



EXPLORATION AND EVALUATION OF KNOWLEDGE-BASED ENGINEERING APPROACH FOR LIQUID HYDROGEN TANK INTEGRATION IN EXISTING FUSELAGE

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Abstract

This paper introduces an initial analysis conducted on an aft-type *Liquid Hydrogen* (LH2) tank in an aircraft, exploring different cabin definitions and tank configurations. Additionally, it delves into an investigation of the utilization of a web application to depict a *Knowledge-Based Engineering* (KBE) application that was developed. As aviation technology advances towards a more sustainable future, there is a growing necessity for innovative concepts to achieve zero emissions and sustainability goals. In pursuit of these goals, a preliminary study is conducted that encompasses the assessment of stability factors such as the *Center Of Gravity* (CG) and *Static Margin* (SM), along with an exploration of the range achievable when utilizing LH2 as a fuel source. For the analysis, a virtual in house cabin design tool is used, known as *Fuselage Geometry Assembler* (FUGA), this provides a digital model of the cabin of both single and twin-aisle configurations of commercial aircraft. The information on aircraft characteristics is provided to FUGA using the *Common Parametric Aircraft Configuration Schema* (CPACS). Coupling both CPACS and FUGA provides the user with a consistent model of aircraft and cabin design. For ease of use and better visualization of information from FUGA, a web-based application is developed using Flask. This enables the user to access the FUGA tool without the need to install the tool on their devices.

Keywords: Knowledge-Based Engineering, Liquid Hydrogen Tank, Aircraft Design, Web Application, Sustainability

1. Introduction

Configurations of hydrogen-powered aircraft focuses on reducing the global carbon footprint of aviation [1]. A LH2-propelled gas turbine is a strong consideration towards flight-path 2050 [2] with a greater vision towards a greener aviation industry and contribution to different platforms and companies in research and development for reducing emission. Incorporating digital technology in the initial stages of aircraft development serves as a driving force toward achieving net-zero emissions. A digital application approach derived from years of solid experience of engineers in the domain of aircraft designing, development, and manufacturing will greatly benefit digital technology implementation. One such approach of KBE [3] increases the efficiency of digital processing by reducing computational time, enabling innovative designs and adhering to the industrial standards of aviation manufacturing.

This paper is derived from the master thesis “Knowledge-Based Engineering Application For Fuselage Integration And Cabin Design” on KBE application for fuselage integration and cabin design for a detailed understanding and analysis of LH2 tank configurations on varied single and twin-aisle configurations. The study has been carried out at the Institute of System Architecture in Aeronautics of the *German Aerospace Center* (DLR) [4]. The institutes main focus is to introduce digital aircraft architecture and systems to increase interdisciplinary capabilities with a common design application or

interface medium. The common design application enables engineers and researchers from different domains to access and modify the same system, thus enabling unified performance and parameters of the aircraft. One such implementation of a unified aircraft parametric model is the CPACS. It provides access for engineers and researchers of different disciplines to exchange information on the same aircraft using different tools, hence enabling multi-fidelity design capabilities in a distributed environment [5].

To carry out the study analyzing different cabin configurations with LH2 tanks, parametric digital cabin mock-up models are required. DLR has developed an internal tool called FUGA capable of generating details of cabin models based of KBE, making parametric in nature [6]. The introduction of a web-based application makes the interactive experience more user-friendly and engaging with immediate representation of cabin design.

A major contributor to the sustainable aircraft developments is the introduction and research of LH2-propelled engines [7]. Through the study and analysis of different LH2 tank configurations integrated into existing aircraft fuselages in both single and twin-aisle configurations, this paper will explore the advantages and disadvantages of retrofitting a liquid hydrogen tank. FUGA had the modularity to integrate liquid hydrogen tank configuration, this yields more accurate and realistic digital cabin mock-up models for conducting the studies. Discussions about the proposed method are presented at the end of the paper, together with brief thoughts about possible next steps for this work.

2. Fundamentals

This section is intended to highlight and explain various fields and methods related to the presented work and problem outlined in the introduction.

2.1 Knowledge Based Engineering

KBE is utilized to automate repetitive design procedures and arrive at the optimum design, saving time and enabling the designer to explore vast design points [8], hence, KBE has been a major advantage for aerospace and automotive industries. The competitive world and demanding markets require means of increasing the rate of product development while reducing the time and costs that are incurred in the process. To achieve the demand, especially in a design domain, the technology that supports rapid and modular design is KBE [3].

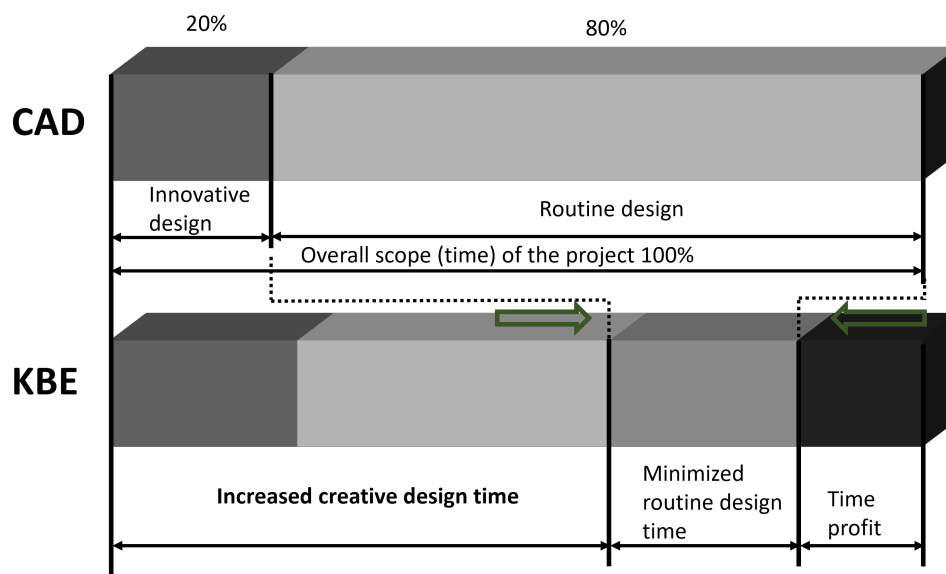


Figure 1 – Time Profit through KBE approach diagram adapted from Skarka [9]

Skarka [9] states that there is no unambiguous definition of KBE. But the noticeable advantage of KBE is illustrated in Figure 1 which shows the time profit achieved by using KBE. The KBE approach is used to automate repetitive design tasks which allow the designer to focus on creative tasks.

2.2 Fuselage Geometry Assembler

Fuselage Geometry Assembler (FUGA) is a tool that provides preliminary cabin design, structural design, cargo hold designs, and aircraft design closely interlinked into a single frontier. The main design characteristics of the aircraft such as fuselage profile, wing box location, wing properties, etc are derived from CPACS.

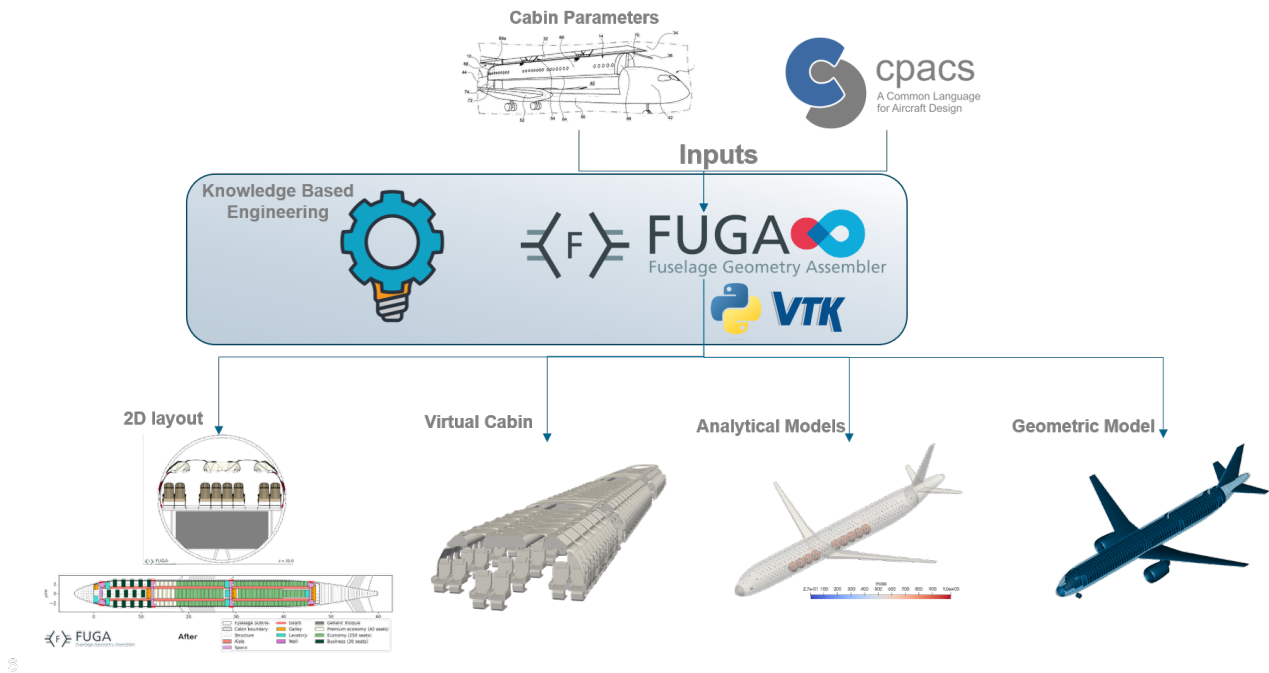


Figure 2 – Overview of FUGA

The position of components that are present inside the cabin needs to be co-related to one another and should not overlap. This consistency is maintained through various numbers of rulesets that are implemented in FUGA using a knowledge-based engineering approach. As illustrated in Figure 3 from Walther JN, et al. [6].

The MCG as shown in Figure 3 represents the relationship between different components of the design system. At the initialization of the FUGA tool, the necessary data required for the optimum functioning of the tool is imported from the data repository, which is CPACS for FUGA. The rulesets that are visualized above are coded in Python using the NetworkX python package as the basis. [10]. This nodal-based approach and graphical visualization help FUGA in easing the implementation of the KBE approach and providing a sound relationship between multiple design components within the design system. The KBE approach that is inherited in FUGA from La Rocca [11] consists of 3 fundamental elements in KBE approach. Those elements are 1. data repository, 2. knowledge repository containing design rulesets, and 3. An inference engine to select the corresponding rule-sets to generate additional data. This rule-based approach provides FUGA the flexibility and ability for Multi-Model Generation.

2.3 Common Parametric Aircraft Configuration Schema

CPACS is a widely used central data exchange format that allows engineers and researchers from various domains to collaborate on a common platform. it provides a source for creating multi-fidelity

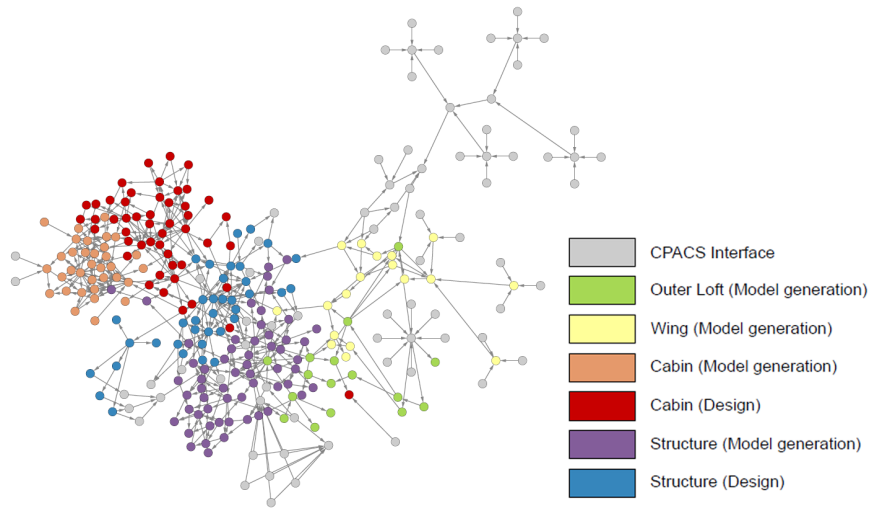


Figure 3 – *Maximal Connectivity Graph (MCG)* of rule sets.[6]

models and has been used in the application of many projects in the German Aerospace Center [12]. It also acts as a common platform in which experts from multiple disciplines can share their opinions on a single aircraft model.

CPACS is designed in a *XML Schema Definition (XSD)* document for its advantage of the hierarchical structure, this is also highly defined for the development phases of an aircraft. This hierarchical structure yields advantages for parametric abstracts and mapping of aircraft geometry [13]. A more detailed structure of CPACS is seen in Figure 4.

The primary purpose of CPACS was initially discussed to bridge the gap between different institutes and fields and to establish a co-relation between the professionals in the respective fields [15]. This would in turn provide a multi-disciplinary description of an aircraft, which not only defines a structural understanding of the aircraft, but also the performance, system details, the flight path taken by the particular aircraft, and much more.

2.4 Liquid Hydrogen in Aviation

The air transportation industry will witness an increase of 4.3% in commercial operation in the next two decades [2]. the aviation industry is now moving towards LH2 propulsion as an alternative due to increased consumption of fossil fuel[16],. The aviation sector today produces around 2% of the global greenhouse gas emissions, which contributes to 8% of the total world economic activities in terms of *Gross Domestic Product (GDP)*. Aviation industries are pushing their work towards using *Sustainable Aviation Fuel (SAF)* and LH2 fuel as an alternative source with a reduced carbon emission of up to 40% when blended with fossil fuel [17]. This aids in tackling the rising *Carbon Dioxide (CO2)* global emission projected at 61% every 5 years[18]. To achieve zero carbon emissions by the year 2050, it is crucial to take the next step by undergoing intensive research, development, testing, certification, and multiple processes within the industrial standard [18].

Transitioning from conventional aviation fuel to LH2 fuel necessitates substantial modifications in fuel storage for aircraft. The traditional practice of storing fuel within the wings is impractical due to specific design criteria that must be satisfied to ensure the proper and safe utilization of LH2 tanks [19]. Furthermore, Hydrogen possesses three times more heat content for each mass when compared to kerosene, thereby affecting the range of the aircraft.

W Xu, Q Li, and M Huang [20], explore the practical implementation and design of cryogenic hydrogen storage tanks for unmanned aircraft. Figure 5, shows the comparison between LH2 and

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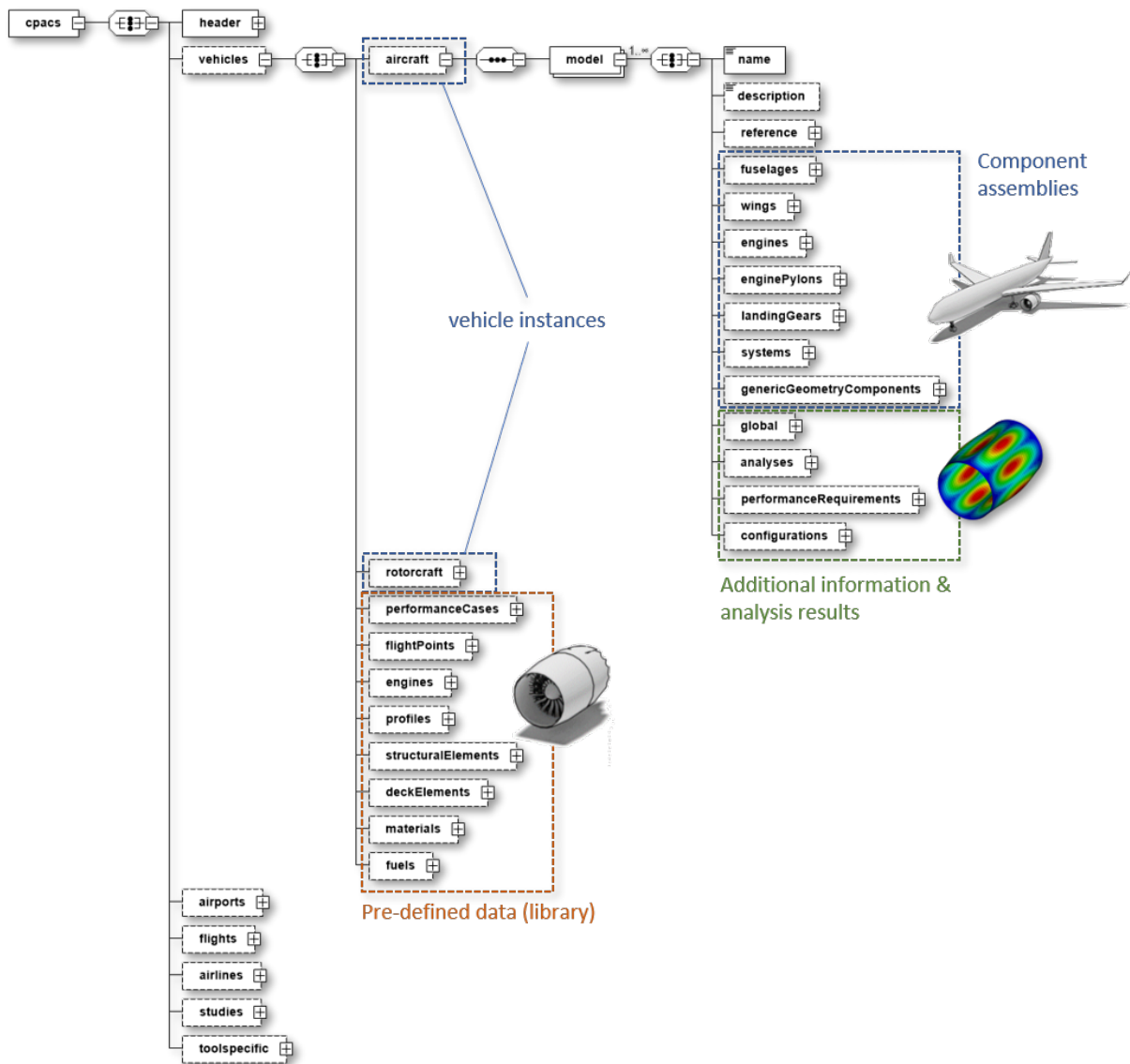


Figure 4 – CPACS Data structure tree illustrated in [14]

kerosene over weight and volume. However, for the same mass it is seen that the LH2 has 2.8 times more energy than that of kerosene which can be advantageous for having a longer cruising time. However, the volume of LH2 is 4 times more than kerosene or any conventional aviation fuel, making it consume greater space for fuel storage. LH2 can only maintain its liquid state at a temperature below 33 [Kelvin]. This would require an additional system to sustain the desired temperature, in turn contributing to energy consumption and utilization of cabin space and weight.

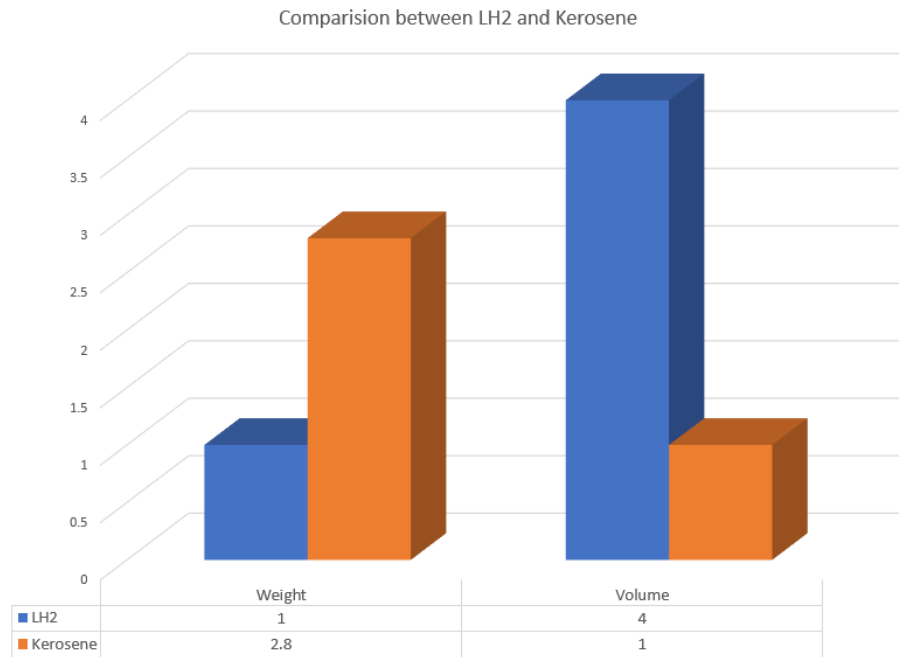


Figure 5 – Ratio of weights and volumes for LH2 and Kerosene

D. Verstraete [21] discusses the potential of hydrogen utilization in transport aircraft, marking a significant stride toward sustainability in aviation. The conceptual retrofit design focuses on narrow-body and wide-body configurations, thereby minimizing the need to extend the aircraft fuselage. To accommodate the required tank volume, the cabin was modified to share space with the LH2 tanks, resulting in a reduction in *Passengers* (PAX) capacity. The integral tank configuration considered two designs: one with two integral tanks at the front and back, leading to the separation of the cockpit and cabin; the second design involved a “top tank” positioned on the top and in the aft region, allowing connection of cockpit and cabin but with a substantial increase in tank weight. Opting for the top tank resulted in a 28.1% weight increase compared to integral tanks for short-range and a 50% increase for medium-range aircraft. Notably, the energy efficiency observation for long-range missions showed an improvement of around 12%, while for short-range missions, there was an energy penalty of 18%, attributed to the tank’s weight.

2.5 Utilizing KBE Techniques in Web-Based Application

In the domain of KBE, where automation is employed to achieve specific product outcomes and results, it is important to have a suitable platform for user interaction and results, thereby increasing the collaboration and Utilizing for the Tool or product, a web application emerges as a viable solution. A KBE approach plays an important role in the initial stages of aircraft design. The work carried out by Munjulury, R.C. [22] on the knowledge-based aircraft conceptual design applications, to facilitate interaction among various applications, a multifaceted user interface was developed, which uses a data-centric approach by using *Extensible Markup Language* (XML) for parametric data definition with generation of 3D *Computer-Aided Design* (CAD) with the same parametric data set. Three modules were integrated, with XML serving as the central database. These modules include a sizing tool with CAD components, an aerodynamics estimation and analysis module, and another module dedicated to estimating and integrating system architecture for the analysis of system-to-system interactions. The study also outlines the use of a multidisciplinary design optimization platform for evaluating diverse designs.

Reddy et al. [23], highlight the role of a web application within a KBE system, emphasizing its role in improving user interaction and effectively addressing customer needs when compared to traditional design approaches. The product visualization developed includes 2D drafting and 3d models with an

interactive window allowing the user to select requirements for better understanding [23]. The user experience is improved by the incorporation of audio, video, text, and animation using *Hyper Text Markup Language* (HTML) technology. In addition, the work carried out by Tu Y. and Xie S., in [24], delves into the efficient inter and intra-communication among companies. This efficiency is achieved by incorporating a Web platform facilitating faster responses to customer requirements, resulting in saved production costs and improved globalization.

A Web app was developed by Qin SF. group [25] as seen in Figure 6, this platform establishes connections among design partners, sales, customers, and manufacturers. Additionally, it enables rapid internet-based simulation of product behavior during the design phase, with the results displayed.

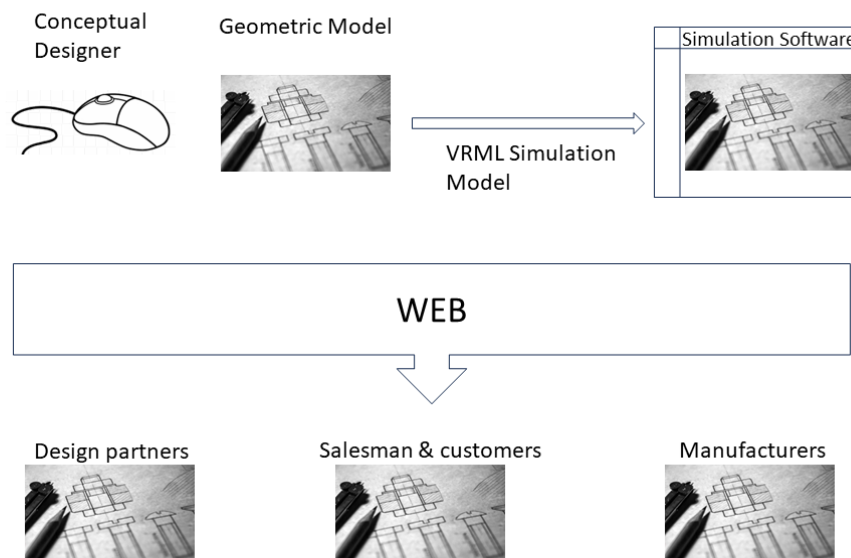


Figure 6 – Adapted Example showcased by Qin SF. [25] for a potential application scenario.

3. Method

This section is divided into two sub-sections: sub-section 3.1 presents and demonstrates the method followed for generating the different aft-tank configurations, and the latter sub-section 3.2 shows the method used for the implementation of web-based application for a KBE systems.

3.1 Hydrogen Tank Implementation

The aft-type hydrogen tank was implemented using FUGA, with appropriate changes done to CPACS input file, following which the tank configuration changed during the FUGA structure running. The adaptable implementation of the tank allows users to design the optimal tank configuration for their cabin setup and input information to the desired level of detail. Additionally, upon executing the configuration, diverse output data is generated. This includes calculations and details for individual tanks if multiple tanks are utilized, encompassing tank volume, fuel weight, and total tank mass, inclusive of miscellaneous weights. The method and workflow of obtaining the desired configuration are summarized in Figure 7.

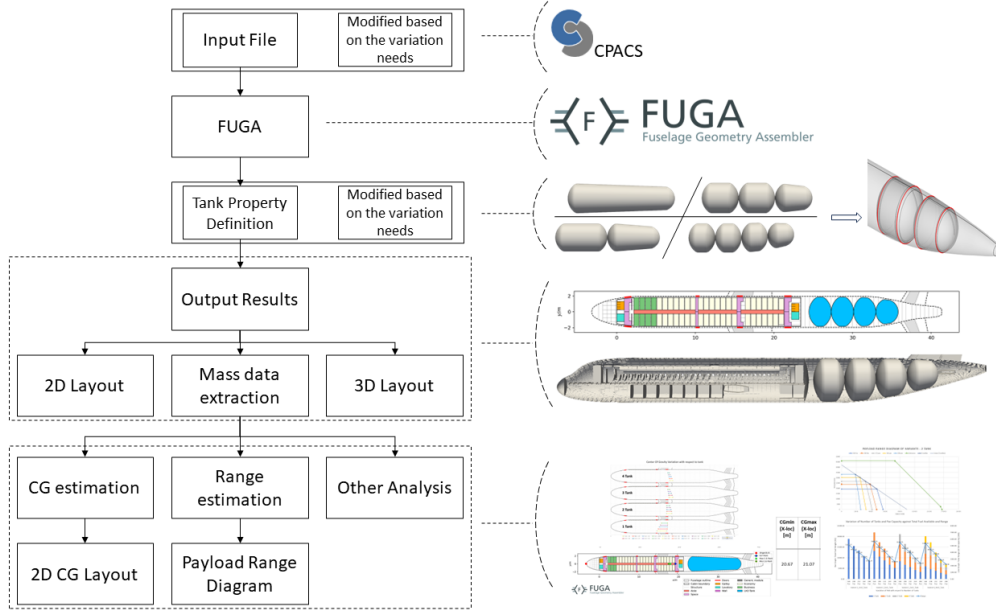


Figure 7 – Process of generating results for different variations of PAX capacity with tank configuration.

Evaluating and analyzing configurations based on variations in tank quantities and passenger capacity is essential to achieve the optimum design for both single and twin-aisle configurations. To reach all points in a design space, a wide range of tank quantities and passenger capacity were combined and varied in both single and twin-aisle configurations to find the optimum design.

To calculate the CG and SM, component weights were derived from the Mass model within the FUGA tool. This model encompassed the x, y, and z locations along with their respective masses. The SM, expressed as a percentage of the *Mean Aerodynamic Chord* (MAC), was determined using Equation 1.

$$StaticMargin(SM) = \frac{NeutralPoint(NP)location[m] - Mass(x/y/z)Location_{min/max}[m]}{MeanAerodynamicChord[m]} * 100 \quad (1)$$

The aircraft's range is computed utilizing Breguet's range equation [26]. Equation 2 considers various factors such as flying conditions, engine performance, weight differentials, and overall flying performance.

$$R = \frac{v}{g * TSFC} \frac{L}{D} \ln \left(\frac{W_{initial}}{W_{final}} \right) \quad (2)$$

3.2 Implementation of Web Application

The FUGA web application was implemented using the Flask framework. The choice of Flask was primarily due to the ease of tool implementation because both Flask and FUGA were programmed in Python.

Before choosing Flask, various web frameworks were examined using evaluation criteria such as being lightweight and flexible, ease of learning, modularity, scalability, and cross-platform compatibility. Using these factors, the various frameworks were scored to inform the selection process. The scoring and selection process of the web framework can be seen in [4].

The overall flow of the webpage and the general architecture implemented for FUGA is depicted in Figure 8. All the Flask modules created correspond to the options made available on the web screen. That is, when a particular option or button on the screen is clicked, the respective module in the FUGA-Flask framework runs and executes, and the modules can be programmed for n number of tasks like opening a new window, inputting/outputting files, pop-up displays of 2D layouts, 3D model generation, and download options.

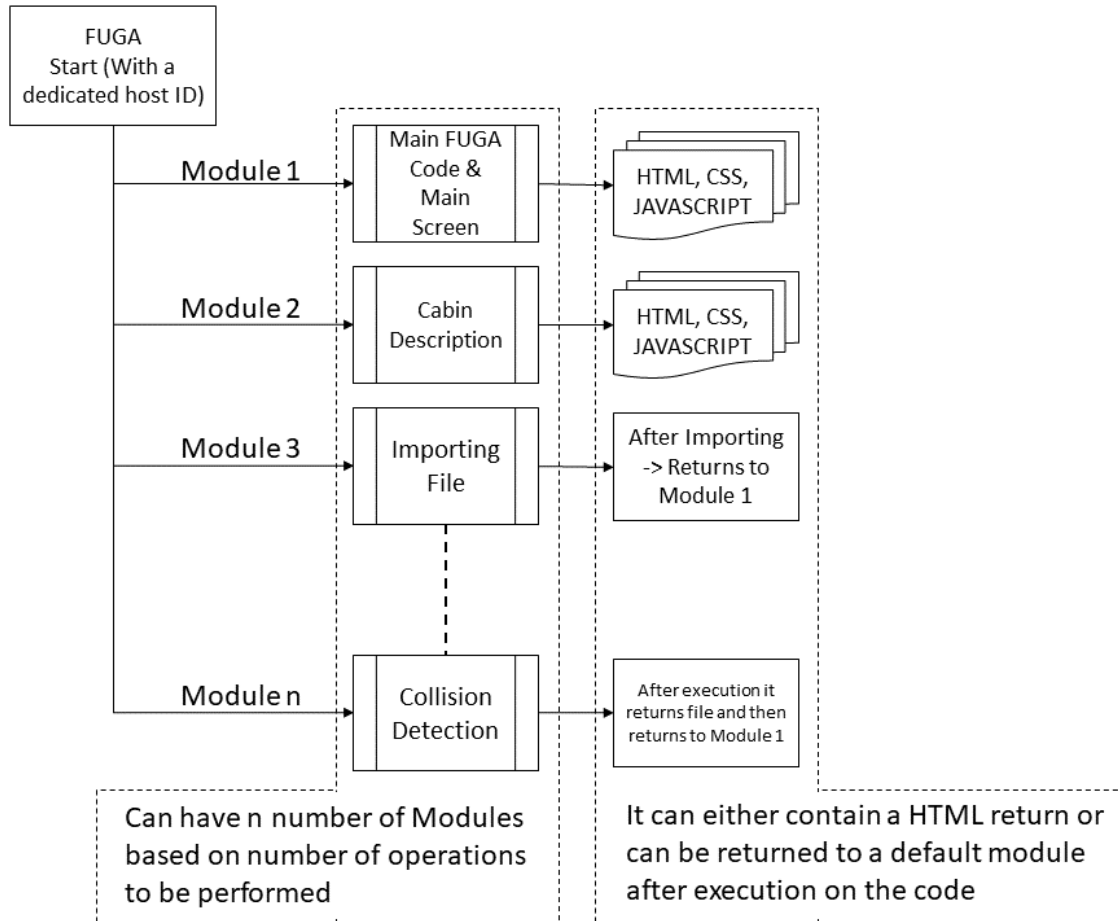


Figure 8 – General Flask architecture for FUGA application.

4. Case study Implementation

To evaluate various aircraft aisle configurations, a case study is implemented where the aircraft will fly under specific configurations and conditions. This approach ensures comparability among different aircraft configurations by subjecting them to the same conditions. The methods are presented in section 3. lays the foundation on which the studies will be implemented.

4.1 Case Study Delimitations

The delimitation that are present in this paper are tabulated below. The duration of the study and level of complexity in applying the concept play a crucial role in representing the delimitation of the paper.

- The accuracy and current effectiveness of FUGA, and its aisle configuration capabilities.
- The knowledge level of LH2 tank for the purpose of retrofitting into existing fuselage of commercial aircraft.
- Initial stages of web-based application limiting the flexibility of KBE through a web-based application.

- Total passenger capacity of single-aisle configuration capped to 192 PAX and twin-aisle configuration to 288 PAX.
- Assumptions on LH2 tank integrity and approximate space allocation for supporting systems such as pumps, etc.

4.2 Single and Twin-aisle Configuration

The conditions for both aisle configurations are maintained the same to derive results based on equal conditions and boundaries. The aircraft of both aisle configurations are considered to be flying at the speed of 220 m/s at 35,000 feet. It is also assumed that all configurations have the same lift-to-drag ratio of 17. With the common boundaries implemented, single and twin-aisle configurations have specific conditions within themselves.

4.2.1 Single-Aisle Configuration

For the single aisle configuration, 4 variants of passenger capacity configuration along with 4 tank configurations are taken into account for this study. The configuration details are seen in Table 1.

Table 1 – Single-aisle configuration variant parameters

	Variant 1	Variant 2	Variant 3	Variant 4	Reference A320
Pax Capacity	132	150	168	192	240
Number of Rows	22	25	28	32	40
TSFC (kg/kNs)	1.603E-5	1.603E-5	1.603E-5	1.603E-5	2.004E-5
Cruise Velocity (m/s)	220	220	220	220	220
Cruise Altitude (ft)	35000	35000	35000	35000	35000
L/D Ratio	17	17	17	17	17

Different tank configurations are given by the variants 1-4. The tank is automatically sized depending on the remaining space available.

4.2.2 Twin-Aisle Configuration

The twin-aisle has 5 variants of PAX configurations with the same quantity variation from 1 to 5. Information related to Thrust specific fuel consumption and passenger configurations are tabulated in Table 2.

Table 2 – Twin aisle configuration variant parameters

	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Reference A330-neo
Pax Capacity	168	208	232	264	288	400
Rows in Middle	20	27	30	34	37	50
Rows in Side	22	25	28	32	35	50
TSFC (kg/kNs)	1.32×10^{-5}	1.32×10^{-5}	1.32×10^{-5}	1.32×10^{-5}	1.32×10^{-5}	1.65×10^{-5}
Cruise Velocity (m/s)	220	220	220	220	220	220
Cruising Altitude (ft)	35000	35000	35000	35000	35000	35000
L/D Ratio	17	17	17	17	17	17

For both aisle configurations, the tank quantities and capacities vary depending on the remaining space at the aft region of the fuselage. This volume variation with passenger capacity provides a vital change in the range and balance of the aircraft. Different PAX configuration with respect to alternative

tank configurations from Table 1 and 2 can be seen in Figure 9.

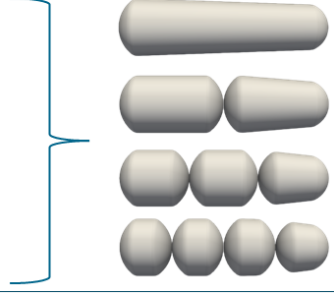
Single Aisle	Twin Aisle	Tank Variation
 132 Pax	 168 Pax	
 150 Pax	 208 Pax	
 168 Pax	 232 Pax	
 192 Pax	 264 Pax	
	 288 Pax	

Figure 9 – Different variants evaluated in single and twin-aisle configuration

5. Results, Discussion and Outlook

The results of the studies implemented through the methods described above are briefly explained and illustrated in this section. The discussions on how the result is obtained is discussed in this section. The outcomes of the aft-type retrofit configuration of the hydrogen tank are shown in section 5.2 and 5.3 and the implementation of a web-based application and study of LH2 tank retrofit for different aisle configurations is explained briefly in section 5.4.

5.1 LH2 tank retrofit to existing aircraft fuselage

The purpose of retrofitting a LH2 tank into an existing aircraft fuselage is to reuse the existing aircraft fuselage and reduce research and development costs. Additionally, the cost related to research, development, and manufacturing of LH2-specific aircraft is comparatively higher than a retrofit approach. Through this study, the efficiency of retrofitting such configurations to existing fuselages is conducted and analyzed.

Two-aisle configurations (single and twin-aisles) are taken into consideration. Reference aircraft for single-aisle configuration is Airbus A320 and for the twin-aisle configuration is Airbus A330-Neo. These aircraft are considered the benchmark of their respective purposes in the regions of Asia and Europe. Parameters such as aerodynamic effects on the fuselage, and other external factors are assumed from the reference aircraft A330neo for twin-aisle and A320 for single aisle in FUGA tool to design a detailed description of the aircraft cabin and fuselage.

5.2 Single Aisle Configuration

This section presents the results and discussions specifically focusing on the single-aisle configuration. It is important to note that only key results or those derived from the optimal design are showcased here. Additional results can be found in [4]. Figure 10 depicts the 2D layouts that were obtained. Starting with the CG variation, the measurements of CGmax and CGmin were taken with the hydrogen tank at full capacity and when the tank was empty. Figure 10 visually illustrates the shift in CG from the maximum to the minimum position. Additionally, utilizing the CG and *Neutral Point* (NP) values, the SM was computed using equation 1. Observations regarding the CG variation reveal that the higher band of CG variation is prominent in the 132-PAX configuration, primarily due to the weight contribution from the hydrogen tank. An interesting deviation from the conventional trend is observed in the CGmin, where, contrary to most aircraft designs, it moves forward or farther away from the NP. This is attributed to the aft location of the fuel tank, the trend can be seen in Figure 10.

For a fixed 150-PAX capacity with varied tank capacity, changes in the SM min and max (expressed as a percentage of MAC) were calculated based on CG and NP values, with tank variation from 2 to 4, there is a gradual increase in SMmin from 45.9% to 51.4% and a corresponding rise in SMmax

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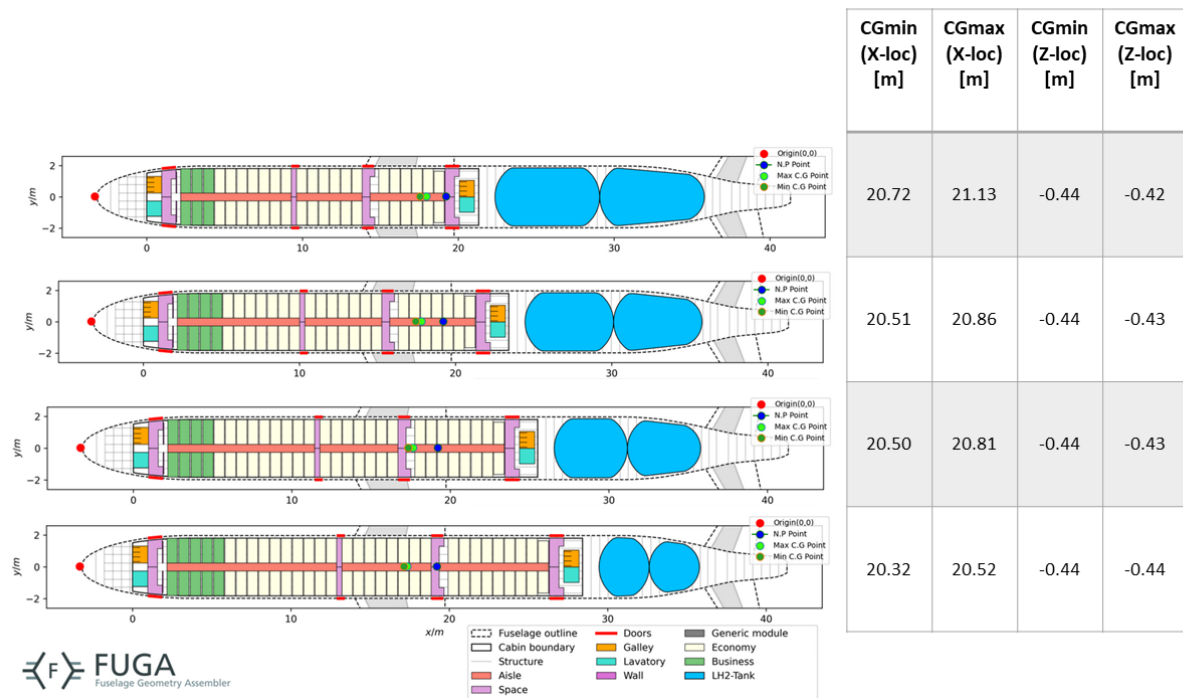


Figure 10 – 2D layouts with CG point variation

from 34% to 43.6%. The lowest SM variation is observed in the two-tank configuration for all comparisons. The preference for the two-tank configuration is justified by the redundancy of the system and the reduction in sloshing with multiple tanks [4].

However, opting for more tanks for system redundancy and sloshing reduction isn't universally optimal. Figure 12 (Left) illustrates the total tank fuel and range (at full load) concerning an increased number of tanks in a specific pax capacity. With an increasing tank configuration, there is a decrease in fuel capacity and, consequently, a reduction in the available range. This reduction is primarily attributed to the structural space occupied by the increasing number of tanks, which can be seen in Figure 12 (Right). Furthermore, the percentage dip in range from 2 to 3 tanks is 6.55%, and from 3 to 4 tanks is 2.07%. Therefore, a 2-tank configuration emerges as a more feasible option.



Figure 11 – (Top) Variation of Payload Range Diagram for PAX capacity (132, 150, 168, and 192 PAX) in 2 tank configurations and (Bottom) Variation with fixed PAX capacity (150 PAX) in reference to Airbus A320neo

In the range study, the Payload Range diagram provides the most comprehensive illustration of the range variation based on payload as seen in Figure 11. In the Single-aisle configuration, the Airbus A320neo serves as the reference aircraft (indicated with a Green trend line in Figure 11 (Top)), and the depicted variation is visible with regard to the range of retrofitted aircraft in Figure 11 (Top). The percentage difference between the range at full capacity/load (for 150 Pax) to the reference aircraft when retrofitted with a hydrogen tank is 78% reduction in range.

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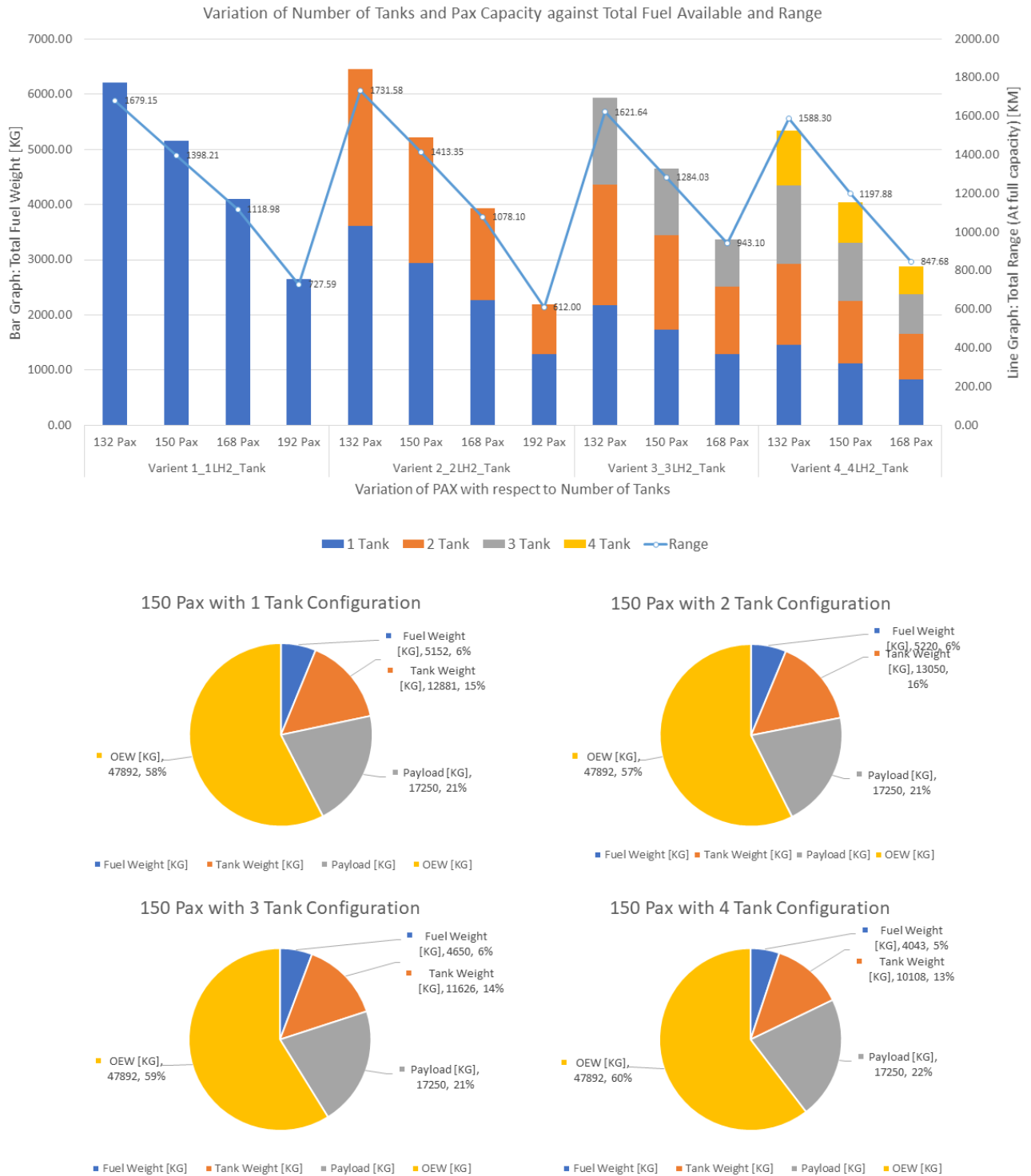


Figure 12 – (Top)Variation of Number of Tanks and Pax Capacity against Total Fuel Available and Range and (Bottom)Weight distribution for 150 pax with different tank configurations

In the comparison of range among different PAX configurations, the 192 and 168 PAX configurations emerge with the least available range, attributed to the limited space available for tank integration. However, in an intra-comparison focusing on the range within a specific PAX capacity, as exemplified in Figure 11, the 2-tank configuration consistently exhibits higher range capabilities. This underscores its feasibility as the preferred option across all PAX configurations. Additionally, the weight distribution study also plays a vital role in explaining the variation seen in the SM and range, an example of weight distribution for varying tank in 150 PAX can be seen in Figure 12 (Bottom).

5.3 Twin Aisle Configuration

For the twin-aisle configuration, 5 variants of seating capacity and 4 variants of tank quantities were investigated. The 2-tank configuration was taken as the optimum configuration for its redundancy and range capability. The study and result from aircraft cabin design and fuselage integration [4] is taken as a reference in this investigation. The range increases with a decrease in passenger capacity but is also directly proportionate to the volume of LH2 and the tank mass. This is not only because of the shift of weight but also because the fuselage is being shared by payload and aircraft fuel. This is illustrated in Figure 13.

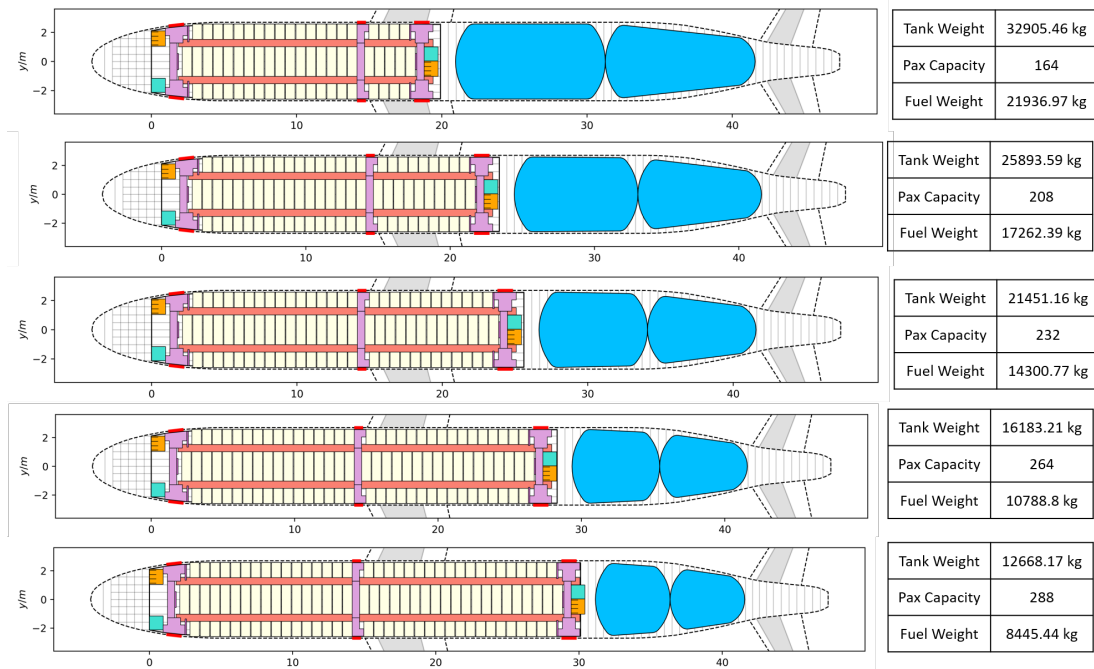


Figure 13 – Variation in PAX and Fuel for twin-aisle configuration

The variation in tank size and passenger capacity is vividly seen and is also the core reason for the impact of range and shift in CG. The range of the configurations is seen along with its reference aircraft in Figure 14.

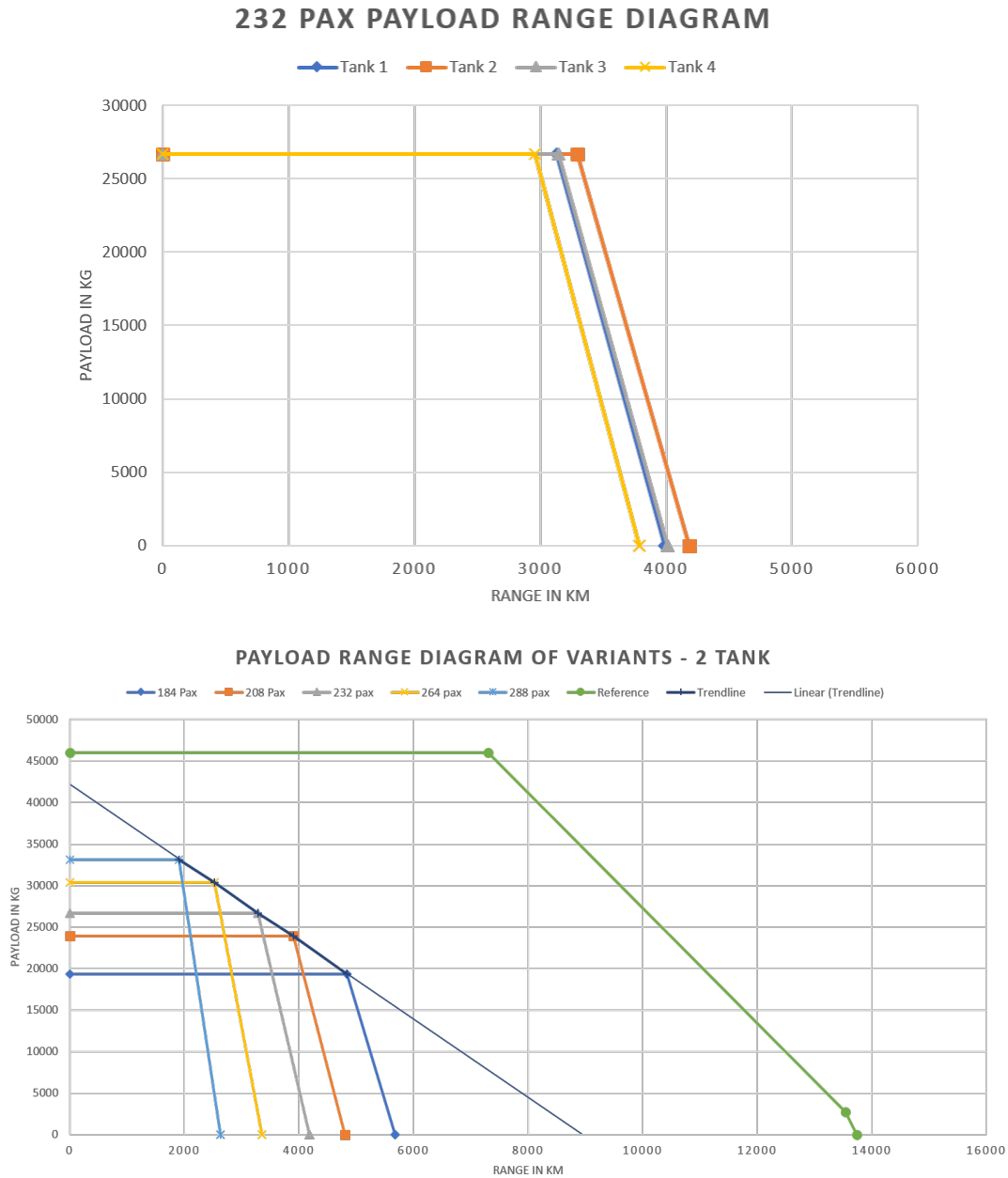


Figure 14 – Range variation with respect to passenger capacity (Top) and tank configurations (Bottom)

From the Figure 14, the range of the aircraft increases with a decrease in payload and also a decrease in the number of tanks. When increasing the quantities of the tanks, the redundancy and safety factor of the configuration increases. However, due to the curvature of the tanks, it reduces the total usable volume to store fuel. The curvature is crucial to eliminate strain/stress points at high pressure. The passenger configuration of 232 is selected as the optimum point for the balance of the liquid hydrogen tank and passenger capacity. The capacity of 232 provides a 10.3% increase in passenger capacity but reduces the volume capacity by 20.70%. Additionally, the liquid hydrogen tank weight also reduces by 20%.

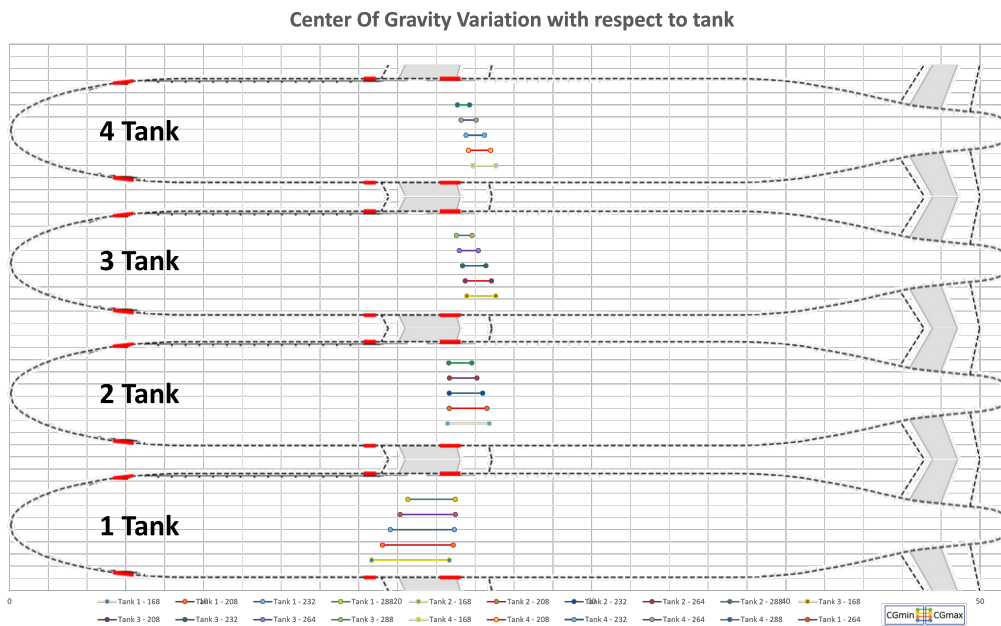


Figure 15 – CG shift with different tank variants in twin-aisle configuration

The *Maximum Take-off Weight* (MTOW) of the reference aircraft is significantly higher and beyond the trendline of the retrofitted configuration. This implies that the aircraft's structure and framework are designed to carry a payload on the fuselage and fuel in the wings. But with the wing box and fuel tanks, being a non-optimal solution for LH2 storage, the LH2 tanks are sharing the fuselage with the payload. This also reduces the total carrying capability of the aircraft, making the aircraft carry a lower payload than it is designed for. However, in a complete re-design of fuselage with LH2 tank in mind, there may be more room for optimization, resulting in longer range and passenger capacity. The CG affects the twin-aisle flying performance noticeably. The shift in CG is seen in Figure 15. It is an interesting study that reveals the aircraft's ability to perform based on tank configurations. With increasing the number of tanks, the shift experienced in CG reduces. This phenomenon is seen as the distribution of fuel increases the flexibility of placing available fuel on the desired tanks.

Though the 4-tank configuration provides the best optimum performance and CG, the range of the 4-tank configuration is significantly lower in comparison to the optimal configuration of the 2-tank. Considering the SM of different configurations, the 1-tank configuration has a SM between 22.65 (55.74%) and 18.66 (154.6%). This configuration makes the aircraft too nose-heavy, and significant trim is required that will contribute to trim-drag during cruise. The 4-tank configuration has a SM between 25.06(-3.7%) and 23.87 (25.65%). This provides a very feasible flying performance, but in some instances, makes the aircraft slightly tail-heavy, which can be trimmed out. The optimal configuration of 2-tank configuration has the SM at 24.71 (4.93%) to 22.56 (57.94%), though the shift also is viewed as drastic and noticeable trim is to be implemented, this configuration provides the maximum range excluding other factors such as trim-drag. The drastic shift in CG can be minimized with the introduction of auxiliary tanks in the front region to balance the weight.

Concluding the study on LH2 tank retrofit into twin aisle-configuration, the optimal configuration that yields a balanced passenger capacity, range, and redundancy results in 232 passenger capacity and 2-tank configuration. This 232 PAX configuration triumphs other PAX and tank configurations in terms of providing a balance between range and capacity, but has a poorer CG balance. With 2-tank configuration, there is redundancy in the event of hydrogen tank failure, and with increases quantity of tank reduces total range. Through the study, it is observed that range, passenger capacity, redundancy are the 3 trade offs that directly affects each other.

5.4 Web Application

The implementation of the web app for KBE tools, like FUGA, makes the tool more reachable and can be easily accessed. The implemented web app can be seen in Figure 16, where the output of the 2D layout can be also seen.

Once the tool is hosted either locally or globally, it becomes accessible for use. To initiate the process, users are required to upload the CPACS and Cabin definition files, with the option for manual cabin definitions also provided. Upon running the 'Compile' function, users can view the available 2D layouts based on their selected options, as depicted in Figure 16.

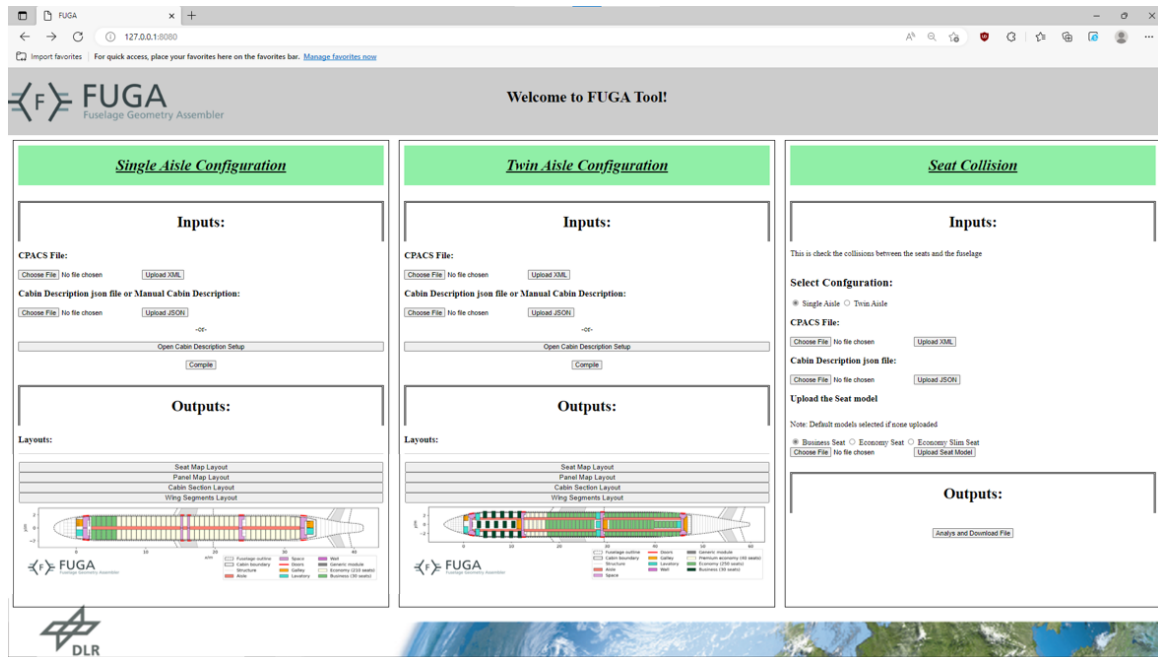


Figure 16 – FUGA KBE tool implemented on the web using Flask framework

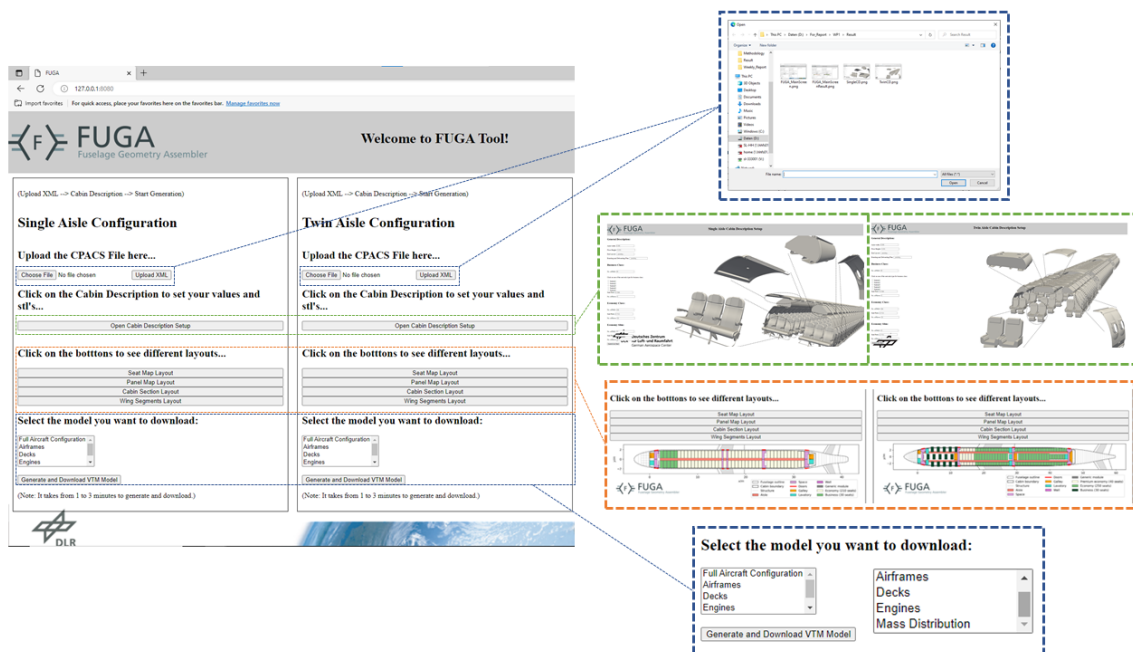


Figure 17 – Summarised view of all the options that are made available on the web screens

For the generation and download of the 3D model, users can utilize the designated options outlined in

Figure 17. This figure provides an overview of various options facilitated by the FUGA tool, including file uploading, manual description screens, 2D layout options, and 3D model generation. An advantageous feature of using Flask is its modularity, allowing for the seamless integration of new modules, such as the seat collision module introduced to meet specific needs. This modular approach ensures that any additions or improvements in the KBE tool can be easily implemented within the web interface.

6. Conclusion

Increasing consumption of fossil fuel have strongly encouraged the need for alternative sources of fuel. With state of the art, digital platform, it is possible to experiment and study alternative methods and concepts digitally. This paper have provided a brief study and evaluation of KBE approach through LH2 tank retrofit. The retrofit in 2-aisle configuration further helped in understanding the advantages and disadvantages of different aircraft types (Single and twin aisle).

FUGA was developed in DLR which adapted the 3 fundamental elements taken from KBE approach of La Rocca [27]. The KBE approach enabled users to implement desired configurations and design criteria to yield practical cabin models through KBE approach. A feasible model for both single and twin-aisle configurations can be achieved and studied through digital modeling, and it is possible to study and simulate the retrofit of a liquid hydrogen tank into the existing fuselage. The ease of using FUGA is achieved with the introduction of a web-based application.

A detailed study on LH2 tank being retrofitted into an existing aircraft fuselage was performed for narrow and wide-body aircraft. Through different configurations in terms of passenger capacity, tank configurations, and aisle configurations, an optimal design for each configuration could be concluded through the utilization of FUGA. Single aisle configuration arriving in 168 PAX and 2-tank configuration. In terms of twin-aisle configuration, 192 PAX and 2-tank configuration is selected as the most optimum design.

Retrofitting LH2 tank into an existing fuselage may reduce the cost, time, and manpower required when compared to conducting research, conceptual designs, and proceeding through a life-cycle assessment for complete re-design of aircraft for hydrogen-powered propulsion. However, the question remains whether having a retrofit model of hydrogen-powered aircraft is truly beneficial. Some of the factors that challenge the concept are the age of the aircraft, the total pressure cycle the cabin has experienced as it reduces the total useful life of the aircraft and many more.

Though retrofit has a lower cost, it still requires extensive research and other factors to be considered. One such factor may be installing the tank inside the fuselage without compromising the structural strength, overall CG balance of aircraft during the cruise, the optimized balance between payload and fuel, etc. This paper has great potential that open the door for future research into aviation with liquid hydrogen propulsion. Some interesting examples of studies are mentioned below:

- How could the LH2 tank be optimized in terms of shape and size for better capacity?
- What are the possible locations inside the aircraft fuselage that can accommodate LH2 tank and what are its trade-offs?
- How can the systems supporting LH2 tank be optimized for reduced size utilization and better operational efficiency?

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