



PRELIMINARY SIZING OF HYDROGEN-BURNING JETLINER FOR DIRECT OPERATING COST OPTIMIZATION

Hamid Mohammadi¹, Gabriele Sirtori¹ & Lorenzo Trainelli¹

¹Department of Aerospace Science and Technology (DAER), Politecnico di Milano, Via La Masa 34, 20156 Milan, Italy

Abstract

The objective of this paper is to perform the optimization of the preliminary sizing of both short- and long-range hydrogen-burning aircraft. The goal of the optimization is to minimize the Direct Operating Costs (DOC), given a set of design parameters, whose varying values define the design space. Furthermore, the mission, identified by the payload and range at maximum payload, has been defined thanks to a market analysis to identify the optimal mission design point to satisfy the market expectations. Sweet spots of 200 passengers, and 350, over a distance of 4,000 km, and 12,000 km, respectively for narrow-body and wide-body aircraft have been identified. The DOC optimization for short-haul aircraft allows for the extension of the design range to the indicated value. In contrast, for long-range aircraft, the mission is maintained constant and the DOC drops by almost 16% with respect to a baseline LH₂ configuration, thanks to the design space exploration.

Keywords: Hydrogen Aircraft, DOC, Preliminary Sizing, Sustainable Aviation

1. Introduction

This work aims to conduct a comprehensive design study on the use of LH₂ (liquid hydrogen) as a direct-burning aviation fuel in passenger aircraft. The goal is to minimize direct operating costs (DOC) associated with LH₂ fuel usage, considering the impact of adapting the current tube and wing jetliner configuration to accommodate LH₂ as a fuel source. Additionally, the objective is to find optimal solutions for narrow-body (NB) and widebody (WB) aircraft that meet market demands. The aviation industry significantly contributes to greenhouse gas emissions, accounting for about 2.5% of global carbon emissions annually. Long-haul flights consume more fuel, and emissions are directly proportional to flight distance. In fact, flights over 3,000 km, which make up only 10% of total flights, contribute to over 50% of the fuel consumption and CO₂ emissions [1]. In the current context of strong environmental attention, liquid hydrogen (LH₂) is considered as a promising solution to reduce the climate impact of commercial aviation. LH₂ is a net-zero carbon fuel, at aircraft level or on its entire life cycle, depending on the hydrogen production method. In fact, its primary byproducts when combusted are water vapor and NO_x, reduced by approximately 70% compared to those of comparable kerosene aircraft [2]. However, it presents challenges in production, transport, distribution, fueling, and adaptation aircraft to it. Its low density compared to kerosene and extremely low boiling temperature of -253 °C pose significant obstacles in its development as an aviation fuel, because of the need of bulky cryogenic tanks that need to be integrated in the fuselage, causing radical differences in the preliminary aircraft design methodologies.

Nonetheless, the challenges are not only technical but also linked to the economics of hydrogen aircraft. In fact, the introduction of a new technology to the market must be economically compatible with existing products. Therefore, economic analysis and design for a profitable LH₂-burning aircraft are crucial from the beginning of the research concerning such aircraft. The work presented here sets a group of study cases in the narrow-body (NB) and wide body (WB) aircraft categories to cover market requirements and conducts preliminary sizing using HYPERION (HYbrid PERformance SimulatIOn) [3] to obtain clean sheet designs given a set of Top Level Aircraft Requirements (TLARs).

A cost model is used to assess the results and find the optimum solution in terms of DOC. The main objective of this work is to assess and optimize passenger capacity (PAX) and design range combinations, considering variations in wing parameters and different operational scenarios. In the NB class, the number of seats ranges from 180 to 220, with a design range of 2,000 km to 6,000 km. For the WB studies, the number of seats ranges from 250 to 400, with a design range spanning from 6,000 km to 15,000 km.

The paper includes in ch. 2 a brief description of the market outlook for commercial aviation, followed by the description of the used cost model and aircraft sizing methodology, used to perform trade-off studies in ch. 3. Chapter 4 and ch. 5 detail the trade-off analyses and optimal DOC results for NB and WB aircraft respectively.

2. Market outlook and performance requirements

To accurately analyze the market demands and performance requirements, it is essential to consider forecast data and statistics on passenger jet liners' current utilization and performance.

2.1 Market outlook

Currently, the demand for passenger traffic stands at approximately 10 trillion RPK (Revenue Passenger Kilometers). Over the next twenty years, this demand is projected to double to 20 trillion RPK [4]. Looking ahead, it is expected that airline fleets will nearly double in size over the next twenty years to accommodate the increased air passenger demand. By 2041, the fleet is expected to reach 47,000 aircraft [4]. New NB deliveries will account for 75% of total deliveries, while WB deliveries will make up the rest [4]. The backlog list of major manufacturers indicates that orders are primarily focused on new-generation NB aircraft with capacities ranging from 150 to 200+ seats. The introduction of a New Midsize Airplanes (NMA) might bridge the gap between NB and WB aircraft and will be used for up gauging from NB routes. Currently, the most favorable airliners in terms of orders in 2040 are projected to be the class of A321neo. In fact, the market trend for most of this decade suggests that the major players in the NB class are and will continue to be the B737 and A320 families, while in the WB class, the Boeing 787 and Airbus A350 play a central role.

2.2 Performance requirements

Different classes of aircraft are used for different average stage lengths. NB aircraft are commonly used for short and medium-haul flights, typically up to 4,000 km, while WB aircraft are used for long-haul flights up to 15,500 km. When selecting optimum parameters for aircraft, it is important to consider average utilization and reasonable range. The most common sector length for NB cover distances of about 1,300 km, with the average EU flight being 981-km long [5], and for WB, it is 7,400 km [6]. The cost study in this analysis is based on the average utilization length. Without competitive performance characteristics, new aircraft will struggle to gain market share. Therefore, TLARs were selected so as to align the novel proposed aircraft with the market expectations, and the preliminary sizing process was based on these requirements.

3. Methodology

This chapter aims to introduce the used cost model and the preliminary aircraft sizing methodology, used to carry out the trade-of analyses that allow the optimization of the DOC.

3.1 Cost model

Cost estimation during the conceptual design phase relies heavily on statistics. In this study, the method presented in [7] is adapted to LH₂ aircraft, and the fiscal year 2020 was selected as the reference year. The life cycle cost of a commercial airliner includes Research, Development, Test and Evaluation (RDT&E) costs, Acquisition (ACQ) costs (which contribute to the purchasing price), and operational costs. The assumption here is that the DOC estimation is referred to a situation in which the novel hydrogen-powered aircraft have reached sufficient maturity, meaning that they are widespread and that the initial teething issues, both in production, maintenance and operations, have been mostly overcome. In fact, during the initial production and entry into service, economies of scale are not achieved yet, indeed making hydrogen less attractive than kerosene economically [8].

3.1.1 Purchasing price

RDT&E and ACQ costs are recurring and based on the number of produced aircraft. The flyaway (production) cost of the aircraft includes the per capita cost of each Q number of manufactured aircraft, as well as interior costs. The purchasing price is determined by adding a profit margin and spare factor. The method utilizes regression formulas for various cost items, including engineering, manufacturing, tooling, quality control, development support, and manufacturing material costs. The cost of avionics and engines is treated as purchased equipment. The regressions are based on factors such as empty mass, maximum velocity and production quantity. The costs of engineering, tooling, manufacturing and quality control are calculated by multiplying the respective man-hours by the appropriate hourly rates. Development support, flight test and manufacturing material costs are estimated using relevant regression formulas.

3.1.2 Direct operating costs

DOC encompasses all expenses associated with a flight, including fuel, ownership, maintenance, insurance, airport fees, navigation costs and crew wages. The major components of DOC, such as fuel, navigation, and crew costs, are directly proportional to the block hour (BH), which is calculated based on flight hours linearly related to distance. The remaining components of DOC, including maintenance, ownership, insurance, and airport fees, are determined by the flight cycle (FC).

3.1.3 Validation of cost model

The cost model is applied to the A321 aircraft, and the deviation between the actual listed price of the aircraft [9] and the estimated purchasing cost was approximately 1%. This indicates that the method accurately estimates RDT&E, ACQ, and purchasing prices. To evaluate the method in terms of DOC, the aircraft was analyzed across various sectors (fig. 1). The method correctly predicts the trend of cost, but there is a significant numerical offset for sectors less than 1,000 km. However, the method effectively captures the overall trend of DOC versus flight range. Furthermore, when considering the average utilization, the distribution between the components of DOC as shown in fig. 2 aligns with real-world data, including airport fees, fuel, and ownership costs.

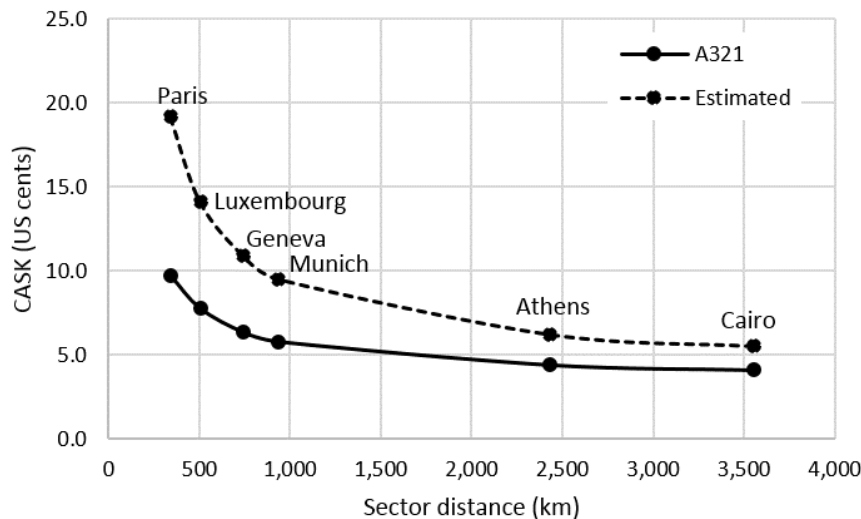


Figure 1 – CASK (Cost of Available Seat Kilometer) as a function of sector distance for Airbus A321 on routes departing from London (2020).

3.2 Aircraft sizing methodology and design trade-off framework

3.2.1 Aircraft sizing methodology HYPERION

The Department of Aerospace Science and Technology at Politecnico di Milano has developed a proprietary in-house aircraft preliminary sizing methodology dedicated to innovative propulsive and aero-

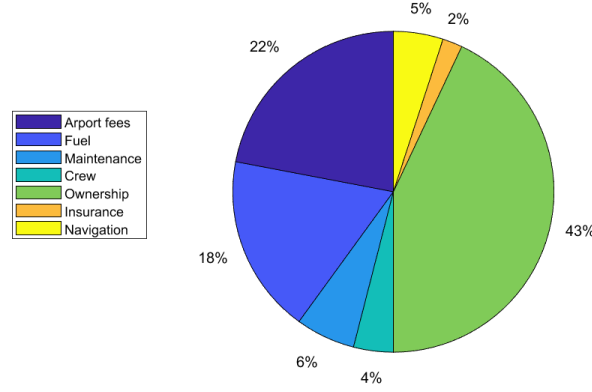


Figure 2 – A321 DOC subdivision for a 1,300-km mission.

dynamic architectures, which enables the preliminary design of electric, hybrid-electric and hydrogen-burning aircraft. A fundamental tool in this methodology is a preliminary sizing program called HYPERION (HYbrid PERformance SimulatIOn). Various propulsive architectures can be applied to aircraft across all classes using the latest version of HYPERION. Regarding hydrogen-burning jet aircraft, the tool outputs the mass breakdown, wing area and span, together with the jet engine mass and thrust and the hydrogen tank size and mass. HYPERION computes the outputs blending data from statistical regressions and from the modular modeling of subsystems. Based on first principles (i.e. including the thermodynamics cycle), the turbofan model has been implemented and the complete sizing procedure has been successfully validated against existing short-, medium-, and long-range jetliners. The inputs needed by HYPERION to perform the initial sizing procedure are specific information regarding the aircraft (payload, crew), its aerodynamics (lift coefficients in different configurations and drag penalties due to landing gears and flaps [10]), jet engine configuration (two or three spools, turbine entry temperature), wing sweep angle and other characteristics.

The mission requirements are characterized as follows, to define the different mission phases: information regarding the desired payload and range, by definition of the corner point in the payload-range diagram; the diversion range; the desired cruise altitude and speed; the loiter time and altitude. Particularly, the modeling of the diversion and of the loiter is necessary to show that the aircraft is capable of carrying out a specific mission while having sufficient reserves to comply with regulations applicable to fuel planning, contained in Annex IV - Part CAT of Air Op.

HYPERION computes the fuselage length starting from the length of the kerosene-burning aircraft, as a variation of the number of abreast seats has not been explored here. Therefore, the length of the cabin, of the front and back sections of the fuselage remains unchanged, given that the fuselage diameter also remains unchanged. The final aircraft length is computed by adding the hydrogen tank length, sized considering the constraint of the internal diameter of the fuselage, and the original fuselage length. Further details concerning HYPERION can be found in [3].

3.2.2 Design trade-off framework

In preliminary sizing, key parameters such as engine bypass ratio (BPR) and wing Mach drag divergence need to be specified as inputs, allowing to determine the trade-off matrix if a variation of the parameters is explored. The maximum BPR for future advanced conventional tube-and-wing aircraft configurations is typically around 12. Therefore, a coherent value of BPR=12 is considered in this study. The trade-off of wing parameters, including sweep, aspect ratio (AR), and thickness-to-chord ratio (t/c), needs to be defined to avoid patch-up tendencies and drag divergence. An empirical trend, shown in eq. 1 suggests that for a given AR, the highest sweep angle provides the best performance. This boundary is respected in the trade-off study [11].

$$\Lambda_{c/4limit} \leq 23.436[\ln(17.714(2 - \lambda)) - \ln AR] \quad (1)$$

The selection of wing sweep angle and t/c must ensure that the drag rise effect at the required cruise Mach number is not significant. The upper limit of t/c is related to the drag divergence Mach number by eq. 2 [12].

$$M_{DD} \cos \Lambda_{c/4} + \frac{\bar{t}}{c \cos \Lambda_{c/4}} + 0.1 \left(\frac{1.1 C_L}{(\cos \Lambda_{c/4})^2} \right)^{1.5} = M^*$$

(2)

$$M^* = 0.95$$

The Oswald efficiency factor varies based on design parameters and needs to be computed and inputted into HYPERION for each studied aircraft. The Shevell method [13] was selected for its ease of use and accuracy in determining the Oswald factor. To validate the model, assumptions, and methodology, a kerosene-burning NB case was sized and compared to the A320 aircraft. The optimum values for aspect ratio and cruise speed closely matched those of the A320, as shown in fig. 3 indicating the method's potential for design studies.

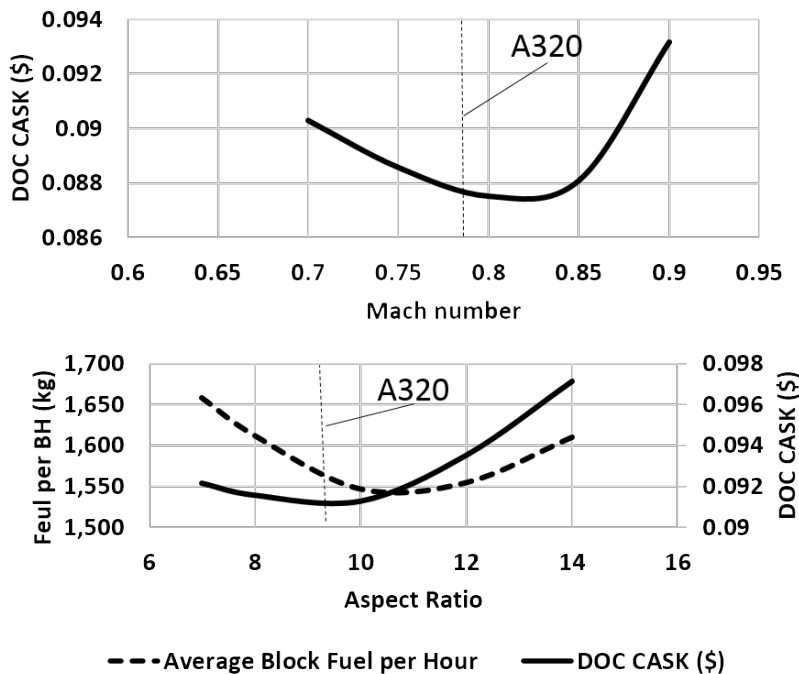


Figure 3 – Validation of methodology for a kerosene-burning aircraft of the size of the Airbus A320.

4. Narrow-body design study

The trade-off study provides valuable insights into the design considerations for a narrow-body aircraft, taking into account various parameters such as engine and material technologies, range, passenger capacity, wing parameters, and cruise speed. The baseline for the trade study was an aircraft with a capacity of 198 passengers, a seat pitch of 28 inches, and a design range of 3,700 km, comparable to the Airbus A321.

The trade-off between engine and material technologies was examined to understand their impact on DOC. Applying high BPR engines and advanced composite materials can potentially reduce fuel consumption and overall DOC. In fact, it was found that the version with old technology had higher Maximum Take-Off Mass (MTOM) and DOC compared to the version with new technologies by 13%. The new technologies resulted in a significant reduction in mission fuel, by 35%.

Range and passenger trade-off

The trade-off between range and PAX shows that there is a stronger sensitivity on CASK to the

variation of the number of passengers than to the variation of the design range. In fact, 20 more passengers increase the DOC more than an increase of 1000 km of design range, as seen in fig. 4. Intuitively, increasing PAX and range leads to an increase in operating empty mass (OEM) and fuselage slenderness, as depicted in fig. 5 and fig. 6. To meet the demands of domestic and intracontinental flights, the aircraft range must be at least 2,500 km, although the average European flight is only 978-km long [5]. Furthermore, transcontinental North American flights cover a distance of up to 4500 km. Based on these requirements, a reference design range of 4,000 km at maximum payload, similar to that of the Airbus A320, with 200 PAX was selected as the best compromise for the narrow-body aircraft, to meet the NMA expectations.

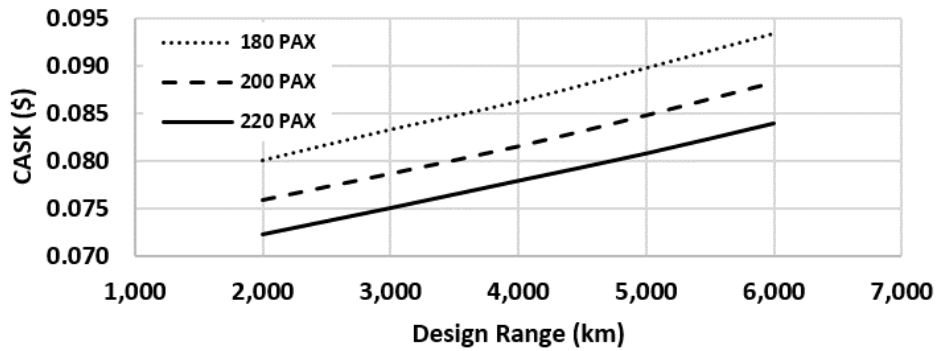


Figure 4 – Effect of passenger number and design range on CASK for NMA aircraft.

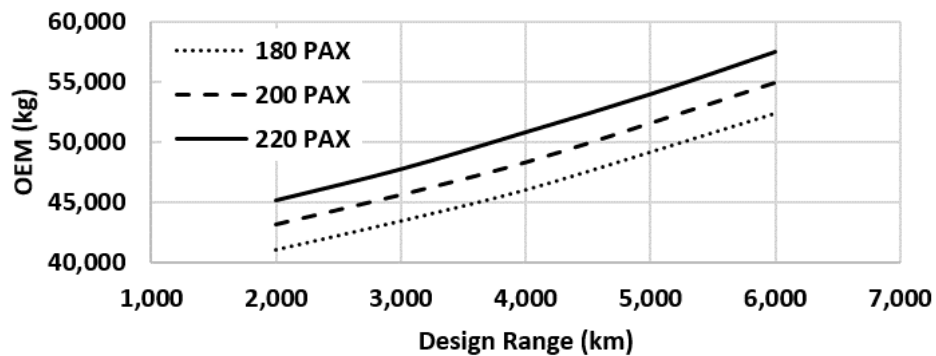


Figure 5 – Effect of passenger number and design range on OEM for NMA aircraft.

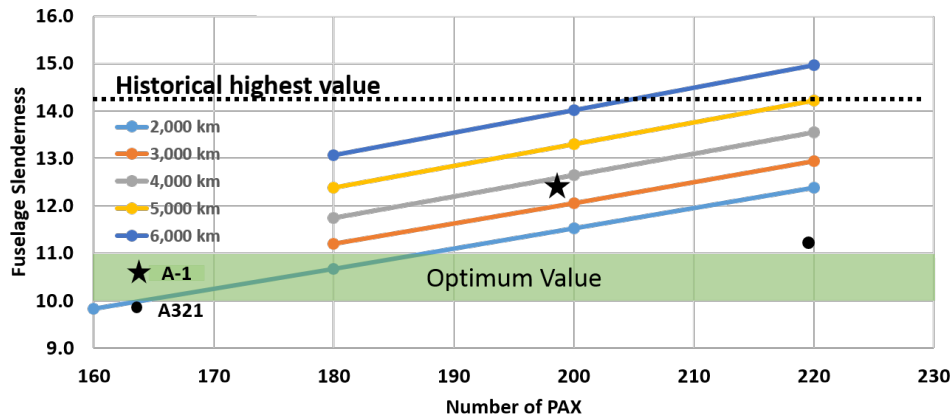


Figure 6 – Fuselage slenderness for NB study cases

Wing parameters trade-off

A trade-off analysis determines the optimal values for wing parameters, including sweep angle, aspect ratio (AR), and thickness-to-chord ratio (t/c). It is observed that the increase of AR and the decrease of t/c result in higher MTOM, as seen in fig. 7. However, a higher AR reduces induced drag and fuel burn. The optimum values for the wing were determined to be a sweep angle of 25° , an AR of 10, and a t/c of 12%. These values provide a lower fuel burn, as seen in fig. 8 and achieve a DOC close to the optimum.

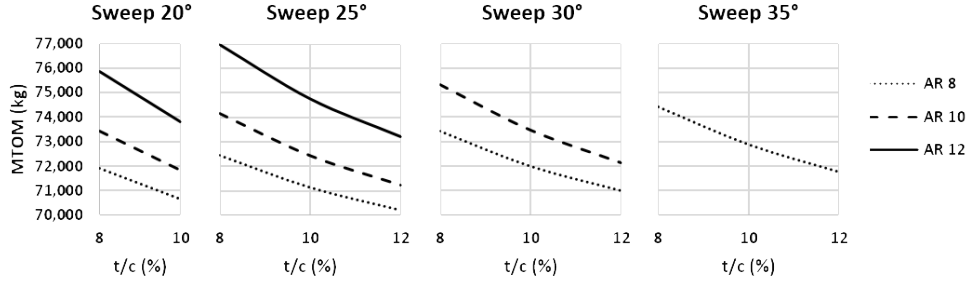


Figure 7 – MTOM for narrow-body aircraft wing parameters variation.

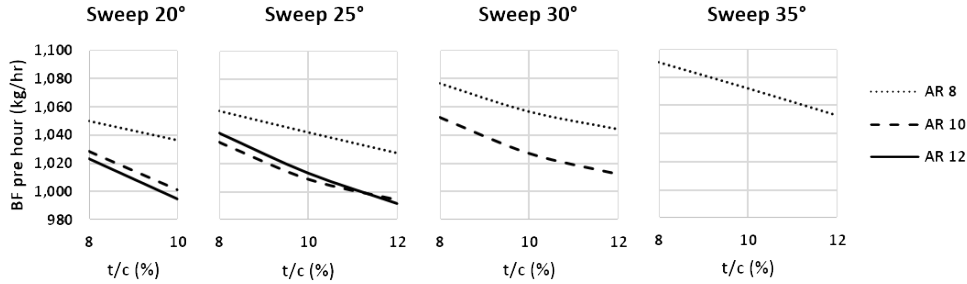


Figure 8 – Block fuel per hour of cruise for narrow-body aircraft wing parameters variation.

Cruise speed trade-off

The trade-off analysis for cruise speed considers different Mach numbers. Increasing the Mach number leads to a decrease in BH but an increase in fuel consumption. However, cost parameters dependent on BH are more impacting on the DOC than fuel cost. Besides, the optimum cruise Mach number strongly depends on fuel price, with lower prices shifting the Mach number to higher values, as shown in fig. 9.

4.1 Narrow-body design solution

The preliminary sizing of the DOC-optimised NB LH₂ aircraft is based on the most promising parameters identified in the trade studies optimization. The NB LH₂ (optimal solution) enables an increase of 8% of the design range and 5% of the cruise Mach number, with the same CASK as the baseline LH₂ aircraft. Although this reduction may not be significant, it is worth noting that the baseline design parameters were already close to those of the highly efficient A320 aircraft. Furthermore, it is important to notice that the DOC CASK remains the same, as some cost components of the DOC, such as insurance and ownership, depend on the number of flight cycles and a higher cruise speed increases the cycles that the aircraft can operate over its lifespan, and not just on the mere aircraft performance. The increase of cruise speed slightly worsen the energy efficiency of the aircraft, as measured by the Payload-Range-Energy Efficiency (PREE) [14], which quantifies the efficiency of the aircraft as the ratio between the mission work (payload weight transported over the design range) and the energy used for the mission. Relevant parameters resulting from the sizing are presented in table 1. The reference aircraft has been sized considering input parameters equivalent to those of the A320 family, except for the range and payload, which have been identified from the previous market analysis. The DOC-optimised aircraft instead is sized based on input parameters identified in the previously presented trade-off analyses. For reference, Aegean Airlines, whose fleet is only

PRELIMINARY SIZING OF LH2 JETS FOR DIRECT OPERATING COST OPTIMIZATION

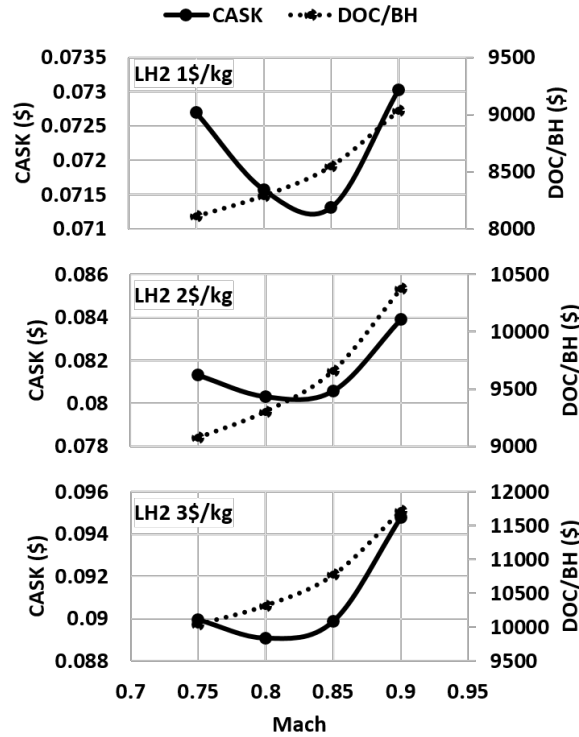
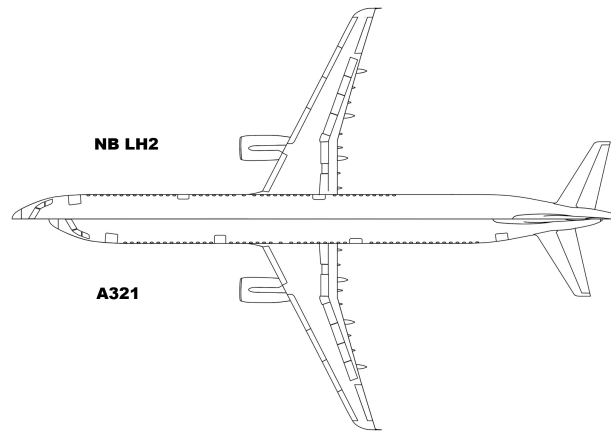


Figure 9 – Effect of cruise Mach number on DOC for NB aircraft for different hydrogen prices spanning from 1 \$/kg yo 3\$/kg.

Parameter	Unit	Reference A/C	DOC-optimized A/C	Δ%
MTOM	kg	71,218	72,675	2.05
OEM	kg	47,257	48,199	1.99
Hydrogen	kg	5,344	5,859	9.64
Tank	kg	2,559	2,766	8.09
Payload	kg	18,414	18,414	0.00
Design Range	km	3,700	4,000	8.11
AR	-	9.5	10	5.26
Average t/c	%	11	12	9.09
Cruise M	-	0.78	0.82	5.13
Hourly fuel consumption	kg/h	1,002	1,065	6.29
DOC CASK	\$	0.081	0.081	0.00
DOC/BH	\$/h	9,229	9,527	3.23
Purchasing price	M\$	119.8	121.7	1.59
PREE	-	1.18	1.17	-1.39

Table 1 – Preliminary sizing results for NB LH₂ aircraft, subject to DOC optimization.

composed by regional narrow-body aircraft, showed a CASK of 0.078 \$ in 2023 [15], showing a 3.8% increase for hydrogen aircraft. Nonetheless, this true CASK value is only reported as a reference, as the unknown concerning the entry into service of hydrogen aircraft are still too many, including how kerosene could be taxed or hydrogen incentivised, which could potentially modify which energy source is more interesting economically. Furthermore, as mentioned in ch. 3, the considered DOC model does not consider the transient, but a situation in which hydrogen aircraft are already widespread. Furthermore, it was observed that within the expected range of fuel prices, the deviation of MTOM and empty mass in the optimum case is only 0.5% for each 1\$/kg variation in fuel price. This suggests that the effect of changing fuel prices on the optimum point is negligible. Figure 10 compares the external dimensions of the NB LH₂ and A321.

Figure 10 – Size comparison of NB LH₂ and A321.

5. Wide-body design study

The baseline for the WB trade study is an aircraft with a capacity of 300 PAX, a seat pitch of 32 inches, and a design range of 14,800 km, similar to the B787-8. The overall procedure follows the same approach as that of the NB aircraft.

Number of abreast seats trade-off

The trade-off analysis shows that the 8-abreast configuration has lower DOC and MTOM compared to the 9-abreast configuration. Although the 9-abreast case shortens the fuselage, the greater fuselage diameter increases the fuselage mass, offsetting the mass savings achieved thanks to the length reduction. In the 9-abreast configuration, the MTOM increases by 0.6% and cost by 0.4%. The reduction of fuel mass by 0.4% indicates a decrease in drag due to the shorter fuselage length.

Range and passenger trade-off

Similar to the NB aircraft, there is a greater CASK improvement at lower ranges and higher passenger capacities. The trends related to mass are also similar. It is possible to imagine a family of long-range aircraft, meeting the market requirements of a design range up to 15,000 km and 400 PAX, not necessarily concurrently. In fact, given that the hydrogen tank is placed at the back of the fuselage, it is possible to foresee that an aircraft with a given external dimension will offer multiple combinations of passenger and range. The decision on the fuselage length allocated to the tank and to the passenger cabin will have to be made before the final assembly of the aircraft, still leaving some flexibility in the design phase. To avoid exceeding the historical highest value of slenderness ratio for any combination of passengers and range, the design range is limited to 12,000 km with 350 PAX, which is found to be the best solution for the basic version, as shown in fig. 11. This allows for shorter and longer derivatives to cover different market demands.

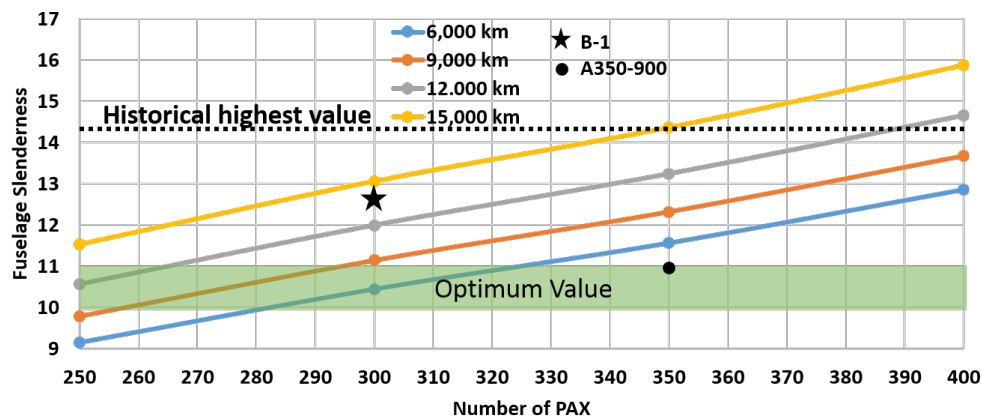


Figure 11 – Fuselage slenderness for wide-body aircraft.

Wing parameters trade-off

As expected, all observations for wing sizing are the same as for the NB aircraft, except that due to the higher cruise Mach number required by this class, a sweep angle of 30° at $AR=10$ are closer to the optimum point of CASK and fuel flow, as shown in fig. 12. t/c is set to 10% to maintain a safe margin from the insurgence of aeroelastic effects.

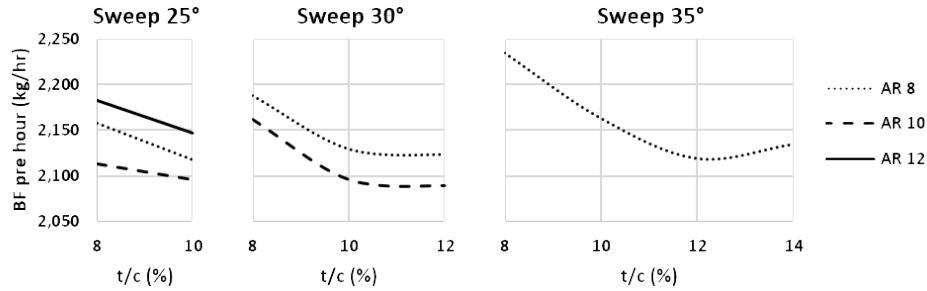


Figure 12 – Hourly block fuel for wide-body aircraft as a function of wing parameters.

Cruise speed trade-off

Figure 13 demonstrates how cruise speed affects DOC parameters. In these cases, an increase of the LH_2 price from 1\$/kg to 3\$/kg would decrease the optimum cruise speed from $M=0.87$ to $M=0.85$. It is also observed that the sensitivity of CASK vs cruise Mach number is not as strong as in the NB case.

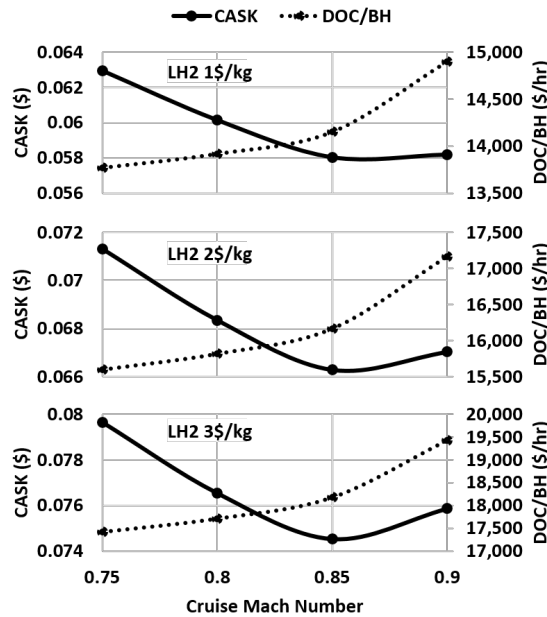


Figure 13 – Effect of cruise Mach on DOC for WB aircraft.

5.1 Wide-body design solution

Preliminary sizing of the final solution for the WB LH_2 aircraft was performed based on the parameters observed in the trade-off analysis. The results show that the optimum solution has a 17% higher payload weight, a 19% lower design range, and a 16% lower CASK compared to the baseline, as shown in table 2. For reference, the Boeing 787-8 has a maximum payload of 41 t with a corresponding range of 9720 km.

For comparison, the CASK of the Lufthansa group, including both short and long haul operations is equal to 0.068\$ [16], showing that long haul hydrogen aircraft can be comparable to current ones, or better if the optimization happens. Nonetheless, it is necessary to remind that the DOC model relies on the MTOM, which varies significantly from the Boeing 787-8 (227,900 kg) to its hydrogen

PRELIMINARY SIZING OF LH₂ JETS FOR DIRECT OPERATING COST OPTIMIZATION

Parameter	Unit	Reference A/C	DOC-optimized A/C	Δ%
MTOM	kg	191,909	185,238	-3.48
OEM	kg	123,613	124,150	0.43
Hydrogen	kg	36,203	28,350	-21.69
Tank	kg	15,647	12,527	-19.94
Payload	kg	27,900	32,550	16.67
Design Range	km	14,800	12,000	-18.92
AR	-	9.5	10	5.26
Average t/c	%	10	10	0.00
Cruise M	-	0.85	0.85	0.00
Hourly fuel consumption	kg/h	2,103	1,647	-21.68
DOC CASK	\$	0.069	0.058	-15.94
DOC/BH	\$/h	16,872	16,432	-2.61
Purchasing price	M\$	323.5	309.3	-4.39
PREE	-	1.06	1.21	14.30
Length	-	1.06	1.21	14.30

Table 2 – Preliminary sizing results for WB LH₂ aircraft, subject to DOC optimization.

counterpart, because of the significant fuel fraction in the mass distribution of the original aircraft. Additionally, unlike the NB LH₂, the elongation of the fuselage is significant compared to the current Boeing 787-8, as seen in fig. 14. This will cause an extensive redesign of, among others, of the landing gears, to ensure safe take-offs and landings.

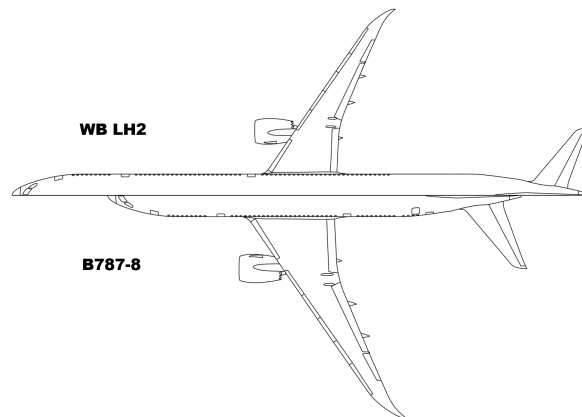


Figure 14 – LH₂ widebody size comparison with B787-8.

6. Conclusion

The study explores the optimal design solution in terms of DOC for hydrogen-powered aircraft. The mission, identified via a market expectation analysis, is defined by the maximum payload and corresponding maximum range. The selected parameters offer eventually a reference point for the development of short- and long-range aircraft families, to cover the vast majority of the commercial aviation market and not just the sweet-spot for the two categories. The in-house preliminary sizing methodology, HYPERION, combined with the cost model, are accurate enough for conceptual design optimization and capable of calculating the optimum point the aircraft, given a design space based on various values for significant design parameters. The analysis also found that the ownership cost is the main driver of DOC. Technological advancements that improve fuel consumption do not significantly reduce DOC. However, the major variables in the trade-off sizing for DOC are technology level, number of passengers, and design range.

The optimal aircraft in for the NB category has a range of 4,000 km and 200 passengers, while for WB aircraft the sizing mission carries 350 passengers over 12,000 km. However To accommodate cryogenic tanks, the fuselage needs to be elongated by approximately 20% for NB aircraft and 35%

for WB aircraft, compared to current kerosene counterparts. Furthermore, it is found that LH₂-burning aircraft have higher operational empty mass by 15% for NB and 5% for WB, as well as lower maximum takeoff mass by 1% for NB and 19% for WB compared to kerosene versions, detailing how impacting the switch of energy source is. It is also found that while fuel prices do have an impact on the operational scenario via the modification of the cruise speed, they have a negligible effect on the optimal solution.

Contact Author Email Address

Mail to: gabriele.sirtori@polimi.it

Copyright statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

- [1] McKinsey. Hydrogen-powered aviation a fact-based study of hydrogen technology, economics, and climate impact by 2050, 2020.
- [2] M.A.H. Khan, J. Brierley, K.N. Tait, S. Bullock, D.E. Shallcross, and M.H. Lowenberg. The emissions of water vapour and NO_x from modelled hydrogen-fuelled aircraft and the impact of NO_x reduction on climate compared with kerosene-fuelled aircraft. *MDPI Atmosphere*, 2022.
- [3] L. Trainelli, C.E.D. Riboldi and G. Sirtori. Methodologies for the Preliminary Sizing of Hydrogen-Powered Aircraft and Supporting Airport Infrastructures. *34th ICAS Congress*, Firenze, Italy, 2024 (submitted).
- [4] Airbus. Global market forecast 2022. <https://aircraft.airbus.com/en/market/global-services-forecast-gsf-2022-2041>, 2022.
- [5] EUROCONTROL. Data snapshot: average flight distance in 2020. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.eurocontrol.int/sites/default/files/2021-04/eurocontrol-data-snapshot-9-average-flight-2020.pdf&ved=2ahUKEwiNh9rNkKSGAxU3S_EDHRggBjUQFnoECBcQAQ&usg=AOvVaw0J1xzym-3uGUdPNf0PEYdo, 2021.
- [6] J. Wilkerson, M. Jacobson, A. Malwitz, S. Balasubramanian, R. Wayson, G. Fleming, A. Naiman, and S. Lele. Analysis of emission data from global commercial aviation: 2004 and 2006. *ATMOSPHERIC CHEMISTRY AND PHYSICS*, 2010.
- [7] L. Trainelli, C.E.D. Riboldi, A. Rolando, F. Salucci, F. Oliviero, J. Pirnar, T. Koopman, and A. Znidar. D1.2: The design framework for an NZE 19-seater. *UNIFIER19*, 2020.
- [8] K. Oesingmann, W. Grimme, and J. Scheelhaase. Hydrogen in aviation: A simulation of demand, price dynamics, and co2 emission reduction potentials. *International Journal of Hydrogen Energy*, 2024.
- [9] R. Doganis. *Flying off course: airline economics and marketing*. Routledge, 2019.
- [10] J. Sun, and J.M. Hoekstra, and J. Ellerbroek. Aircraft Drag Polar Estimation Based on a Stochastic Hierarchical Model. *Eighth SESAR Innovation Days*, Salzburg, Austria, 2018.
- [11] S. Gudmundsson. *General aviation aircraft design: applied methods and procedures*. Elsevier, 2014.
- [12] E. Torenbeek. *Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes*. WILEY, 2013.
- [13] R.S. Shevell. *Fundamentals of flight*. Pearson, 1988.
- [14] K. Abu Salem, G. Palaia, and A. Quarta. Impact of figures of merit selection on hybrid-electric regional aircraft design and performance analysis. *Energies*, 16, 2023.
- [15] Aegean. Second quarter first half 2023 financial results, 2023.
- [16] C. Spohr and R. Steenbergen. Lufthansa group: Full year 2022 results, 2023.