GEOMETRIC OPTIMIZATION OF HYDROGEN AIRCRAFT FUSELAGES IN PRELIMINARY DESIGN

Marc Engelmann[1] & Mirko Hornung

Bauhaus Luftfahrt e.V.
Willy-Messerschmitt-Str. 1, 82024 Taufkirchen, Germany

[1]marc.engelmann@bauhaus-luftfahrt.net

Abstract

This paper introduces a methodology to assess hydrogen aircraft fuselages in preliminary design. Considering the overall tank arrangement, number of passengers, seat abreast and more, the tool derives a variety of fuselage geometries. These concepts are then evaluated on both fuselage and overall aircraft level using key parameters to identify the optimum configurations for the given input.

Keywords: hydrogen, aircraft design, optimization, fuselage, cabin

1. Introduction

Climate change poses an existential threat to humanity, necessitating a reduction in greenhouse gas emissions to curb global warming. Achieving climate neutrality requires various industries, including aviation, to explore pathways for transition. The aviation sector is considering hydrogen as an alternative to conventional jet fuel. However, due to the need for storing hydrogen in a liquefied state within pressurized and insulated tanks, conventional wing storage is impractical. The fuselage emerges as a suited potential location. This results in the need for a redesigned fuselage to accommodate both the payload and hydrogen tanks.

This paper thus presents a framework for the creation and assessment of aircraft fuselages comprising of a cabin as well as hydrogen tanks. The geometrical arrangement of both hydrogen tanks and the cabin opens up a large design space for the geometric design of the fuselage. This is highlighted by the variety of different research project concepts presented in the following chapter.

2. Literature Review

In general, hydrogen in aviation is not a brand new topic, but the current climate impact reduction efforts have sparked renewed interest as indicated by a variety of research projects. The aspects of the projects presented below focus on the geometric arrangement of tanks and cabin inside the fuselage. Regarding the tank configurations, many of the projects differ in their tank arrangement although their aircraft and passenger size do not differ significantly.

Beginning with the concept by FlyZero [1], the project considers a fuselage concept with an A320 size cabin containing 180 passengers. The aircraft has two liquid hydrogen tanks that are located behind the cabin. Considering the regional concept, two tanks are placed in the tail of the fuselage as well. The two concepts are depicted in Figure 1.

Figure 1 - FlyZero regional (left) and narrow-body (right) concepts [1]

There are two more examples with this configuration that are notable. Airbus, the global leading aircraft manufacturer has introduced multiple concepts for a hydrogen aircraft future, seen in Figure 2 (left). The so-called ZEROe [2] project considers both a regional and an A320-like aircraft with both concept's hydrogen tanks being located in the aft of the fuselage, behind the cabin pressure bulkhead. Similarly, in the DLR-internal project Exact [3], one of the possible tank location options, depicted in Figure 2 (right), is also an aft cabin configuration with two tanks. The project is based on an Airbus A321 with around 250 passengers.

Figure 2 – Hydrogen fuselage concepts presented by Airbus ZEROe [2] (left) and DLR [3] (right)

Roughly two decades earlier, Airbus together with multiple large industry partners already assessed hydrogen aircraft concepts in the Cryoplane project [4]. Figure 3 (left) depicts the selected hydrogen tank configuration for an A321-sized aircraft with 185 passengers. Different to the previous presented concepts, this configuration uses hydrogen tanks above the cabin inside a fairing as well as an additional fourth tank behind the cabin pressure bulkhead.

Building on the foundations of this concept, the EU funded ENABLEH2 [5] project considers an hydrogen powered A320 style aircraft with roughly 200 passengers. Comparable to the Cryoplane project, the hydrogen tanks have been positioned above the cabin in a separate hydrogen tank fairing that is independent of the fuselage. In contrast to the Cryoplane project however, the configuration lacks an additional tank inside the aft fuselage as can be seen in Figure 3 (right).

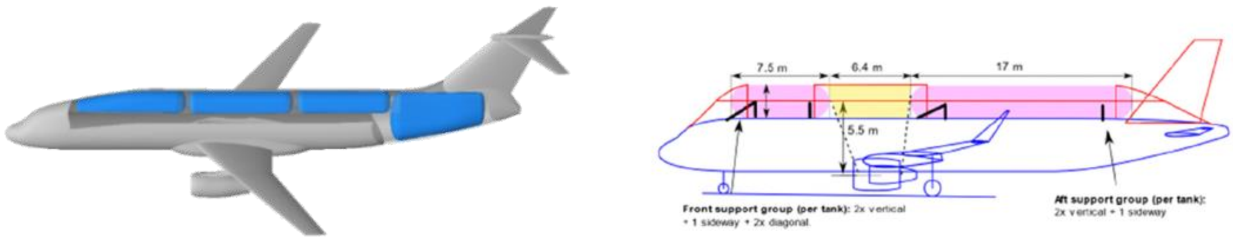


Figure 3 - Airbus Cryoplane Project [4] (left) and EnableH2 [5] (right) tank concepts

Lastly, three concepts employ a tank between cockpit and cabin for storing hydrogen. First, DLR uses this arrangement in combination with an aft cabin tank in its second concept for the Exact project [3] (Figure 4, left). Next, researchers from Cambridge [6] propose an A320 concept with around 110 passengers with a similar tank arrangement. However, the front tank has a reduced diameter, enabling a connection between cockpit and cabin (Figure 4, center). Third, Bauhaus

Luftfahrt (BHL) also already published research on a hydrogen aircraft [7] with a front and aft tank configuration. The long-range concept called the HyLiner contains 400 passengers in a two-deck arrangement. A three-view can be seen in Figure 4 (right).

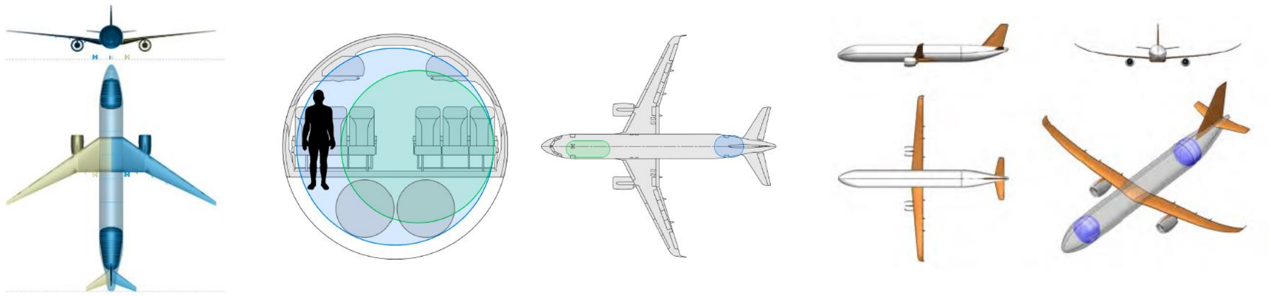


Figure 4 – DLR [3] (left), Cambridge [6] (center) and Bauhaus Luftfahrt HyLiner [7] (right) aircraft concepts

Concluding, there is a large collection of different hydrogen concepts for all ranges and passenger numbers, with multiple additional concepts not listed in detail above [8–11]. The aim of this paper is thus to assess this variety of different tank arrangements and identify the best geometric configuration of a fuselage shape with a cabin and hydrogen tanks. The focus lies on the application case of an Airbus A320neo. In particular, the paper aims to identify beneficial overall arrangements of tanks and the layout of the cabin. The assessment includes a geometry, mass, drag and center of gravity evaluation while neglecting aspects such as detailed hydrogen tank component design, detailed fuselage structural design or cabin emergency evacuation requirements.

3. Methodology

3.1 Overall

The overall methodological structure of this paper is presented in Figure 5. All processes are linked via the CPACS file format [12, 13]. The process is centered around the cabin and fuselage design tool CAFE [14]. One of the required tool inputs is the hydrogen mass to be fitted inside the fuselage. In order to generate this value, an initial hydrogen powered Airbus A320 style aircraft is designed using the Bauhaus Luftfahrt aircraft design environment BLADE [15]. Together with other input values, CAFE provides an integrated cabin, fuselage and hydrogen tank design. The concept is assessed on fuselage level and is then integrated into an overall aircraft design (OAD) loop. The purpose of the OAD is the evaluation on aircraft level by considering higher order mass effects and geometry changes of other aircraft components. This enables the impact evaluation of a center of gravity shift, fuselage drag change or structure mass change on the maximum take-off mass and fuel burn. The OAD does not represent a fully optimized hydrogen aircraft design and its sole purpose is the assessment of fuselage design changes on the overall aircraft. It is furthermore also out of scope for this paper to look into the causes of aircraft level results.

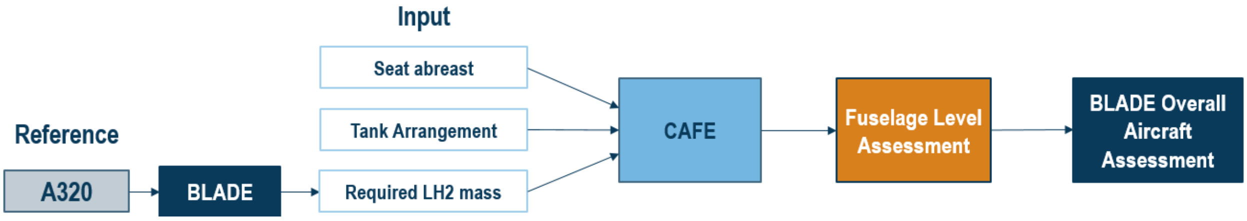


Figure 5 - Workflow Overview

3.2 BLADE

BLADE is an innovative aircraft design framework developed by Bauhaus Luftfahrt e.V. in Python 3.12 [15]. It is characterized by its multidisciplinary and multi fidelity approach, revolving around the widely adopted aircraft parametrization CPACS by DLR. Its architecture empowers aircraft designers to customize workflows efficiently, tailoring them to the desired level of detail and investigation scope with a high degree of automation. The standard workflow incorporates common semi-empirical sizing and calculation methods for all major aircraft components, alongside detailed table-based or neural-net-based engine models. Additionally, it features a physics-based mission analysis. Figure 6 depicts the flow diagram for a typical BLADE aircraft design loop.

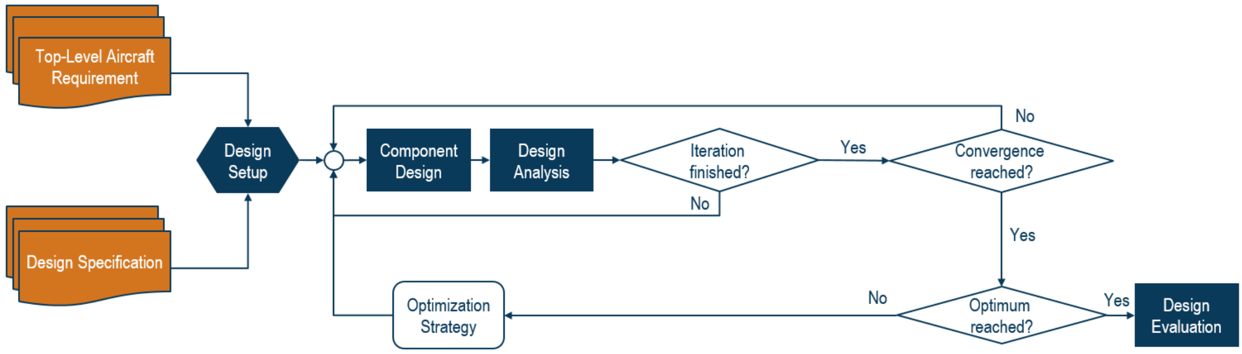


Figure 6 - BLADE Flow Diagram [15]

The two component level design tools that are presented in this paper are CAFE [14], the cabin and fuselage design tool as well as HyDRA, the hydrogen tank design tool.

3.3 Overall Structure

The fuselage design in CAFE begins with the minimum input consisting of the number of passengers, the seats abreast and the hydrogen mass to store. All other parameters remain constant for the different concepts. As depicted in Figure 7, there are multiple steps to perform in order to retrieve a final fuselage concept.

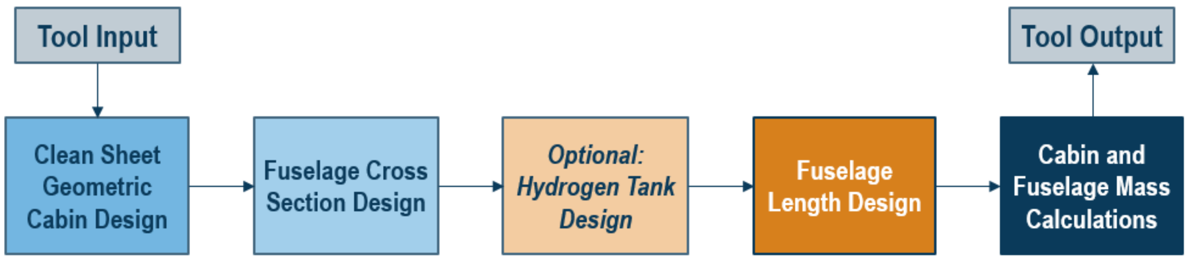


Figure 7 - Depiction of the CAFE modelling process

In the beginning of a clean sheet fuselage design, the cabin is modelled geometrically. Next, an optimized elliptical fuselage shape is generated around the cabin shape, generating the final cross-section. After that, the hydrogen tanks are generated based on various design parameters and the information of the fuselage cross-section. In the last geometric operation, the fuselage constant section is stretched to encompass the additional length of the hydrogen tanks inside. Lastly, the masses of the final fuselage concept and cabin components are calculated using analytical and semi-empirical methods [16, 17]. The next chapters present a deeper insight into the different modelling steps of CAFE.

3.4 Fuselage and Cabin Design

3.4.1 Geometric Cabin Design

The first building block of the CAFE tool is the clean sheet cabin design. The basic input in CPACS comprises a list of decks, each containing a list of passenger classes. Every class contains a number of seats as well as the desired seat pitch. With this information, CAFE starts building each deck from the front, systematically placing each row after the other. According to CS25 rules [18, 19], the doors are positioned at the correct positions, either between classes, in the front and aft of the cabin or when emergency exits are deemed necessary. At certain locations, the tool places lavatories and galleys as well as other miscellaneous cabin components with the help of underlying semi-empirical methods. Figure 8 highlights different cabin layouts for an Airbus A320 with a two-class configuration and a varying seat abreast of 3-3, 3-2-3 and 3-3-3.

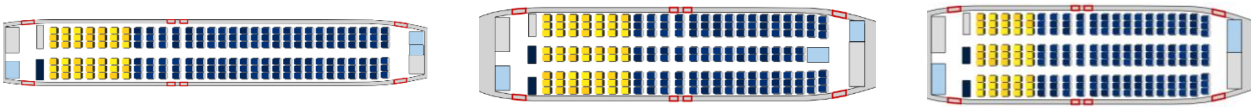


Figure 8 – Cabin creation for different input settings

Similarly, the cargo deck is created based on an option of typical cargo container types as well as the total number of containers that should be included.

3.4.2 Geometric Fuselage Design

The finalized deck shapes are not touched throughout the following steps. The first step in the fuselage cross-section creation logic that is based on a process originating from PreSTo [20] is the stacking of all decks on top of each other, with a still undetermined cabin floor thickness (Figure 9, left). In a next step, the outermost points of a window-seated passenger, seats, the aisle as well as a cargo container are connected into a polygon (red line in Figure 9, center). An optimization procedure that has both the lowest deck z position of the decks as well as the aspect ratio of the fuselage ellipse as parameters then creates a fuselage ellipse with a minimum cross-section area, while keeping all polygon points inside it (Figure 9, right). Both fuselage thickness and deck floor thickness (and thereby the z-position of the decks) is calculated based on semi-empirical formulas for each optimization loop. The overhead bin dimensions are currently not yet part of the cross section design but a sensible space for them is provided due to the available head room and aisle height.

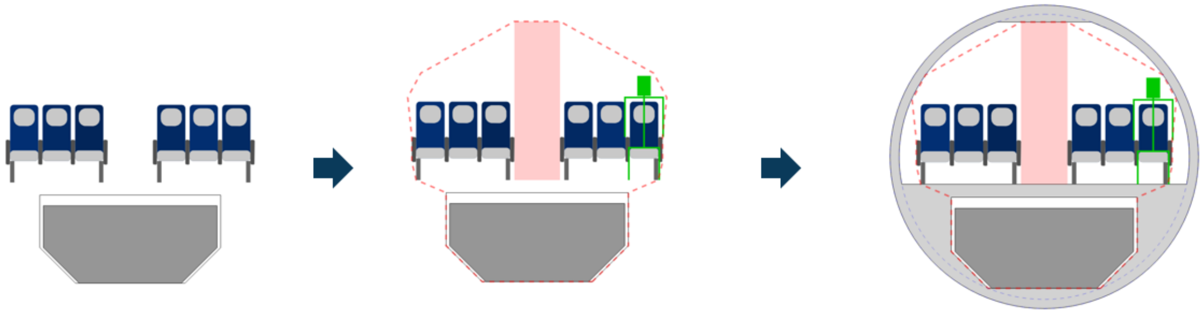


Figure 9 – Cross-section design process

Figure 10 depicts this ellipse design process for a variation of seat abreast in combination with a cargo deck designed for LD3 45W containers. As it can be seen, the amount of unused space inside the cross-section increases drastically if the container width and deck width do not match properly. This characteristic of unused cross-section area is one of the evaluation parameters of the fuselage designs later on.

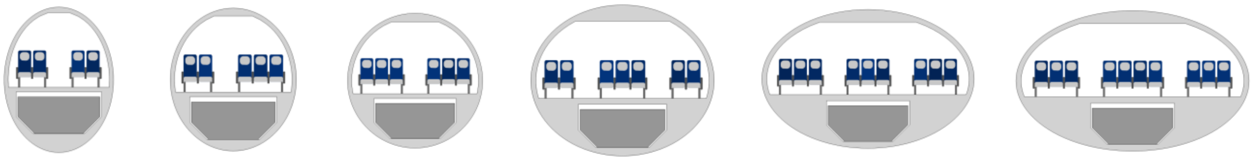


Figure 10 – Cross-section examples

After the design of the cross-sections, a nose and aft section are created. The process encompasses predefined point clouds for a variety of existing aircraft nose and aft shapes. These are discretized and scaled according to the input nose and aft length as well as the constant section diameter designed prior.

For reference kerosene aircraft, the geometric fuselage generation process ends here and the final step is the estimation of all component masses. If, however, hydrogen tanks are part of the concept, the fuselage has one parameter still undefined – the fuselage constant section length. This length is only determined after the design of the hydrogen tanks themselves.

3.5 Hydrogen Tank Design

The hydrogen tanks are created and designed depending on the user input definition as well as their rough placement inside the fuselage. First, a constant diameter tank can be placed in front of or aft the cabin, filling out the complete fuselage cross-section. Second, a tapered tank can be fitted inside the fuselage aft cone. Third, multiple tanks can be placed on top of a fuselage. In that case, an additional fairing object is created that tightly fits around the tanks. Additionally, combinations of the tank options are possible as well. However, before looking at the different tank options in CAFE, it is important to understand the underlying process of calculating the hydrogen and tank structure masses.

3.5.1 HyDRA Tank Design Process

HyDRA is based on OpenMDAO [21], an open source multi-dimension optimization framework. The tool supports both foam and vacuum insulations and performs both the mechanical design of the relevant structural tank layers as well as the thermal design of the relevant insulation layers. Tool inputs comprise the design boil-off rate, the ambient conditions, the venting and filling pressure, safety assumptions as well as material properties for all layers. Figure 11 depicts the two possible insulation types and layers of the hydrogen tanks.

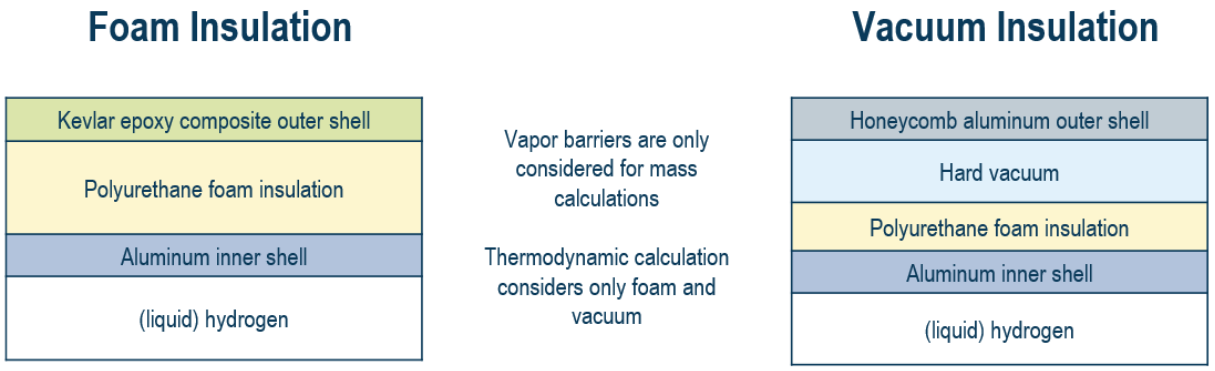


Figure 11 - HyDRA insulation options

The tank design process starts by passing HyDRA a 3D ellipsoid volume with elliptical end caps that represents the outermost tank layer. This shape is created by CAFE depending on the tank location and the target integration space inside the fuselage. The tool then builds up the tank layers and, depending on the insulation type, either iterates the foam insulation thickness for foam insulations [22, 23] or iterates the vacuum pressure for the vacuum insulation [24, 25]. The tool provides the containable hydrogen mass as well as the respective masses of the structure as output.

3.5.2 Front Cabin Tanks

As mentioned in section 3.5.1, CAFE provides HyDRA with the outer tank shell geometry. This geometry is generated by CAFE depending on the tank location inside the fuselage. Regarding the front cabin tanks, the tank cross-section follows the contour of the fuselage cross-section, maintaining a predefined gap. The length of the tank is a variable in this state of the process and is only determined in a later step. Both end caps are semi ellipsoids with a user defined height. The tank shape can be seen in Figure 12. The position of the tank inside the fuselage is defined by a gap to the cockpit as well as to the following cabin.

Figure 12 - Front Cabin Tanks

As the front cabin tanks are located in between the cockpit and the cabin area, it is important to note that certain safety assumptions are not accounted for in the tank modeling. For example the inclusion of a “cat-walk” to establish a connection between the cockpit and cabin is neglected in the tank geometry. Additionally, the fuselage mass is not considering a potential pressure vessel cut.

3.5.3 Aft Cabin Tanks

Aft tanks are integrated into the fuselage similarly to front cabin tanks. In contrast to the constant-only shape of the front cabin tank, four configurations can been defined: a tapered-only aft tank, a tapered-and-constant aft tank, a constant aft tank and a dynamic aft tank which automatically switches it’s configuration and number of tanks based on the input LH2 mass. The different concepts can be seen in Figure 13.

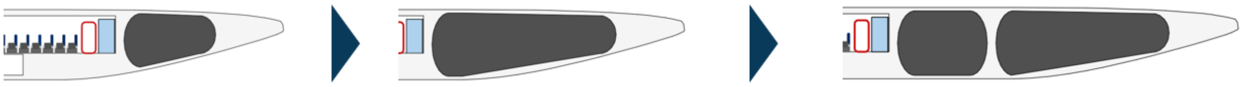


Figure 13 - Aft tank options for increasing hydrogen mass to be stored

For small hydrogen masses, the tank remains inside the tail section of the fuselage and comprises an elliptical cone frustum with semi-ellipsoid end caps that fit inside the fuselage, maintaining a gap to the outer shell (Figure 13, left). For larger hydrogen masses, this tank grows into the constant section of the fuselage, maintaining the predefined gap in the aft (Figure 13, center). In case the hydrogen mass is large enough, two separate aft tanks are created. One tank fills out the entire tail section of the fuselage, while an additional tank is created in the fuselage constant section (Figure 13, right).

3.5.4 Over Cabin Tanks and Fairing

The over cabin tanks outside the fuselage structure and the respective fairing are modelled according to the schematic depicted in Figure 14. The required user input for the tanks consists of the number of tanks in front and aft of the disk burst corridor, the tank cross-section aspect ratio, the gaps to the fuselage nose and end as well as the z axis gap to the fuselage skin.

Depending on the predefined start and end positions of the fairing as well as the respective input angles, tanks with a tapered section or constant section can occur. The cross-section scaling factor of the tanks is a variable that is defined in a later step. This means that the tanks and fairing creation process is a dynamic function depending on the selected scaling factor, with the fairing dimensions adjusting accordingly. The tanks maintain an empty space near the engine disk burst areas, preventing any bursting engine components from penetrating the pressurized liquid hydrogen tanks. The disk burst corridor dimensions are estimated using an FAA advisory circular [26] and the position of the engine components in CPACS.

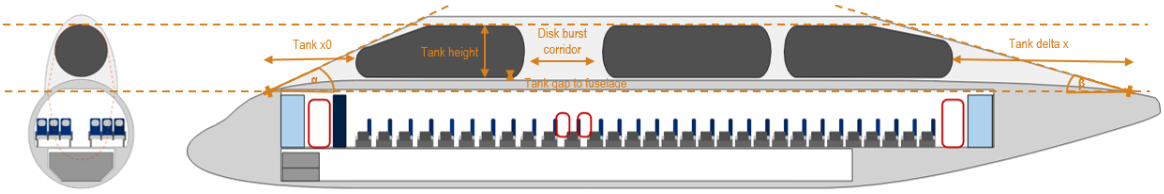


Figure 14 - Over cabin tank and fairing geometry

The fairing is modelled using a semi-elliptical cross-section that is fitted around the hydrogen tanks by minimizing the fairing cross-section area, similar to the fuselage creation process (see chapter 3.4.2). The fairing thereby maintains a safety gap to the hydrogen tanks.

3.6 Integrated Fuselage and Tank Sizing

As mentioned, for full cross-section hydrogen tank geometries the length of the tank and for over cabin tanks the cross-section factor are variables. In the overall integrated fuselage and tank sizing, CAFE iterates these variables until it meets a target containable hydrogen mass (Figure 15). For full cross-section tanks, each tank is iterated separately based on a predefined share of the overall hydrogen mass. For the over cabin tanks, all tank cross-sections are scaled synchronously as a system. The tank sizing does not take into account any fueling, defueling or center of gravity implications.

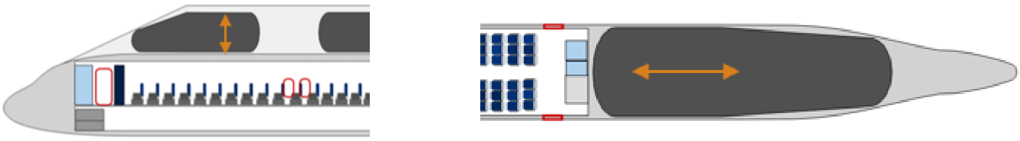


Figure 15 - Tank sizing options (Left: Over cabin tanks, right: full cross-section tanks)

After the tank lengths are fixed, the fuselage constant section is then stretched to encompass both the tanks as well as the passenger and cargo decks inside. For the over cabin tanks, the fuselage length does not need to be adapted but rather the tank fairing is scaled in order to encompass all tanks inside. After this, all geometric variables are determined and the geometric design of the fuselage and all components is completed.

CAFE can run this process in a standalone fashion as well as integrated into the BLADE hydrogen aircraft design loop. The process is depicted in Figure 16 and comprises the inner CAFE-HyDRA iteration logic as well as the outer BLADE logic (dashed lines). For this paper, both process options are utilized in the later chapters.

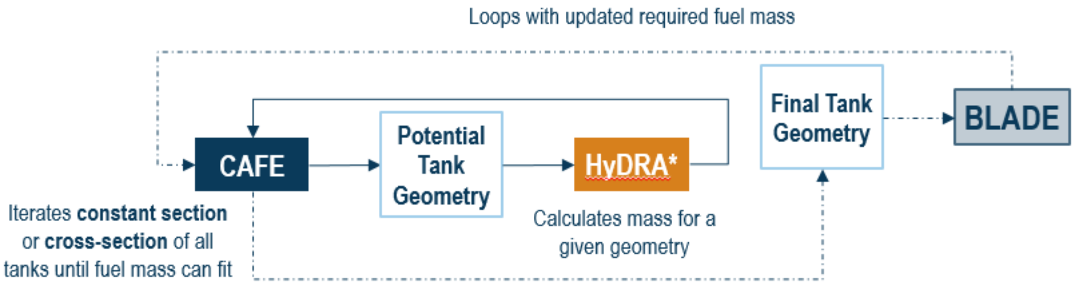


Figure 16 – Sizing methodology as standalone tool (solid lines) or in overall BLADE loop (dashed lines)

3.7 Mass Modelling

After the completion of the geometric modelling, the mass calculations for the cabin, the hydrogen tanks as well as the fuselage itself are performed.

3.7.1 Cabin Mass

The cabin mass is calculated using two different approaches. First, all components that are generated using the geometric cabin design in CAFE base their masses at least partly on their geometrical properties. For example, the galley mass and lavatory mass is scaled depending on the floor area covered. The seat mass is dependent on the preselected seat model and the overhead bin mass is dependent on the number of aisles and the length of the cabin. Second, other smaller components are calculated solely using semi-empirical or statistical methods from literature. For the cargo deck, similar techniques apply. [16, 17, 27, 28]

3.7.2 Hydrogen Tank and Fairing Mass

The hydrogen tank mass is calculated in HyDRA using the layer thicknesses and respective material properties to generate a mass for each layer. Additionally, attachment masses, safety factors and additional component masses such as a potential vacuum pump are applied according to Brewer [25]. This results in an overall hydrogen tank mass that is located in the volumetric center of the outer shell geometry of the tank.

Concerning the fairing mass, a simpler approach described in formula F.1 is applied. The relevant area is defined as half the fairing surface area, neglecting the lower half of the fairing ellipsoid located inside the fuselage shape. After multiplying this wetted area with the material density and the fairing shell thickness, the final mass results. The volumetric center of the semi ellipsoid is selected as the center of gravity.

$$m_{fairing} = 0.5 * S_{\text{fairing}} * \rho_{material,fairing} * t_{fairing} \quad \text{(F.1)}$$

3.7.3 Fuselage Mass

The fuselage mass estimation is a critical part of the whole modelling approach, as the fuselage is very sensitive to the mass and placement of tanks. The modelling is split into two parts, first dealing with the effect of hydrogen tanks that are located inside the fuselage primary structure, and second the effect of the hydrogen tanks and fairing that are located on top of the fuselage.

For the hydrogen tanks inside the fuselage primary structure, an approach presented by Balack [29] is selected. This method covers tanks that are placed aft of the cabin and fill out the whole aircraft cross-section and can be seen in formula F.2. For this paper, this approach is also selected for the front-cabin tanks, but keeping the limitations mentioned in chapter 3.5.2 in mind.

$$m_{fuselage} = \left(55\% + 45\% * \frac{l_{cabin}}{l_{fuselage}}\right) * m_{fuselage,LTH} \quad \text{(F.2) [29]}$$

The method assumes that the fuselage mass is split into two parts, the primary structure comprising of roughly 55% of the overall mass, as well as the secondary structure that comprises around 45% of the overall mass. Furthermore, Balack assumes that the secondary fuselage mass is mainly defined by the cabin dimensions. The assumption is thus that the 45% of secondary structure scales with the length of the cabin in relation to the overall fuselage length. This assumption yields very similar results to those of the PANDORA numerical design tool [30].

Regarding the over cabin tanks and the fairing that are located outside the fuselage structure, a different approach is used. Similar to the hydrogen tanks attached to the outside of the fuselage at a given x location, aircraft engines can also be attached to the fuselage, for example in a rear mounted configuration. For this case, Seitz [31] has developed a method to estimate the additional reinforcement mass needed for a fuselage structure in order to compensate a generic mass creating a lever arm around the main landing gear during the landing load case. Figure 17 depicts the general schematic of all lever arms considered for a generic penalty mass $F_{penalty}$.

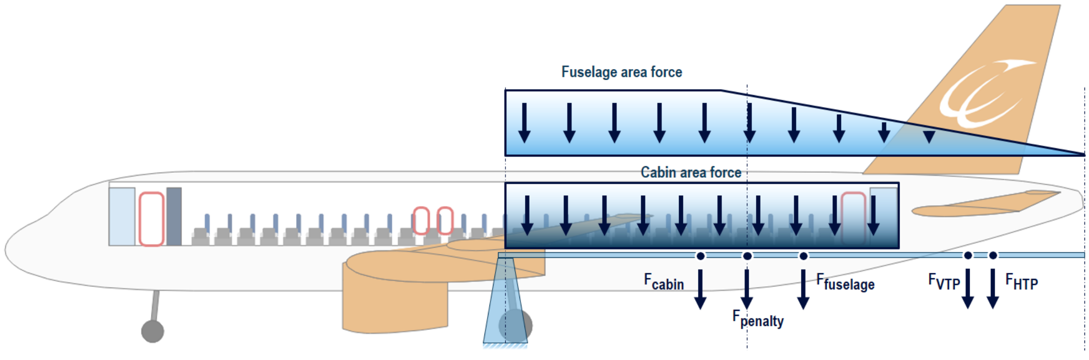


Figure 17 - Schematic of the Seitz lever arm method for a penalty mass $F_{penalty}$ (adapted from [31])

The method compares a reference fuselage that has to withstand a given momentum of cabin, fuselage as well as empennage forces with a fuselage that has to withstand an additional penalty momentum. First, the different momentums around the main landing gear position are defined (formula F.3).

$$M_{ref} = x_{fuselage} * F_{fuselage} + F_{cabin} * x_{cabin} + F_{VTP} * x_{VTP} + F_{HTP} * x_{HTP}$$
$$M_{new} = M_{ref} + x_{penalty} * F_{penalty} \qquad \text{(F.3) [31]}$$

The thickness of the idealized reference fuselage tube is defined by the reference bending moment and material properties, seen in formula F.4.

$$t_{ref} = \frac{2 * M_{ref}}{\pi * 0.5 * d_{fuselage} * \sigma_{fuselage}} \qquad \text{(F.4) [31]}$$

The thickness of the reinforced fuselage tube is calculated using the reference moment and thickness as well as the moment including the additional penalty mass (formula F.5).

$$t_{new} = t_{ref} * \frac{M_{new}}{M_{ref}} \qquad \text{(F.5) [31]}$$

The comparison of these two fuselage tube thicknesses, combined with a calibration factor, yields a penalty factor, representing the difference in the two fuselage tube masses. This factor is applied to a semi-empirical fuselage mass method of choice.

$$f_{penalty} = \left(1 - \frac{1}{f_{calibration}}\right) + \frac{\frac{t_{new}}{t_{ref}}}{f_{calibration}} \qquad \text{(F.6) [31]}$$

In CAFE, this approach is used to calculate the fuselage reinforcement mass due to the hydrogen tanks on top of the fuselage at any x position along the fuselage direction. Additionally, the fairing is split along the main landing gear position and is assumed to create a lever arm for its front and aft parts separately.

The Seitz method was validated using CENTRELINE project results, where an additional electric fan is attached to the aft of the fuselage [32]. Detailed FEM results are available for the reference and fuselage fan cases. When applying the Seitz method together with the LTH fuselage mass method [33] to both of these concepts with varying fan masses, the method delivers deviations from the published data by roughly 0.3% to 0.8%, proving its feasibility for aft mounted masses. When applied for hydrogen tank induced fuselage structure mass increases, this method might lead to optimistic results due to the lack of a pressure vessel cut modelling.

3.8 Concept Evaluation

In order to identify the best hydrogen fuselage concepts out of the many possible options, it is necessary to define key performance parameters as a way of comparison. The primary target is the identification of concepts on fuselage level. This enables a faster and more efficient evaluation strategy, as one fuselage design execution currently takes around thirty seconds, whereas an overall aircraft design can take up to one hour per aircraft.

3.8.1 Evaluation on Fuselage Level

On fuselage level, the key performance parameters fuselage structure mass [33], fuselage zero lift drag area [16], as well as the maximum center of gravity travel due to payload and fuel loadings are evaluated. Additionally, other parameters such as the tank mass, the unused fuselage volume, unused cross-section area, fuselage slenderness ratio and the overall mass of all fuselage components support the concept comparison.

Notably, the input hydrogen mass remains constant for all concept permutations and the other aircraft components such as landing gear, wing and empennage position and mass are not available. This leads to limitations of this evaluation approach for the over cabin tank configurations, as those need information on the landing gear, empennage, engine and wing properties for the disk burst corridor and fuselage structure mass calculations.

3.8.2 Evaluation on Aircraft Level

After the calculations of the concept permutations are completed, the fuselages are evaluated using the overall aircraft design process of BLADE. The key performance parameters consist of the maximum take-off mass and the design fuel mass. Depending on the input parameter set of the concept, BLADE might be unable to converge the given concept considering the boundary TLAR conditions. In this case, the concept is neglected.

The results on aircraft level are not directly comparable to the results on fuselage level, as the hydrogen mass is not fixed anymore but a dynamic variable that is varied to meet the mission requirements (see Figure 16).

The over cabin tanks and the fairing require modelling effort outside the fuselage domain, such as the adaption of the VTP dimensions to compensate for the aerodynamic blocking effect of the fairing and the modelling of the fairing drag. As of the creation of this paper, the implementation is not yet completed. The results for the over cabin tank configurations may therefore change.

4. Application and Results

This chapter first presents the study parameters selected for the study and then highlights the kerosene aircraft studies on fuselage and aircraft level. It concludes with the hydrogen aircraft concept studies on fuselage and, where applicable, aircraft level.

4.1 Study Parameters

The studies performed in this paper are based on Airbus A320 style aircraft concept modelled in BLADE. The overall aircraft TLARs remain constant throughout the studies performed. Table 1 depicts the different parameter inputs.

Table 1 - Study Parameters

	Fuselage Level Study	**Aircraft Level Study**
Seat Abreast	2-2, 2-3, 3-3, 2-2-2, 2-3-2, 3-3-3, 3-4-3	Filtered by feasibility
Hydrogen Mass	7021 kg	dynamic
Passengers	180	180
Sizing variables	Hydrogen tank constant sections / cross-sections to meet target hydrogen mass	Engine design thrust to meet TLARs such as time to climb or takeoff field length
Tank variations	Dynamic aft tank, dynamic aft + front tank, over cabin tank, over + aft cabin tank	Dynamic aft tank, dynamic aft + front tank

In a first study, the models are applied for the reference kerosene aircraft, with the variation in seat abreast being the only altered design variable throughout the aircraft. In a second step, the hydrogen aircraft are calculated, first on fuselage level with a fixed hydrogen mass of 7021 kg, then on aircraft level on a dynamic basis depending on the aircraft needs. The fixed hydrogen mass is selected based on previous studies by BHL with a hydrogen powered Airbus A320 and one aft hydrogen tank.

4.2 Reference Results

4.2.1 Fuselage Level

In this initial study, the whole design space for seat abreast is applied to the reference aircraft with kerosene. The following Figure 18 depicts the key performance parameters of fuselage slenderness ratio, zero lift drag area at cruise conditions, structure mass as well as utilized fuselage volume, all plotted over the cabin width. The labels highlight the seat abreast selected. A trend is created for each group of results that have the same number of aisles, representing groups of cabins with the same cross-section penalty of space not usable for seats. As it can be seen in each of the four graphs, the 3-3 configuration on fuselage level is by far the best in terms of drag, mass as well as volume utilization. This is the expected result, as the 3-3 configuration is the one that is used for 180 passenger aircraft today. The 2-3 configuration has some potential according to the mass and drag results.

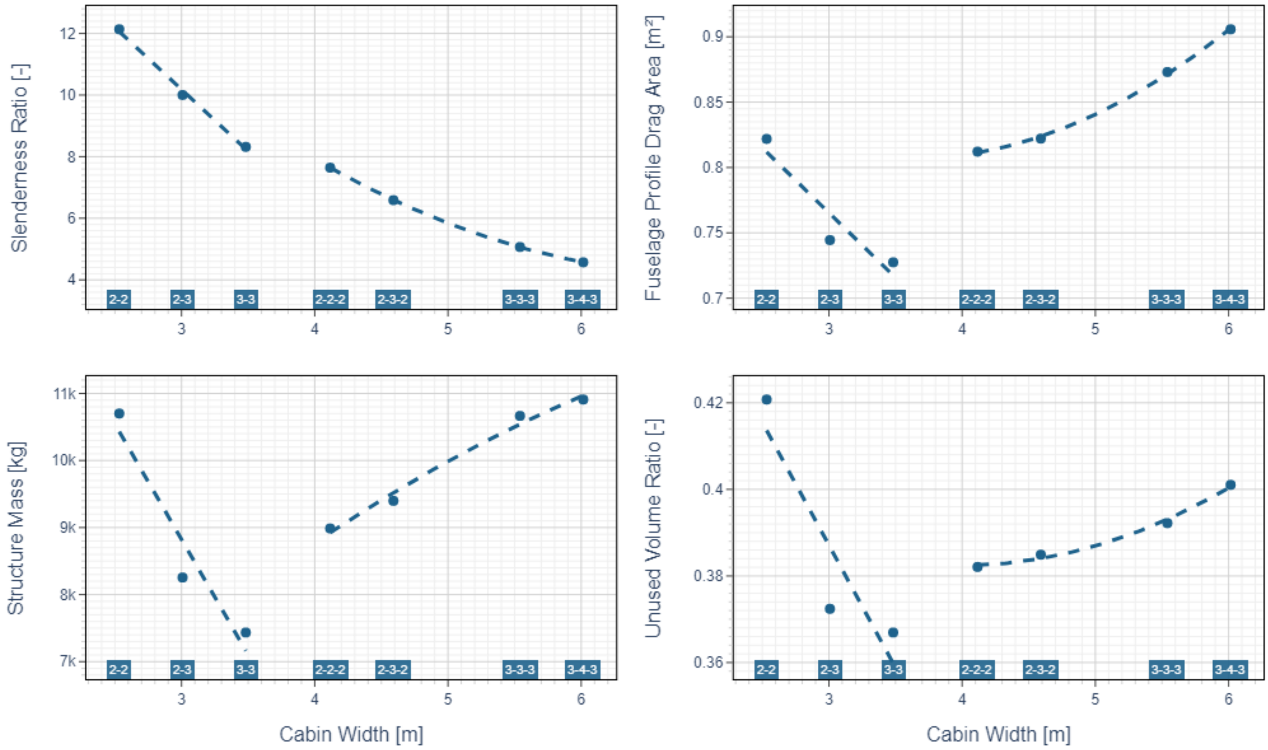


Figure 18 – Fuselage level reference study

On fuselage level, the two aspects significantly affecting aircraft performance (see Breguet range equation) are the drag and mass contributions. Plotting those two parameters in one graph (Figure 19), similar trends to the previous figure occur. The further to the bottom left, the more beneficial a concept is in general. Notably, the more unconventional the shape of the aircraft, the more uncertain the structure mass and zero lift drag area semi-empirical methods are due to the lack of statistical data.

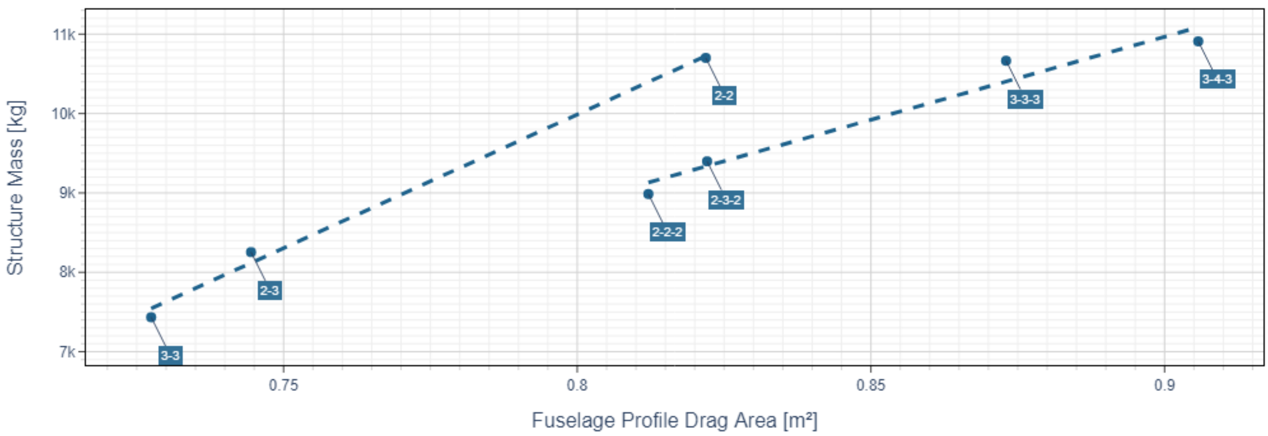


Figure 19 - Reference study mass-drag area dependency

In a future step, this dependency could be used to create a figure of merit to identify beneficial concepts, for example based on their combined structure mass and zero lift drag area impact on the design fuel burn. This step is however out of scope for this paper.

4.2.2 Aircraft Level

Next, the same input parameter variation is applied to the overall aircraft design process, creating the results that can be seen in Figure 20. As the fuselage dimensions do not change in the overall aircraft design loop compared to the fuselage level study for the reference study, only the maximum takeoff mass and design fuel mass are plotted. The largest seat abreast of 3-4-3 is not depicted in the graph as the extremely short fuselage leads to a non-feasible overall aircraft design.

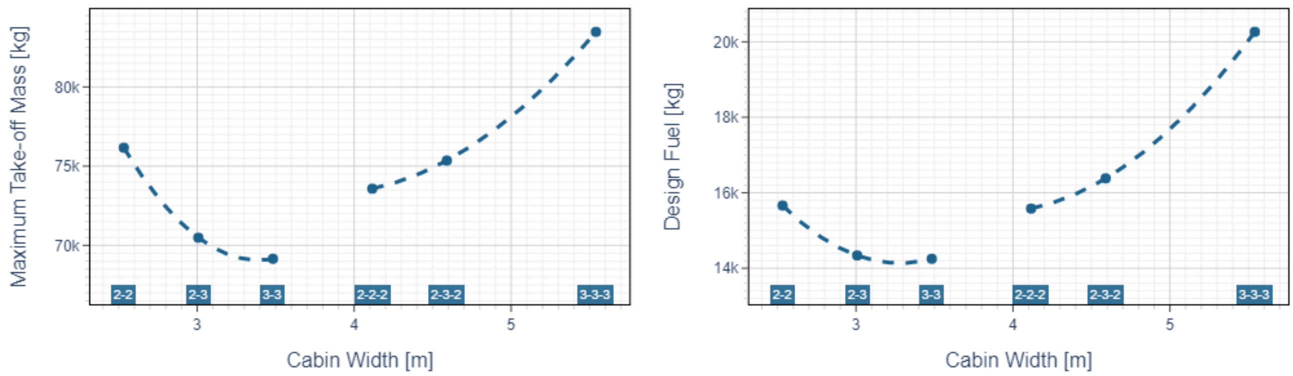


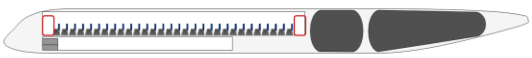
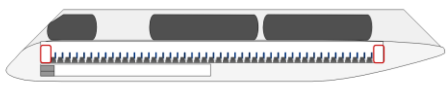
Figure 20- Aircraft level reference study

Generally, these graphs confirm the trends visible on fuselage level and confirm the 3-3 seat abreast choice for current commercial single aisle aircraft. The 3-2 configuration has a very similar design fuel and highlights the potential for this narrower cabin layout. All other concepts seem unfeasible as they have a much higher fuel consumption on the design mission, resulting in uncompetitive high operating cost for the airline. Comparing the results to the fuselage level assessment, the fuselage structure mass and especially the fuselage zero drag area show the same trends as the design fuel mass.

4.3 Hydrogen Tank Study

For the hydrogen concept studies, the tank layouts of Table 2 have been assessed. Note that of course for each seat abreast variation, the dimensions can differ but the overall arrangement remains. The concepts shown are for illustration of the tank locations only.

Table 2 - Tank configuration layout schematics

Tank Type	Plot Color	Configuration Schema
Dynamic aft tank		
Front and aft tank		
Over cabin tank		
Over cabin and aft tank		

4.3.1 Fuselage Level

In a next step, all permutations of the input seat abreast are applied to the hydrogen tank configurations of dynamic aft, front and aft, over cabin and aft as well as over cabin. The results are depicted in Figure 21. Some parameter sets do not result in feasible, converged fuselage concepts due to very short fuselages or very elliptical tanks and are thus neglected.

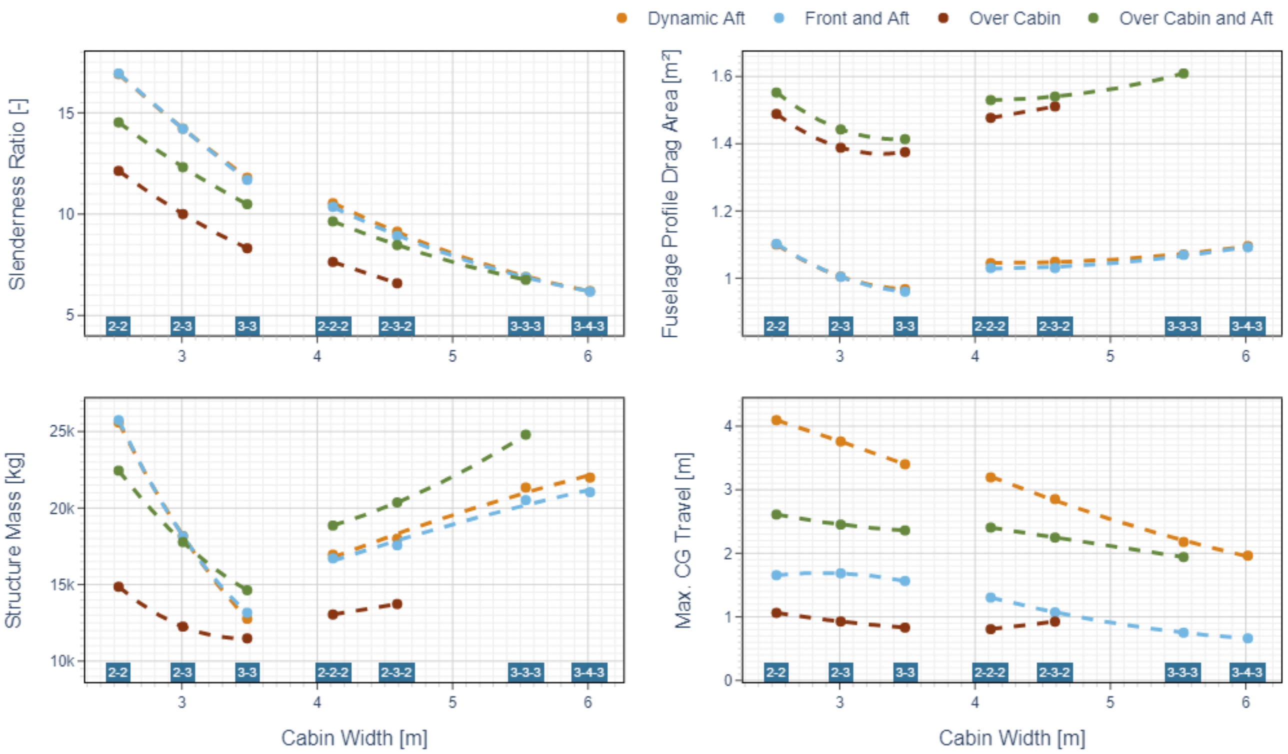


Figure 21 - Fuselage level hydrogen study

There are distinct, clearly identifiable patterns for each tank configuration in the figure. Regarding the total structure mass of tanks, fairing and fuselage, the over cabin tanks seem to be the best choice for all configurations assessed. Over cabin tanks combined with an aft cabin tank perform worse in every category. Regarding drag area, the front and aft tank configurations are superior to the over cabin tanks, whereas regarding the mass the over cabin tank concepts perform better. As mentioned previously, the over cabin tanks modelling is dependent on other aircraft components and their positioning, for example for the disk burst area. The trends can thus differ from the overall aircraft level results.

All tank concepts seem to have a minimum of drag area and mass at the 3-3 configuration, comparable to the reference kerosene aircraft. Only regarding the center of gravity travel, a tendency towards larger diameters can be observed. This hints at the possibility that overall aircraft results could be more beneficial for these concepts with higher seat abreast due to a possibly high impact of CG travel on trim drag. The further the concept deviates from the 3-3 layout, the higher the structure mass and drag area.

Figure 22 again shows the dependency of (fuselage, tanks plus fairing) structure mass versus fuselage drag area. Generally, narrow cabin configurations seem to be beneficial, with the 3-3 and 2-3 configurations being the most beneficial (meaning most left bottom) ones for all concepts. Over cabin tank configurations have a significantly higher drag area that front and aft configurations with partly reduced structure masses. Their performance advantage has to be assessed on overall aircraft level when the center of gravity travel comes into consideration.

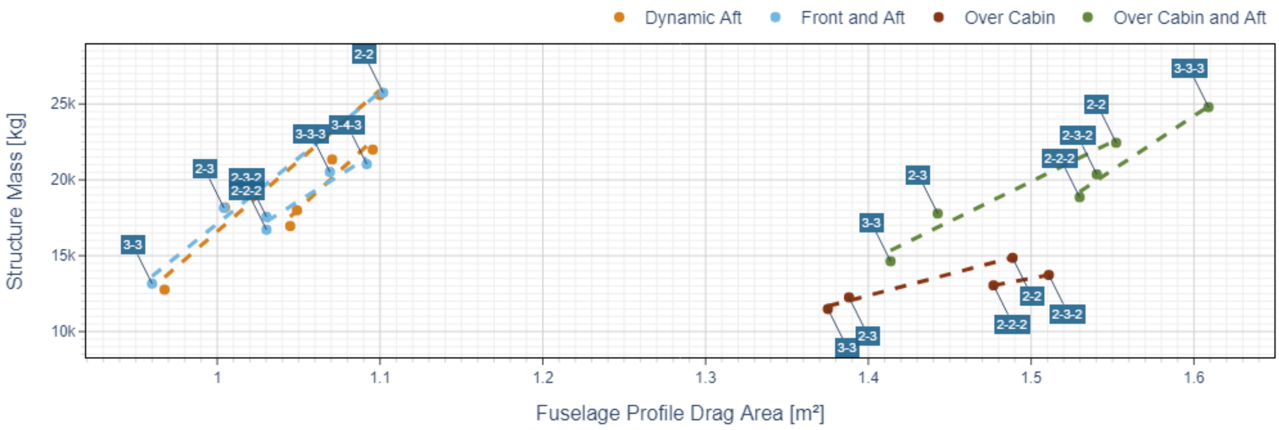


Figure 22 - Drag-mass area dependency for the hydrogen aircraft

4.3.2 Aircraft Level

Finally, various concepts are evaluated in terms of maximum take-off mass and design fuel using the overall aircraft design, as seen in Figure 23. The first noticeable aspect is that some concepts can, at the current time, not be calculated using BLADE. This includes the extreme 2-2 and 3-4-3 seat abreast layouts as well as all twin aisle over cabin tank configurations. The reasons for this are for example limitations to the applied engine model and the occurrence of highly elliptical hydrogen tank cross sections that prevent a converged hydrogen tank design due to numerical instability stemming from the implementation of HyDRA.

The available data points however depict a clear trend. At least for an A320 size aircraft, a deviation from the typical 3-3 cabin layout is not beneficial, as the reduced center of gravity travel cannot compensate the disadvantages of increased structure mass and drag. Comparing the different tank configuration options, similar trends to the fuselage level assessment occur. Keeping the limitations of the over cabin tank modelling in mind, those configurations seems to perform best, at least as hinted by the single aisle configurations. A front and aft configuration yields only slightly increased design fuel masses. Here, with an increased modelling depth, the potential structure mass penalty of a separated pressure vessel is expected to worsen the performance. Over cabin and aft tank or dynamic aft tank configurations represent inferior choices in the current state of BLADE modelling.

Interestingly, the ranking of the different concepts in terms of design fuel mass resembles the ranking of the center of gravity travel in Figure 21. This is caused partly by the resulting trim drag as well as the overall positioning of aircraft components due to the center of gravity shifts.

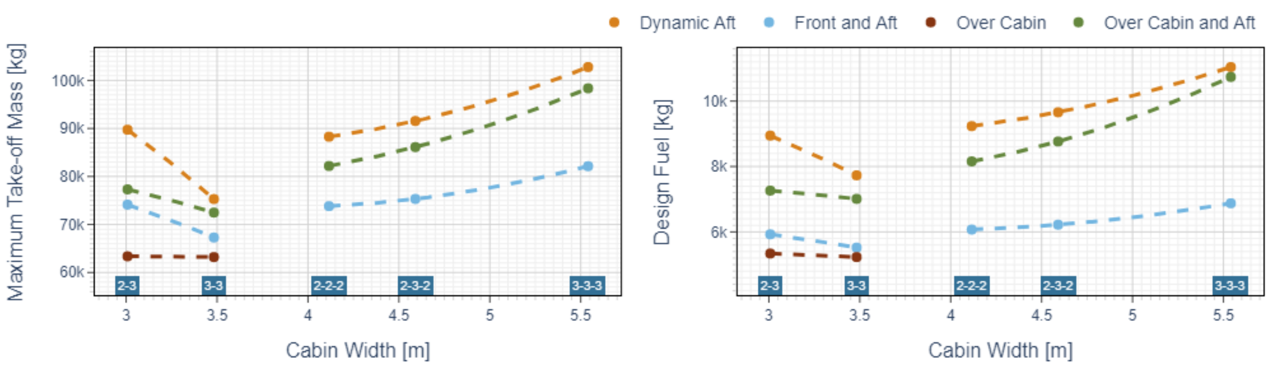


Figure 23 - Overall aircraft design results for the hydrogen concepts

Concluding, this means that for hydrogen tank concepts, the mass and drag results on fuselage level (Figure 22) fail to highlight the overall best configurations because they neglect the center of gravity shift as well as potentially other impactful parameters. A figure of merit to identify the best concepts on fuselage level is thus required to incorporate additional parameters.

5. Conclusions

This paper determines the most promising hydrogen fuselage concepts and evaluates them both on fuselage and aircraft level using key performance parameters such as the fuselage structure mass and zero drag area. The assessment is powered by the integrated cabin, fuselage and hydrogen tank design in BLADE. Using the two modules CAFE and HyDRA, geometrically optimized fuselage concepts can be derived for a given configuration and hydrogen mass, both standalone and as part of an overall aircraft design.

For an A320 class aircraft with 180 passengers and using the current state of the BLADE modelling, the conventional 3-3 seat abreast is the best choice for any configuration, as indicated by the design fuel and maximum take-off mass. For conventional kerosene powered aircraft, the fuselage level trends of drag and structure mass match those of design fuel mass on overall aircraft level. For hydrogen fuselage concepts, these two fuselage level parameters neglect seemingly important effects, as the trends on overall aircraft level differ. In order to identify beneficial hydrogen tank concepts on fuselage level, a future figure of merit needs to include additional parameters such as the center of gravity travel. The overall aircraft results show that, regarding the design fuel mass, the over cabin tank configuration is clearly preferable, while aft tank configurations do not seem feasible. Generally, distributing the tank and hydrogen mass along the fuselage length is beneficial, mitigating CG travel and thus trim drag.

Currently, some limitations apply to the results generated with CAFE, HyDRA and BLADE. First, the overall aircraft design modelling of the over cabin tank arrangements and fairings is not completed yet, limiting their reliability. Second, the effect of an increased cabin and thus fuselage width and their contribution to the overall aircraft lift generation is neglected. Regarding the fuselage structure and the pressure vessel in particular, the effects of a pressure vessel cut due to front cabin tanks, the walkway connecting cabin and cockpit as well as the effect of highly elliptical cabin shapes on the pressure vessel mass are not considered. Lastly, the fuel system model is very simplistic.

For the future, this hydrogen fuel system could be added to the fuselage model in CAFE, creating new sensitivities regarding the distance of tanks to the wing and the engine respectively, potentially shifting the optimum to other cabin configurations. Also, a different variant of over cabin tanks that is not contained in a fairing but rather inside the fuselage primary structure could be assessed. Future studies could also assess a variety of aircraft sizes ranging from the ATR-72 up to an Airbus A380, introducing the number of passenger decks as an additional variable in the design process. Lastly, a figure of merit could be introduced to try to identify promising fuselage concepts for all tank configurations already on fuselage level, increasing speed and efficiency of studies.

Concluding, this paper compares various different cabin and hydrogen tank layout variations and identifies the most beneficial concepts. It thus contributes to the research efforts in the hydrogen aircraft design space and indicates promising pathways to bring aviation a step closer to ushering in a low emission era.

6. Copyright Statement

7. Acknowledgements

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