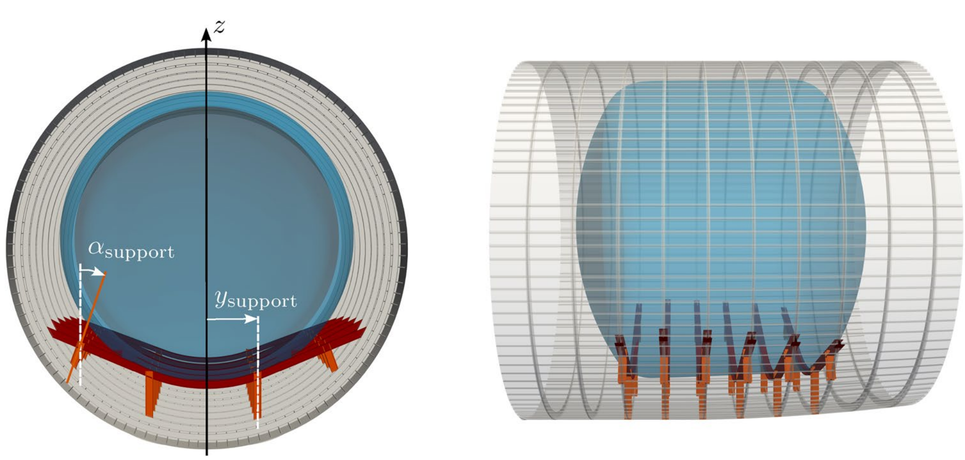


Fig. 8 Supporting mount with four support struts per crossbeam

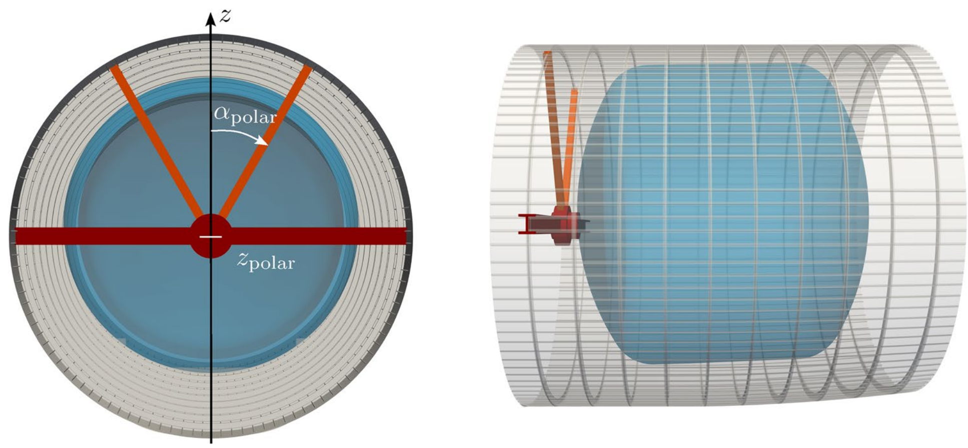


Fig. 9 Polar Mount with two support struts symmetrical to the *z*-axis

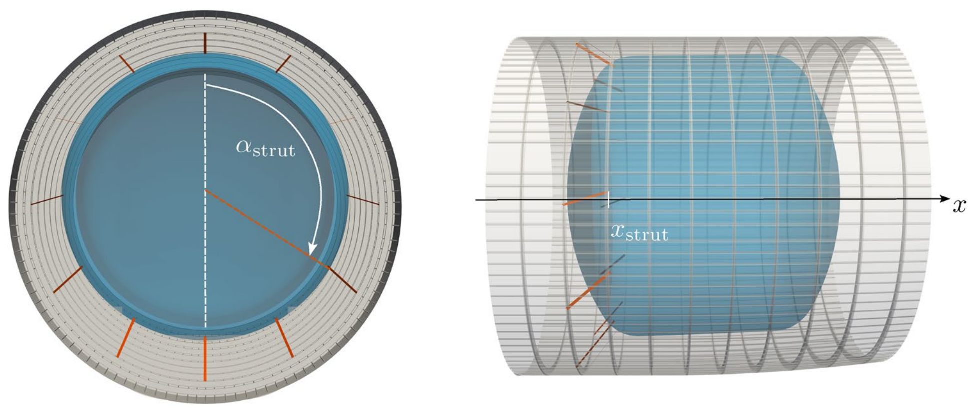


Fig. 10 Tank mount using twelve uniformly distributed struts

3.2.3 Strut mount

Finally, a third mounting variant using struts to directly connect the tank with the primary aircraft structure is described. The struts are placed in the angle α_{strut} radially around the *x*-axis. One end of the strut is connected at the position x_{strut} with the tank, the other end with the mainframe in front or after the tank. The exact mounting point is calculated as the intersection point of the tank or fuselage shell and a ray starting in the centre of the tank or fuselage cross section at the *x*-coordinate of the mounting point with the respective angle α_{strut} around the *x*-axis. A strut mount with twelve radially uniformly distributed struts, which are coloured orange, is shown in Fig. 10.

Every presented tank mounting concept is generated as a detailed CAD or mesh geometry. Material properties supported by *CPACS* can be defined for every mounting part separately. Using several established exchange formats, such as STEP or BLEND, disciplinary experts and their tools can use the tank mount designs for their simulation, optimization or detailed constructions. All presented concepts can be integrated easily in future definition of the *CPACS* and additionally be shared on this way with all disciplines in the aircraft design process.

3.3 Design and integration of liquid hydrogen distribution systems

To design and integrate the hydrogen supply system, the *SArA* and *GeneSys* methodologies are used (cf. Sect. 2.3).

The defined architecture of the hydrogen supply system is illustrated in Fig. 11. For the system design, the tanks and their attached cold boxes are considered power sources. The cold boxes contain system components such as pumps, sensors, and heat exchangers, which are used for hydrogen withdrawal and refuelling. The heat exchangers vaporize a portion of the withdrawn hydrogen and returning it to the tank to maintain constant pressure. The power sinks in the system are the engines and the auxiliary power unit (APU). Each engine is assumed to be supplied by a separate pipe from the tank, while the APU is only connected to tank 1. Additionally, the hydrogen in the distribution network is assumed to be transported in liquid form. The recirculation of unused hydrogen, as well as hydrogen conditioning (vaporizing and temperature increase), is assumed to take place inside the engines. As shown in Fig. 11, the tanks and cold boxes are connected to a venting network, with the outlet being located at the highest point of the vertical tail plane.

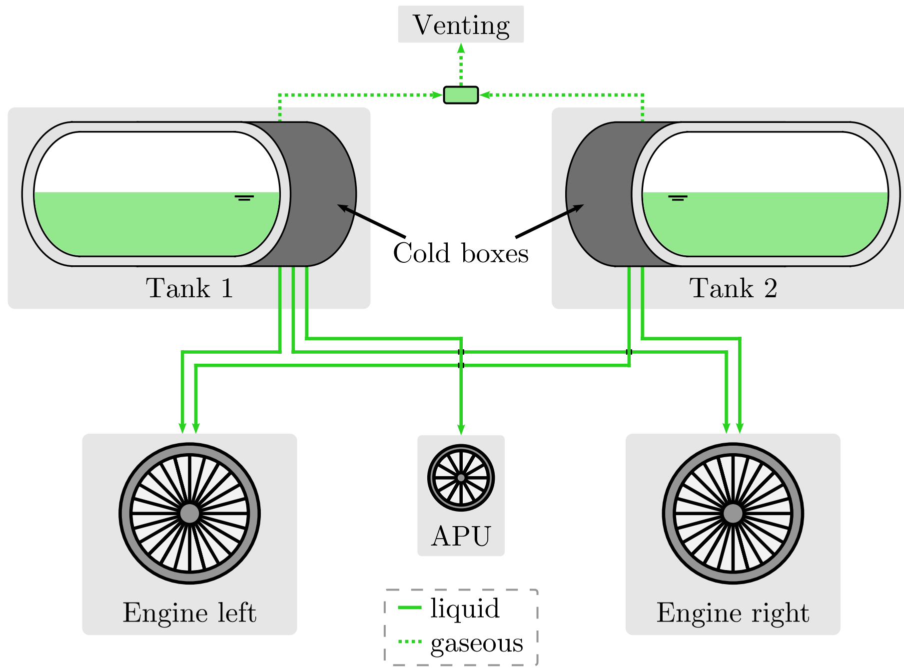


Fig. 11 Hydrogen supply system architecture

Table 1 Parameters of the hydrogen supply system

Description	Unit	Parameter
Specific pipe mass	[kg/m]	9
Max. mass flow	[kg/s]	0.3
Mass of one cold box	[kg]	155

Based on the assumed maximum hydrogen mass flow, the pipes connecting the cold boxes to the engines and the APU are designed. Subsequently, the system components within the cold boxes, such as pumps and heat exchangers, are sized. Relevant system parameters of the hydrogen supply system are listed in Table 1.

The parameters in Table 1 are based on the following assumptions:

- The mass of the cold boxes includes pipes, pumps, heat exchangers, valves and brackets [36].
- The pipes are double-walled and contain multilayer insulation (MLI).
- The pipe mass includes brackets and bellow components.

Since only the latest version (3.5) of *CPACS* supports the exchange of system parameters [27], the OBS geometry parameters are exported to a *XML*-based *CPACS-Sys* file. The file format has been developed at FST in alignment with the *CPACS* design philosophy. In future, the system information can also be directly transferred via *CPACS* between the knowledge systems.

FUGA reads the system information transmitted by the respective exchange format and stores the component names and their connections in an *Ordered Dictionary* to represent the developed system architecture. Using the transferred geometric and positional information, *FUGA* generates *OCC*-components for every system component. The *OCC*-components can be exported to STEP with a feature tree obtained from the *Ordered Dictionary* including the system architecture. Mesh geometries for visualization of the designed systems are generated with *VTK*. The visualization of the geometric results generated by *FUGA* of the knowledge-based system design are shown in Fig. 12. The two turquoise cold boxes are placed in between both geometric tank centres shown in orange. The light blue coloured supply lines connect the cold boxes with the engines shown in dark blue. The APU and its supply lines are shown in red, the venting and the connecting pipes are shown in yellow. An extract of the complete generated feature tree including the hydrogen distribution systems with their names and corresponding ATA-chapters [37] is shown by Fig. 13.

4 Comparison of two research aircraft configurations

This section applies the newly developed knowledge-based engineering methods to a current research scenario by comparing two preliminary aircraft designs for hydrogen direct-combustion propulsion. First, the two research aircraft concepts are introduced, including their mission requirements, design constraints, and key geometric characteristics. Subsequently, the results generated by the knowledge-based engineering process introduced in section 3 are presented, illustrating how the methodology supports the

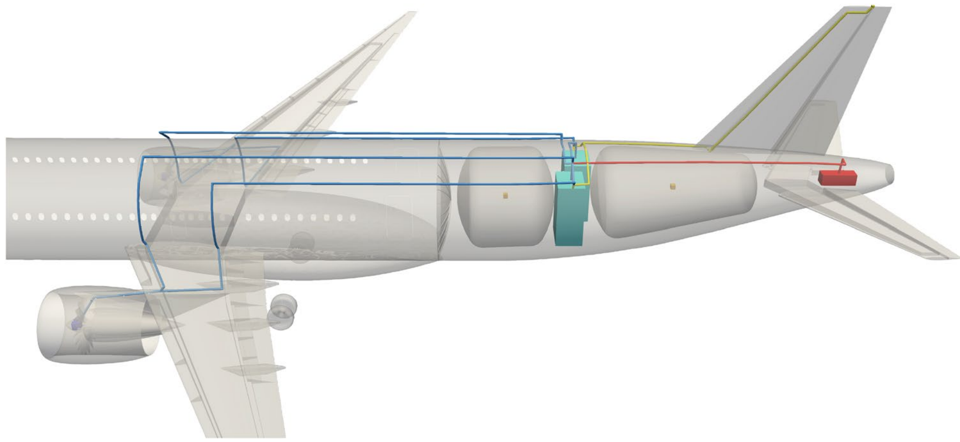


Fig. 12 Visualization of the system geometries

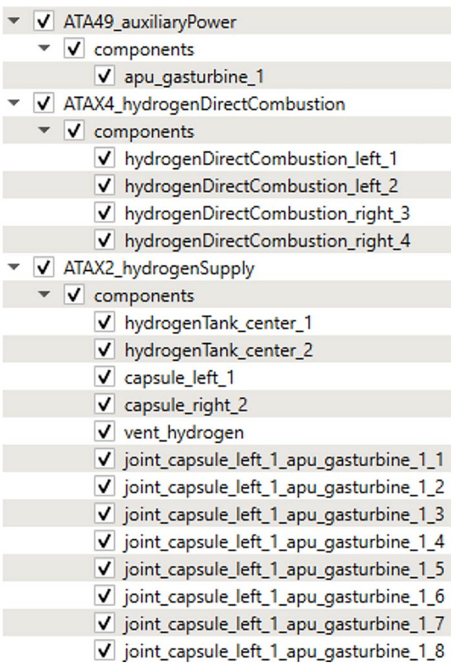


Fig. 13 Extract of the hydrogen distribution systems feature tree

Table 2 Aircraft design parameters

Top-level aircraft requirements	DLH25	FLH25
Design range [NM]	2500	2500
Design PAX [-]	239	239
Design payload [kg]	25000	25000
Cruise mach number [-]	0.78	0.78
Aircraft dimensions	DLH25	FLH25
Fuselage length [m]	51.4	53.8
Fuselage diameter [m]	5.3	5.3
Wing span [m]	45	45
Wing aspect ratio [-]	12.8	12.3
Wing area [m^2]	158	165
Aircraft masses	DLH25	FLH25
Max. Take-off mass [kg]	93400	97600
Operating empty mass [kg]	62000	66000
Max. fuel mass [kg]	6500	6600
Block fuel (2500 NM) [kg]	5400	5500
Tank clearance	DLH25	FLH25
Bulkhead and Tank 1 [m]	0.2	0.5
Tank 1 and Tank 2 [m]	1.5	2.6
Top clearance [m]	0.2	0.3
Bottom clearance [m]	0.5	0.6

automated model generation, assessment, and comparison of the two configurations.

4.1 Description of the research aircraft concepts

The DLH25 is the DLR's research baseline for liquid hydrogen powered aviation in the short/medium range [38], whereas the FLH25 is a project-specific aircraft configuration derived from the DLH25 and based on different assumption about required fuselage space around the liquid hydrogen tanks. Both configurations have identical requirements of accommodation for 239 passengers and a design mission of 2500 M range at a cruise Mach number of $M = 0.78$, placing them in the short–medium-range segment. The most important requirements as well as the key geometric aircraft parameters are listed in Table 2 Currently, independent iterations for cabin and structure layouts are conducted with both aircraft, to establish themselves as research baselines for hydrogen powered aviation. In this paper, the key difference in the assumptions for required distances between the rear bulkhead and the first tank as well as in between both tanks are investigated. The DLH25 has a more optimistic estimation of the required installation space for tank mounts and distribution systems. While the FLH25 was designed with more conservative estimations for installation space specifications in the rear fuselage section. The values for all tank-related clearance distances are also listed in Table 2. In both cases, two hydrogen tanks with their geometry and position were already designed in the overall aircraft design process so the knowledge system can directly import these data. A comparison of the outer mold line and tank positions of both configurations obtained

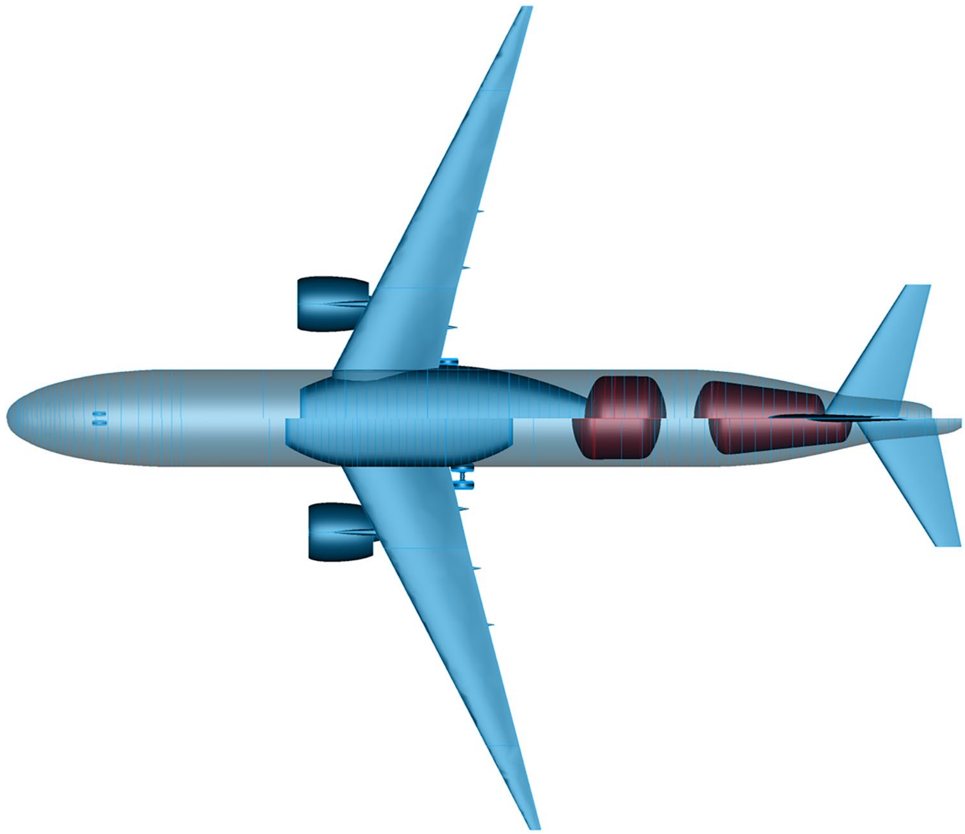


Fig. 14 Comparison of the overall aircraft designs for the DLH25 (top) FLH25 (bottom)

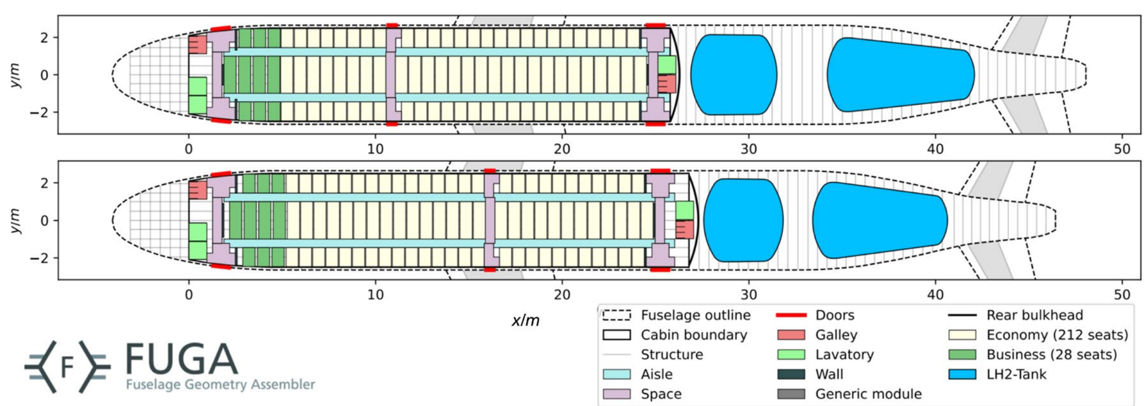


Fig. 15 LOPA inclusive frame and tank positions FLH25 (top) and DLH25 (bottom)

from the overall aircraft design is shown in Fig. 14. In the investigated iteration, the FLH25 shown in the bottom has a denser cabin layout and a resulting shorter cabin length compared to the DLH25 shown in the top. Therefore, the front tank coloured in red is placed slightly more forward although the distance to the rear bulkhead is smaller. Differences in the belly fairing and landing gear positioning and sizing resulted from the described independent iteration states in the overall aircraft design process and their influence on the aircraft performance is not analysed in this study.

4.2 Results of the knowledge-based design and modelling process

For both concepts *FUGA*, as described in Sect. 2.2, generates an initial structure and cabin layout including the newly developed tank mounting concepts, presented in Sect. 3.2. The results of the knowledge-based design and modelling process are shown as a Layout of Passenger Accommodations (LOPA) in Fig. 15 including the hydrogen tanks and frame positions to illustrate the available installation space for the tank mounts and hydrogen distribution systems.

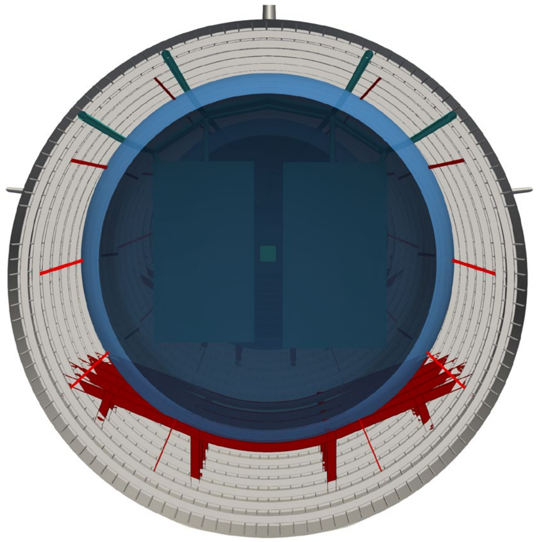


Fig. 16 Section view of the DLH25 including tank mounts and system geometries routed inside the fuselage

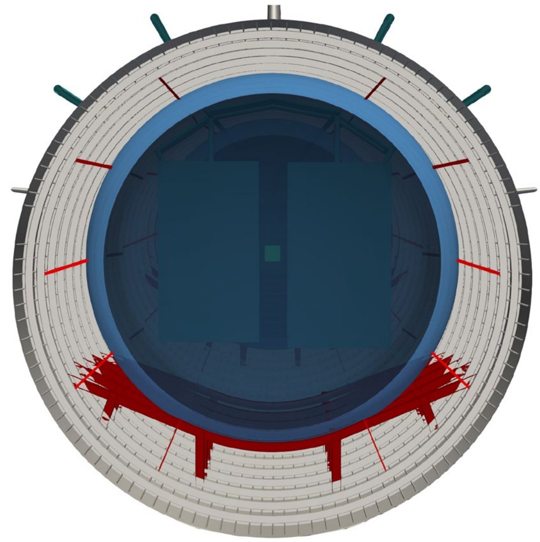


Fig. 18 Section view of the DLH25 including tank mounts and system geometries routed outside the fuselage

The LOPA of the FLH25 is shown on top, the LOPA of the DLH25 in the bottom figure.

Based on the cabin and structure design by *FUGA*, the system design tools *SArA* and *GeneSys* perform an overall system design for the hydrogen distribution systems, as described in Sect. 3.3. For both configurations two variants with hydrogen supply lines from the cold boxes to the engines either inside or outside the pressurized fuselage are considered. Although external routing of hydrogen distribution piping may introduce additional challenges, such as increased aerodynamic drag and added structural weight due to the need for protective fairings, it may still be necessary due to spatial constraints, certification requirements [1, 39], or interdependencies with other onboard systems [29]. In this study, only the geometric integration of the hydrogen system within the aircraft fuselage is investigated. Aerodynamic performance, structural mechanics, and safety regulations are not addressed in the current analysis. In future work, the framework may be extended to include the design and modelling of fairings and structural pipe attachments, enabling additional multidisciplinary analysis including aerodynamics, structures, safety as well as manufacturability.

The installation space in the DLH25 concepts between the rear bulkhead and the first tank as well as between both tanks is not sufficient for the presented polar mount concept. Thus, for both tanks strut mounts on both sides are chosen as the static tank mount and the supporting mount is chosen to absorb the dynamic crash loads. The geometric models of the DLH25 are shown in Figs. 16 and 17 with the hydrogen supply lines routed inside the fuselage and in Fig. 18 as well as Fig. 19 with the pipes routed outside the fuselage. Twelve red coloured struts mount both blue coloured tanks on both sides inside the fuselage. All integrated hydrogen distribution systems are shown in turquoise. Both of the cuboid cold boxes can be accommodated within the smaller installation

Fig. 17 Side view of the DLH25 including tank mounts and system geometries routed inside the fuselage

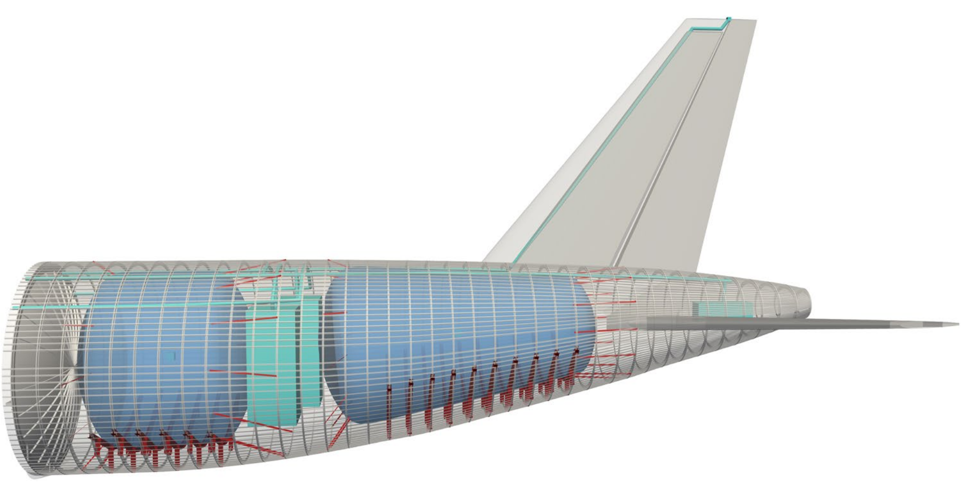
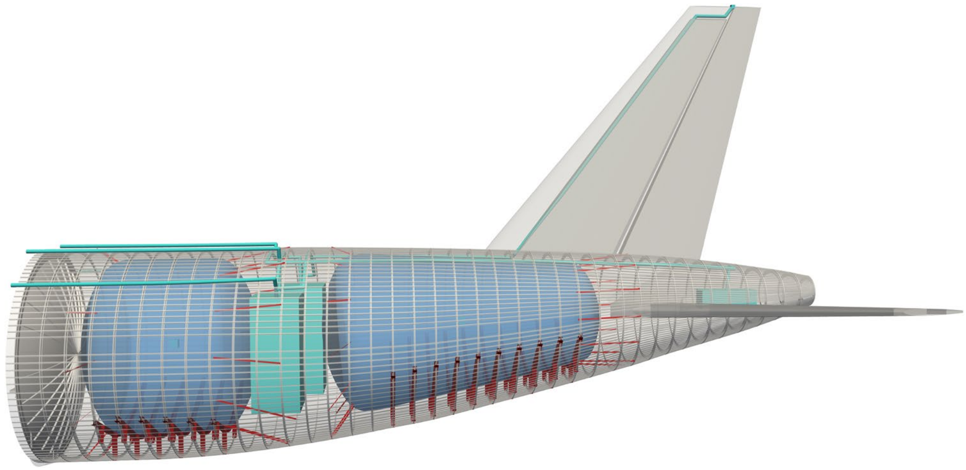


Fig. 19 Side view of the DLH25 including tank mounts and system geometries routed outside the fuselage



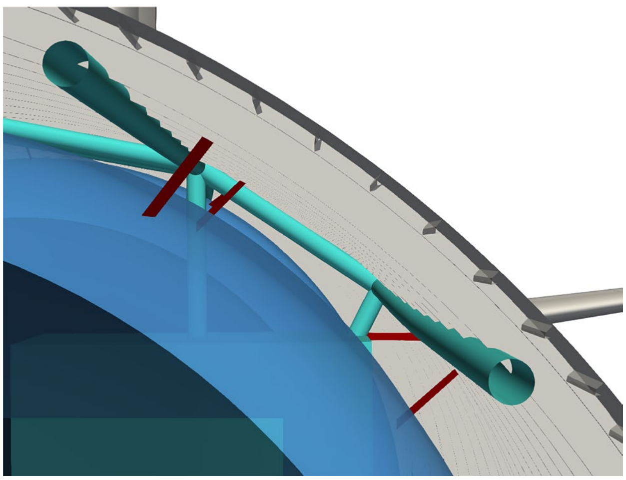


Fig. 20 Intersection in between hydrogen distribution pipes and frames due to insufficient tank clearances in the DLH25

volume of the DLH25. However, the limited available space significantly constrains the geometric design freedom of the cold boxes and leaves very little margin for the integration of safety measures or additional aircraft systems in this fuselage section. A detailed view of the DLH25 with the supply lines routed inside the fuselage, shown in Fig. 20, illustrates this challenge: the hydrogen pipes intersect with the frames surrounding the forward tank. Due to the tight spacing between the tank and the predefined frame positions, there is insufficient installation room to route the hydrogen pipes in the upper region of the fuselage as initially intended. If the detailed design of the frames, based on a subsequent structural analysis, still does not provide enough clearance, several design adaptations may be considered. These include adjusting the tank's vertical *z*-position, adopting an alternative routing strategy that begins on the side of the tanks and transitions to the upper fuselage before reaching the bulkhead, or structurally integrating the pipes within the frame geometry. As an additional option, the conflict can be avoided entirely by routing the supply lines outside the fuselage, which may simplify the integration but would introduce separate aerodynamic and structural trade-offs. In the future the presented method enables such investigations on installation space in the early design stage. The use of extended or virtual reality especially in combination with the co-design method allows respective disciplinary experts to develop suitable solutions for the spatial integration and detailed installation concepts [40].

The distance between the rear bulkhead and the front hydrogen tank in the FLH25 concept is sufficient to use a polar mount at the front end of the tank. The installation space between the tanks is again insufficient to accommodate the polar mount, since the available volume is already constrained by the designed cold boxes using the current assumptions for the performance and spatial requirements of the hydrogen distribution systems. Therefore, the strut mount is used again on all other tank ends. In this concept the cold boxes have a larger clearance to account for security distances to guarantee a redundant hydrogen supply to the engines. The results of the structural and system design for the FLH25 are shown by Fig. 23 for the routing inside the fuselage and Fig. 22 for the routing outside the fuselage. The polar mount including its four support struts is coloured orange, all other mounting and system components are coloured in the same colour schema used for the DLH25 illustrations. Due to the slightly bigger top clearance of the hydrogen tanks in the FLH25 in respect to the DLH25 the hydrogen pipes can be routed between the front tank and the frames without any intersection, as shown in the cross section view of the FLH25 in Fig. 21. The alternative pipe routing concept outside the fuselage is shown in Fig. 24.

Both evaluated configurations provide sufficient installation space to integrate two cold boxes sized for the hydrogen supply of the engines. The FLH25 offers greater margins and more flexibility in the design and positioning of the cold boxes, allowing better accommodation of potential safety measures and the integration of additional

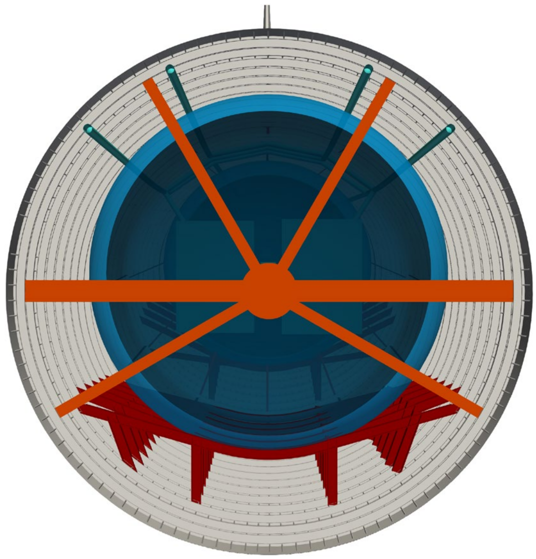


Fig. 21 Section view of the FLH25 including tank mounts and system geometries routed inside the fuselage

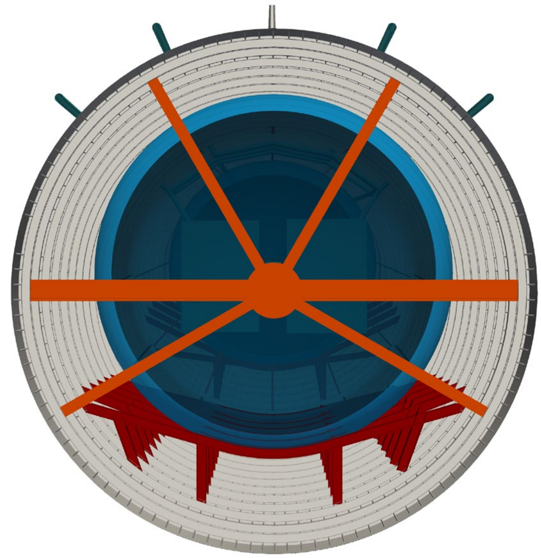


Fig. 24 Section view of the FLH25 including tank mounts and system geometries routed outside the fuselage

systems. In contrast, the hydrogen supply lines routed inside the fuselage of the DLH25 present significant challenges for integration within the rear fuselage section. Among the investigated mounting concepts, the proposed polar mount for hydrogen tanks requires a substantial amount of installation space, which primarily leads to difficulties in the fuselage integration and was only feasible for the front tank of the FLH25. The other mounting concepts can be integrated more easily into the primary aircraft structure in combination with the hydrogen systems. Considering the aspects addressed in this paper, cryogenic hydrogen

Fig. 22 Side view of the FLH25 including tank mounts and system geometries routed outside the fuselage

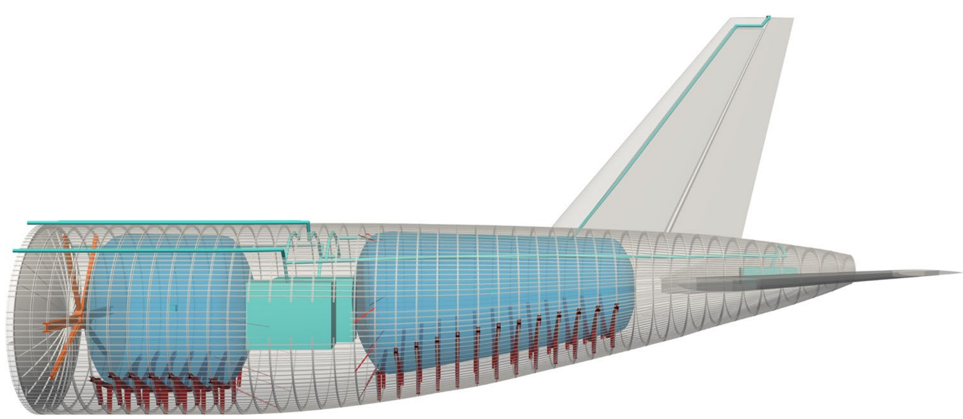
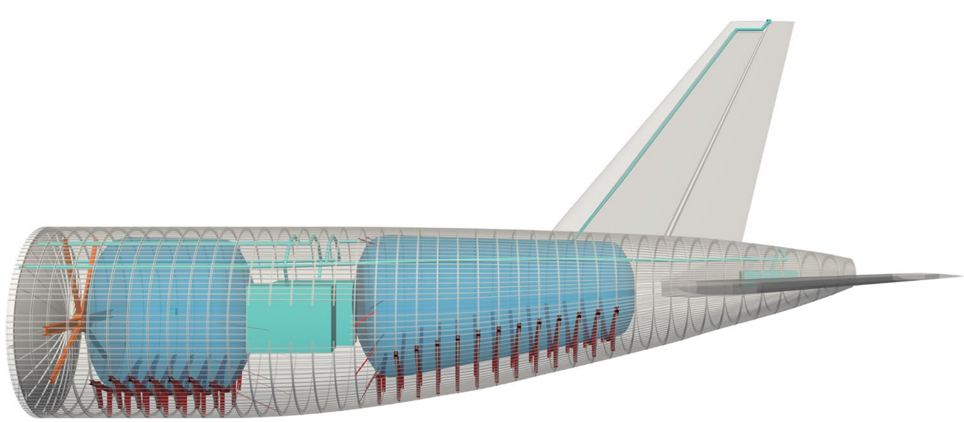


Fig. 23 Side view of the FLH25 including tank mounts and system geometries routed inside the fuselage



tanks, including their structural mounts and associated distribution systems, can be successfully integrated into both configurations.

5 Conclusion

This paper presents a new method for consistent knowledge-based design and modelling of the rear fuselage section of a liquid hydrogen powered aircraft in different fidelity levels. With the generated models, interdisciplinary analysis can be performed on a consistent data basis and the respective disciplinary experts be involved in the early stages of an aircraft design process. An important step for modelling and evaluating the aircraft as a complete system is achieved by integrating designed system geometries from the overall system design in the structural and cabin model and enhancing integration of the overall system design in the overall aircraft design. In the future, this method enables numerous and detailed analysis of the rear fuselage section including the integration of all systems or the impact of hydrogen supply lines with the cabin systems and geometry as well as the consequences of structural integration of aircraft systems. Furthermore, new methods to automatically generate detailed hydrogen tanks and their structural mounting in the fuselage are developed. The detailed models can be used for structural analysis and multidisciplinary optimization processes for the profiles and positions of tank mounts. Further extensions of the knowledge-based tank design, including the modelling of the inner tank structure and detailed material properties, will enable comprehensive analyses of the tank, such as structural integrity assessments, sloshing simulations, and manufacturability evaluations. Additional expansions of the knowledge-base in *FUGA* may also enable a detailed fairing design for hydrogen pipes outside the pressurized fuselage based on the positioned system geometry. Thereby, many different design approaches and the integration in the complete system of the rear fuselage section of hydrogen powered aircraft with cryogenic tanks can be evaluated extensively and the potential of this new technology estimated more accurately in the field of aeronautics.

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Data Availibility All data that are not subject to licensing agreements by third parties can be made available by the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Consent for publication All authors expressed their consent for this publication.

Code availability The software code is proprietary information of the German Aerospace Center (DLR). Therefore, the code cannot be made available to the public or the readers without any restrictions.

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