



Hydrogen Airliner Tank Optimisation

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Abstract

This paper goes over the retrofit design of a Boeing 737-800 with a Hydrogen Electric Propulsion system. It focuses on the trade-offs with liquid hydrogen tank placement. The main trade-offs analysed are range and cost per passenger seat mile. The results are compared in terms of fuel costs against the original airliner and further notes on technology readiness and certification considerations are given.

Keywords: Hydrogen, Sustainable Aviation, Multidisciplinary Design Optimisation,

1. Introduction

The concept of hydrogen aircraft has been gaining traction as a potential solution to meet the sustainability targets set by governments and International Civil Aviation Organisation (ICAO) for 2050. As part of an Innovate UK project to bridge the gap between science and technology education for future flight technologies, a team of engineers from ZeroAvia has attempted to design a retrofit aircraft with potential entry into service by 2035. The design encompasses various disciplines including structures, aerodynamics and cabin layout. In this paper, the design is optimised from the perspectives of aerodynamics and cabin layout. The overall goal is to achieve the lowest possible fuel costs per passenger mile.

The paper is structured as follows: Chapter 2 provides a comprehensive background and literature review. Chapter 3 outlines the methodology employed in aircraft design process and details the analysis tools used. Chapter 4 presents the results and a discussion of these. Chapter 5 addresses further considerations including certification considerations of liquid hydrogen aircraft. Finally, Chapter 6 summarises the findings in the context of other liquid hydrogen designs and proposes aspects for future research.

2. Background and literature review

2.1 Hydrogen Aircraft

Hydrogen aircraft made its first appearance in the literature during the 1950s [1] but was primarily concerned around the burning of hydrogen as a fuel. Further research was carried out throughout the latter half of the 20th century [2]. In 1988, a modified TU-154 flew with one engine powered by hydrogen, utilising liquid hydrogen fuel storage. In the early 2000's, a project called the "Cryoplane" was launched to study the potential of liquid hydrogen-powered aircraft. This project delved deeper than previous studies, comparing hydrogen to traditional kerosene powered airliners; however no tangible conclusions could be drawn due to the uncertainty in the hydrogen fuel cost [3].

While turbines are more advanced than fuel cells for propulsion, fuel cells have nonetheless been trialled in aircraft. To date, 6 prototypes of aircraft have flown using electrical motors

powered by a hydrogen fuel cell, though none have entered commercial operation [4]. These prototypes include those from companies such as ZeroAvia, Universal Hydrogen and H2Fly. On the theoretical side, numerous reports have analysed hydrogen fuel cell powered aircraft, ranging from retrofit studies to clean sheet designs [5] [6] [7].

2.2 Multidisciplinary Design Optimisation

Aircraft design is a multidisciplinary field where structures and aerodynamics disciplines must be studied together to create an optimal design. When optimisation is added to a variety of disciplines, the term Multidisciplinary Design Optimisation (MDO) [8] applies. With the increase of computational power, computational methods are being implemented into early design phases. Nevertheless, these methods are expensive to run, especially when they have to be iteratively run as part of an optimisation algorithm. To solve this issue, reduced-order models are produced. These models are quicker to evaluate while still maintaining the fidelity of the original model [9] [8]. In this paper, an MDO approach is used to design the hydrogen fuel tank placement. Tank placement is inherently a multidisciplinary problem: tanks can be placed on the wings, causing a change to structures and aerodynamics, or they can be placed inside the fuselage, causing a reduction in available passenger space. There must be a balanced trade-off between drag and number of passengers to obtain optimal economics over a certain route.

3. Methodology

3.1 Aircraft Baseline

The aircraft to be retrofitted is a Boeing 737-800, chosen due to the extensive literature available on the aircraft. The airliner typically carries 189 passengers in a two-class configuration [10]. This aircraft is primarily used for short-haul flights, which typically cover on average 1150km [11]. From the certification data sheet, the take-off weight of the aircraft can be obtained, these are key inputs to the retrofit sizing in section 2.2. The fuel system mass is also an important parameter, as it will be removed and substituted for a liquid hydrogen system. This weight has been estimated using an empirical equation from Raymer [12]. The original turbine engine used in this aircraft is a CFM56-7B24, capable of a maximum take-off thrust of 107650 N [13].

Table 1-Weights for the Boeing 737-800 aircraft.

Description	Mass (kg)
Aircraft Maximum Take-Off Mass	79002
Aircraft Operating Empty Mass	40816
Single Engine	2395
Fuel system mass	200
Max fuel mass	20267

3.2 Retrofit Sizing

The aircraft will be retrofitted with a Hydrogen Electric Propulsion System (HEPS). This consists of an Electric Propulsion System (EPS), a Power Generation System (PGS) and finally the liquid hydrogen fuel storage. These systems will be described in detail in the following sections. The sizing method for each of these will be described in the following sections. Since this is a retrofit, the algorithm becomes significantly simpler than that for a clean sheet design. The strategy will keep the same maximum Thrust-to-Weight ratio and Maximum Take-Off Weight (MTOW) as the original aircraft. This means that the payload will vary due to the different weights of the propulsion system. Furthermore, since the thrust must be kept the same, an equivalent electric propulsion and power generation system can

be sized and maintained constant, allowing only the liquid hydrogen storage to be parametrically varied to optimise the aircraft.

3.2.1 Electric Propulsion System

An electric ducted fan design is assumed, as several research papers have proved its viability if the electric motor technology is built to achieve the required levels of power [14] [15]. To size the power required to be delivered by the shaft, a simple physics-based relation is used, as shown in Equation (1).

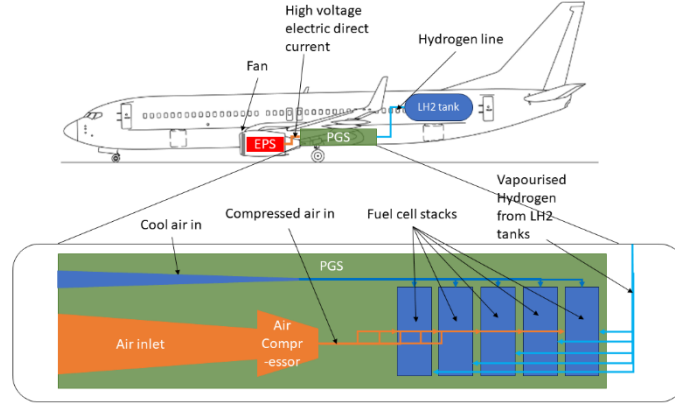


Figure 1-Arrangement of retrofitted components into aircraft.

$$P_{EM} = F_{Max} \cdot v_{TO} / \eta_p \quad (1)$$

where F_{Max} is the maximum take-off thrust, v_{TO} is the rotation velocity at Take-Off and η_p is the propulsive efficiency of the fan, estimated at 0.8 [12]. This relation has proved to provide consistent results with experimental data [15]. From the power of the electric motor, a power density is used that is modified to include aspects such as the fan case, fan and outlet guide vanes. A value of 10kW/kg is used, estimated based on a technology level expected in 2035 [15].

3.2.2 Power Generation System

The power generation system comprises fuel cells and its their supporting system collectively known as the balance of plant. This includes a compressor to supply air, humidity regulators and hydrogen pressure regulators. Figure 1 illustrates how these systems can be integrated into the aircraft.

The fuel cells must generate sufficient power so that, after electrical losses have occurred, the electric motor can still provide the required power P_{EM} . The efficiency chain is depicted in Figure 2.

The power required by the fuel cells can be estimated using the following equation:

$$P_{PGS} = P_{EPS} / (\eta_{EPS} \eta_{PGS}) \quad (2)$$

where η_{EPS} is the Electric Propulsion System electrical efficiency which accounts for the losses across the inverters and electric motor, η_{PGS} is the efficiency of the Power Generation System (PGS) which includes the fuel cells and the balance of plant. The main inefficiency for the PGS is the power required to compress air to a suitable value. The values used in this study are typical projections for 2035 and are shown in Table 2.

System	PGS	EPS	Fan
Efficiency	0.75	0.90	0.80

Similar to the electric motor, the power generation system's weight can be estimated via a power density value of 2.5 kW/kg [16].

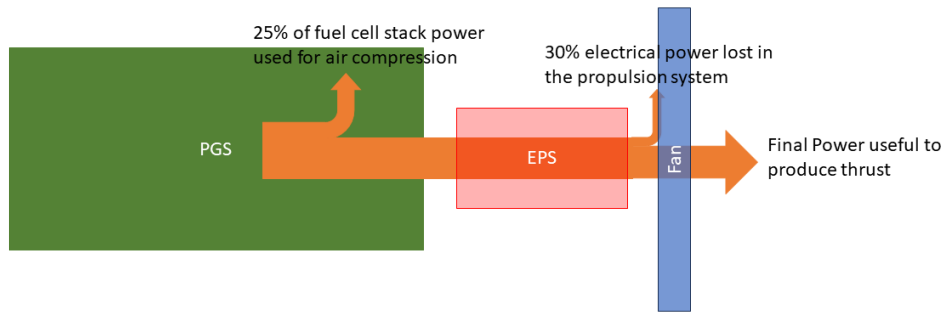


Figure 2- Efficiency chain of the retrofitted hydrogen electric propulsion system.

3.2.3 Liquid Hydrogen Fuel Storage

The liquid hydrogen tanks are the main design driver. There are three main strategies to install these tanks: on the wings, inside the fuselage and on top of the fuselage. The current state-of-the-art for liquid hydrogen tanks designed for aircraft, include the following components: an outer metallic shell, a vacuum gap created by foam with a radiation reflective material and finally an inner metallic layer in contact with the cryogenic liquid hydrogen. An illustration of this design is shown in Figure 3 [4].

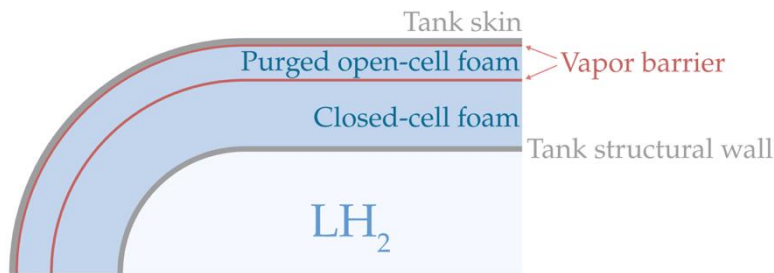


Figure 3- Liquid hydrogen tank structure diagram [4].

To simplify the project, each of the three configurations use a standard cylindrical tank. The dimensions and mass properties are detailed in Table 1. It is assumed that the tanks will weigh 75 kg/m² of outer surface area [17].

Table 3- Dimensions and mass properties of the LH2 tanks.

Tank Position	Diameter (m)	Length (m)	Dry Weight (kg)
Under wing	1.5	4.5	1004
Inside Fuselage	3.1	3.7	2879
On Fuselage	2.5	15	9875

The different style of tanks can be seen in Figure 4 to Figure 6.

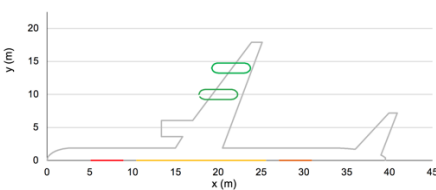


Figure 4 - Wing tank example.

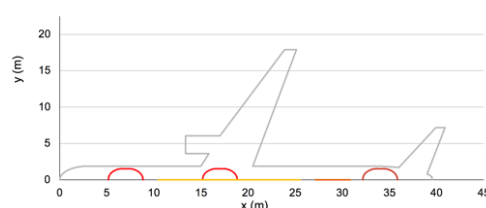


Figure 5- Inside fuselage tank

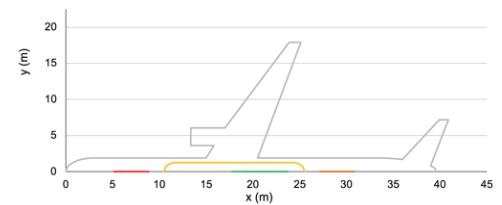


Figure 6 -On top of fuselage.

3.3 Analysis methods

The analysis of the design is conducted in terms of range, making aerodynamic drag a key element in estimating the different designs of hydrogen tank positions. A vortex lattice method with a potential flow tool called VSPAero is used for aerodynamic drag analysis. The full aircraft configuration is analysed for each configuration of tanks. Since the design options are discrete, this allows for each individual tank setup to be analysed individually. The benefit found from this is that each tank configuration impacts the aircraft's drag in an independent manner. Thus, an aircraft with a tank on top of the fuselage and a single wing tank per wing will have a drag equal to the summation of the original aircraft plus the drag induced by the addition of the wing tank and top fuselage tank separately.

The range is then estimated with the Breguet Range equation:

$$R = \frac{v \cdot L/D}{g \cdot c} \ln \left(\frac{W_i}{W_f} \right)$$

where v is the cruise speed, L/D is the lift to drag ratio, g is the gravimetric constant, c is the specific thrust fuel consumption, W_i is the initial weight of the aircraft at the start of cruise and W_f is the final weight at the end of cruise. It is assumed that a cruise climb flight profile will be followed to keep all parameters constant, except for the weight of the aircraft. For the original aircraft, flying at a typical airspeed of 234m/s, the aerodynamic analysis tool predicts a cruise L/D of 12.7. This results in a maximum cruise range of 5984km (3230Nm) which is in line with values quoted by airlines [18].

3.4 Method of finding the optimal solution

The problem at hand has been restricted to several configurations based on either internal, wing or on top of the fuselage tanks. This allows the optimal solution to be found using an exhaustive search, where all combinations are tested. This approach is feasible as the time required to process OpenVSP is short and the addition of external tanks do not affect each other as explained in Section 3.3. Hence, the OpenVSP program must only be run once for each option. The constraints on the discrete optimisation are weight budgets and a minimum range of at least 850Nm. Finally, the objective function is the Cost per Available Seat Mile (CASM), a parameter used by many researchers and airlines to determine the efficiency of a flight. To calculate this, the cost of the different fuels used is shown in Table 4 [19] [20].

Table 4 - Fuel costs estimates.

Cost of fuel per kg (£/kg)	
Liquid hydrogen	Kerosene Jet A1
3.56	0.68

A diagram of how the process will work is shown in Figure 7. To track each configuration, a 3-dimensional coordinate system is used as follows:

- First dimension-top of fuselage tank: 0 – No tank, 1- Tank included
- Second Dimension – number of wing tanks per wing
- Third Dimension – number of internal fuselage tanks

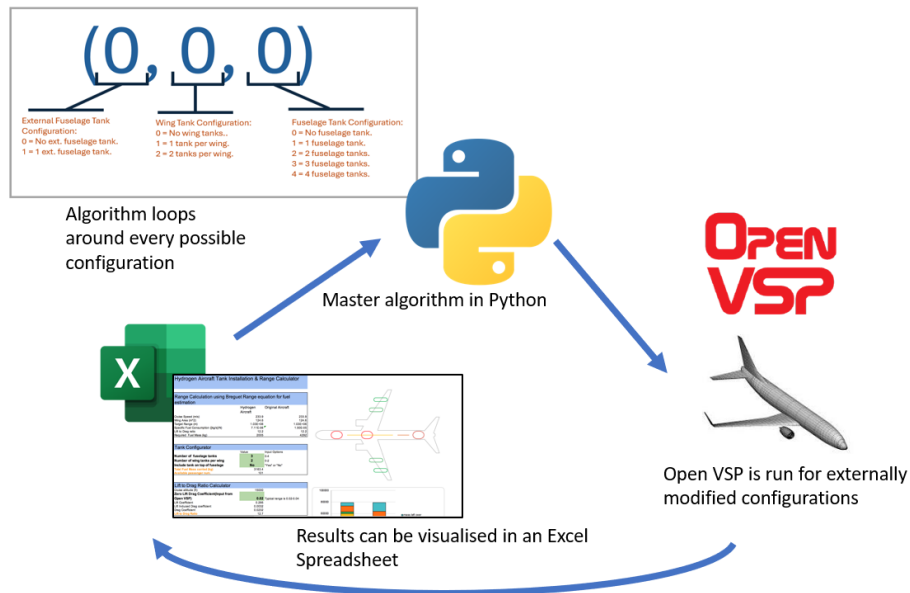


Figure 7 Process followed by the artificial intelligence algorithm.

4. Results

The sizing algorithm has been applied to obtain the weights of the EPS and PGS. These are shown in Table 5.

Table 5 - Weights of the sized components for the HEPS.

Component	EPS	PGS
Mass (kg)	2106	11230

The total propulsion system mass is 13336kg. This is an increase of 180% compared to the original turbofans. The next step is to find the aerodynamic contribution from the externally mounted tanks. The configurations used are shown in Figure 8.

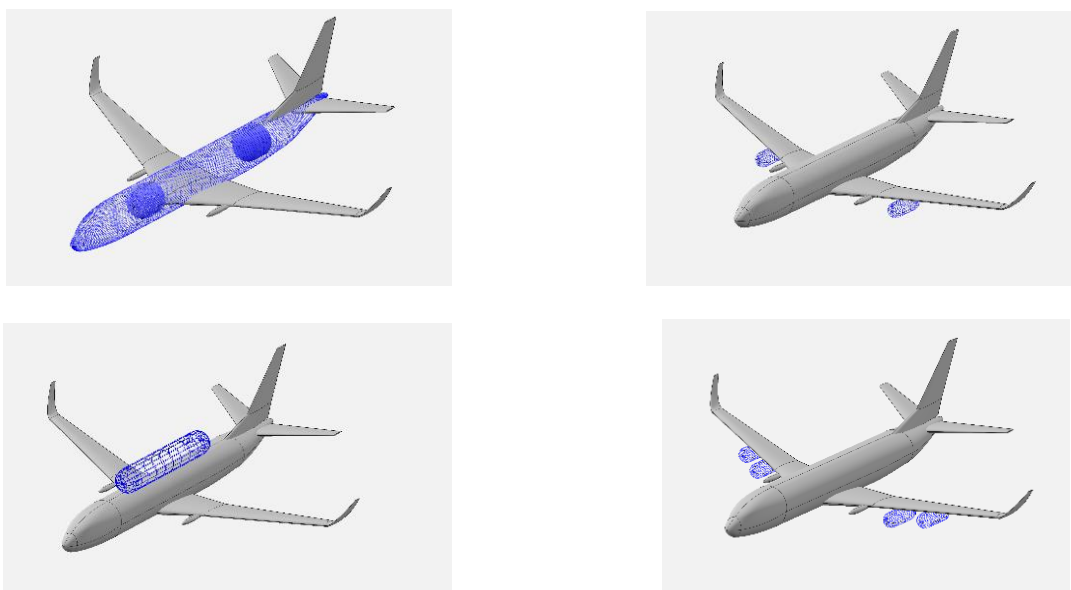


Figure 8-Configurations analysed in Open VSP (Left Top: internal fuselage tanks, Left Bottom: external fuselage mounted tanks, Right Top: 1 wing tank per wing, Right Bottom: 2 wing tanks per wing).

The Zero Lift Drag was analysed with Open VSP and the results are shown in *Table 6*.

Table 6-Zero Lift Drag results from Open VSP on different configurations.

Configuration	Zero-Lift Drag
Original Aircraft	0.01998
External fuselage tank.	0.02207
1 wing tank per wing.	0.02139
2 wing tanks per wing.	0.02276
Fuselage tanks (1 – 4).	N/A

From the aerodynamic results, it can be seen that the increment from one to two wing tanks per wing is the same as that from no wing tanks to one wing tank per wing, for more details on this refer to Section 3.3. The aerodynamic results are now coupled with the algorithm to evaluate the performance of every solution. Solutions that meet the minimum range and are within the MTOW of the aircraft are plotted in *Figure 9*.

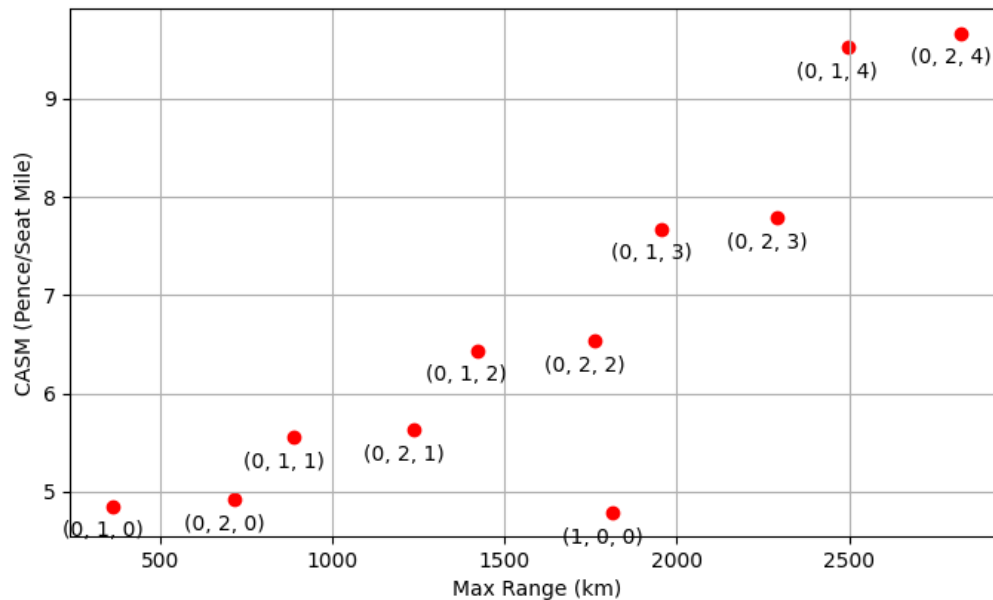


Figure 9-Results of CASM vs range for all feasible designs.

Trends can be observed from the data, such as the fact that by increasing number of internal tanks, you increase the range by about 500 Km for each added tank, but you also exponentially increase the costs per available seat mile as the internal tanks are taking up more space. The most cost-effective solution is to utilise a single external tank on top of the aircraft. Alternatively, having tanks on the wings without any tanks internally also gives good cost effectiveness, albeit with a lower range. The weight breakdown for the lowest CASM result is shown in *Figure 10*.

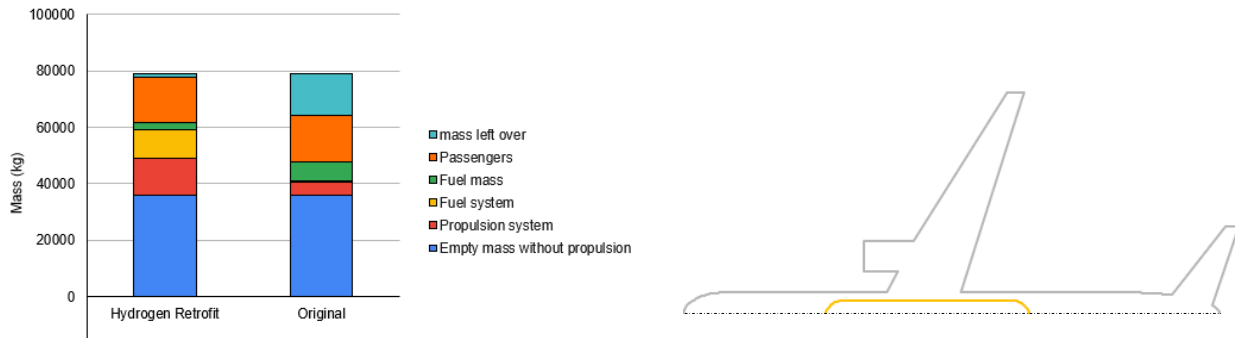


Figure 10-Weight breakdown and configuration of retrofit with externally mounted fuselage tank.

Finally, the retrofitted aircraft is compared to the original aircraft in terms of its maximum range and CASM. These values include the required IFR reserve of 45 minutes. Fuel operating cost can be calculated from the fuel quantities. The CASM results are shown in Table 7.

Table 7-Comparison of CASM between retrofit and original aircraft.

Aircraft	Baseline	Retrofit with External fuselage tank	Retrofit with 4 wing mounted tanks
CASM (UK pence/Seat Mile)	2.59	4.78	4.92
Max. available range (km)	5676	1814	716

The airliner retrofitted with the HEPS is approximately twice as expensive and can only carry passengers over about one-third of the distance. In the next section, further considerations will be discussed that will play a key role in the design, certification and operation of these hydrogen-retrofitted aircraft.

5. Further Considerations

5.1 Technical Considerations

The LH2 tanks are a technology that must be matured. In the present study, we assumed that wing tanks carrying LH2 would be available by the time of entry into service. However, further investigation is needed, as these tanks require auxiliary equipment to keep the hydrogen cool. This would favour internal tanks as they can accommodate such ancillary equipment inside the fuselage.

Another point against the wing tanks is the possibility of aeroelastic phenomena, which involve the interaction between the aerodynamics of the tank and the mounting structure. This must be carefully investigated, especially in scenarios such as cross winds.

5.2 Safety Considerations

When deciding what design to follow, safety is of the utmost importance. All the designs evaluated have different safety challenges due to the positioning of the tanks. The safest option is probably having the tanks far away from the passengers. Having tanks inside the fuselage requires strict zoning via bulkhead to separate the passenger cabin from the liquid hydrogen tanks. This adds weight to the design which we have not accounted for.

5.3 Operability Considerations

Despite a limited range of 1814km for hydrogen retrofitted aircraft, a recent study [18] showed that single-aisle aircraft, typically average trip distances of around 1200km. Hence, a liquid hydrogen airliner would be suitable for the majority of these routes, albeit being restricted to these distances only.

6. Conclusions

Among the range of designs analysed for a Hydrogen Electric Powered aircraft, the most promising concept is a single large tank mounted externally on the top of the fuselage. This design offers superior maximum range and cost per available passenger seat mile. Nevertheless, its success depends highly on the aerodynamic interaction and the ability to provide a good fairing to minimise aerodynamic efficiency losses around the fuselage and tank connection. This has the potential to reduce the benefits from the externally mounted tank. With this in consideration, another potential architecture that would provide sufficient range to cover most single aisle flights, with optimal cost efficiency would be to have a tank mounted internally with a couple of wing tanks per wing. This gives a two-fold increase in costs per flights compared to the kerosene powered baseline, representing a promising solution and a feasible design solution.

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