CONCEPTUAL DESIGN OF A ZERO-EMISSION REGIONAL AIRCRAFT FOR ENHANCED SHORT-HAUL MOBILITY

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Abstract

This paper discusses the conceptual design activities carried out towards the definition of a design solution for a disruptive short-haul air transportation vehicle. This is characterized by a radically new propulsion system guaranteeing zero emissions at aircraft level and by a one-of-a-kind operational mission as a multi-hop commuter for airport feeding and intercity commuting. The challenge called to consider a much wider spectrum of configuration options than usually done for conventional commuter aircraft design, intertwined with the special design requirements stemming from the propulsion system adopted and the design mission. The paper addresses the process of the configuration selection and the preliminary sizing of the vehicle, which provide a basis for the subsequent, successful preliminary design loop.

Keywords: zero-emission aircraft, fuel-cell propulsion, hydrogen for aviation, regional air transportation, distributed electric propulsion

1. Introduction

Enhanced mobility solutions for regions without adequate transport infrastructure are necessary to get closer to Europe's Flightpath 2050 vision, envisaging that virtually all EU citizens shall reach any continental destination in less than four hours, door to door, by the year 2050. An alternative to substantial financial investments to establish an effective ground transport system (highways, high-speed railway) in underdeveloped areas or regions with disadvantageous topographical characteristics is represented by a network of routes exploiting the existing, sparse, and underused small airports and airstrips in Europe. This matter was addressed in the EU-funded Clean Sky programme, the Call H2020-CS2-CFP09-2018-02, topic JTI-CS2-2018-CFP09-THT-03 requested a CS2-RIA Research and Innovation Action on the "Conceptual Design of a 19 passenger Commuter Aircraft with near zero emissions", conceived for the enhancement of the mobility of European citizens. The call asked for the design of a CS-23/FAR-23 compliant aircraft based on alternative propulsion concepts (electric, hybrid-electric, fuel cells, etc.) in the quest for an environmentally-friendly solution. A consortium formed by aircraft manufacturer Pipistrel Vertical Solutions and universities Politecnico di Milano and Technical University Delft devised the UNIFIER19 "Community Friendly Miniliner" project in response to such topic and was accepted for funding, starting operations in October 2019.

The UNIFIER19 consortium performed an initial assessment of the potential of electric and hybrid-electric solutions for reducing the environmental impact with respect to both direct (airframe-related) and indirect (landside) effects, while guaranteeing adequate mission and economic performance. This showed that battery-electric solutions would not be capable to comply with mission requirements and that only incremental benefits would be achieved with hybrid-electric solutions, at the price of complexity. Therefore, the consortium headed decisively towards a radical design where the propulsion system was conceived as a blend of hydrogen-fed fuel cells (FC) and electric batteries that power electric motors (EM) driving propellers. This guarantees rigorously zero emissions when considering CO_2 and NO_x, i.e. the chemicals raising the most concern for environmental sustainability. With the elimination of direct chemical pollution effects, the key metrics considered in the design loop were noise emissions and cost.

The project evolved through three technical work packages addressing the establishment of a design framework, the achievement of a conceptual design solution, and the high-fidelity design and optimization including emission analysis, life-cycle analysis (LCA), certifiability and costs analysis. Detailed information on the results achieved in each work package can be retried by accessing the publicly-available project deliverables [1,2]. In the present paper, the focus is placed on the conceptual design phase, which included a dedicated market study envisioning future transport services operated by the "Community Friendly Miniliner", the definition of design requirements, and a concurrent design competition in which each consortium partner independently addressed the initial sizing and configuration selection of candidate concepts. The candidates were then subjected to a thorough evaluation based on costs and noise emission estimates, as well as manufacturability, operational and maintainability considerations. As a result, a winning design solution was identified for further maturation in a complete preliminary design loop.

Table 1 – Selection of UNIFIER19 driving design requirements.

Mission Leg	Type	Value	Note
Take-off and landing	Runway length	800 m	50% of secondary aerodromes are 800 m or longer
	Runway type	Grass	50% of secondary aerodromes are grass type
Climb	Initial gradient	7 degrees	Up to 1,000 ft AGL, airport near populated area
	ROC	850 ft/min	
Cruise	Block range	300 - 350 km	Block range is a sum of climb, cruise and descend distance → defined as one "hop"
	Altitude	max 8,000 ft	
	Speed	150-200 kn	Potential demand markedly increases from 150 kn to 200 kn
Reserves	Diversion	100 km	90% of secondary aerodrome within 100 km
	Loiter	45 min	IFR requirement
Airport operations	Turnaround time	Max 45 min	Only battery recharged needed at aerodromes, except origin
General	CS-23		Unpressurised cabin
	Cargo variant	3 x LD3 containers	Reconfiguration on airfield
	Number of passengers	19	100 kg for each passenger + carry-on baggage 20 kg checked baggage
	Number of "hops"	min 4	To avoid having refueling infrastructure on all small airports
	Number of pilots	1	Fly-by-wire system, suitable for autonomous or remotely piloted conversion

2. Concept of Operation

The UNIFIER19 commuter aircraft is aimed at two new mobility services: the microfeeder and the intercity miniliner, both exploiting the potential of the wide European small airport and airstrip network (involving over 3,000 aerodromes) to bring citizens unable to access high-speed trains close to their residence for short-haul journeys. The former represents a hub-and-spoke link, used to feed major airports from smaller cities or open country territories, whereas the latter is a point-to-point connection between smaller cities, such as work or school daily commuting. These services, although different in nature, may well be served by a platform such as a new type of CS-23/FAR-23 commuter conceived to be used as the equivalent of a bus.

A thorough investigation of the market potential and the mission requirements for an optimal solution to this new usage framework resulted in the definition of a peculiar mission profile made by a series of "hops" up to 350 km each, without refuelling between each leg. This is motivated by an expected operational scenario in which only a subset of the small airports in the served network will be equipped with a hydrogen refuelling infrastructure, at least initially. A detailed discussion of the process that led to the mission definition, involving an original approach to the estimation of the potential demand for a not-yet existing short-haul transportation service that takes into account the competition with existing road and train options, is detailed in Ref. 1. This work provided crucial to the identification of peculiar operational needs and specifications and to the sensible determination of some of the most important top-level aircraft design requirements, such as payload, range, take-off and landing distances, and cruising airspeed. As an example, while achieving a total range in excess of 1,200 km, the limited size of each "hop" greatly reduces the practical impact of seeking high speeds and altitudes. Consequently, an unpressurized configuration is considered.

A selection of the main UNIFIER19 top-level design requirements derived from the cited market analysis is reported in Table 1, together with some motivational notes. These include a requirement on the ease of cabin reconfigurability and a cargo door, to allow the switch from passenger service to cargo service (3 x LD3 containers), especially at night, a feature pointing at improving productivity and traffic reduction. By looking at Table 1, it is remarked that, among the most innovative elements in the UNIFIER19 configuration, a fly-by-wire (FBW) flight control system (FCS) is envisaged, allowing for single-pilot operations.

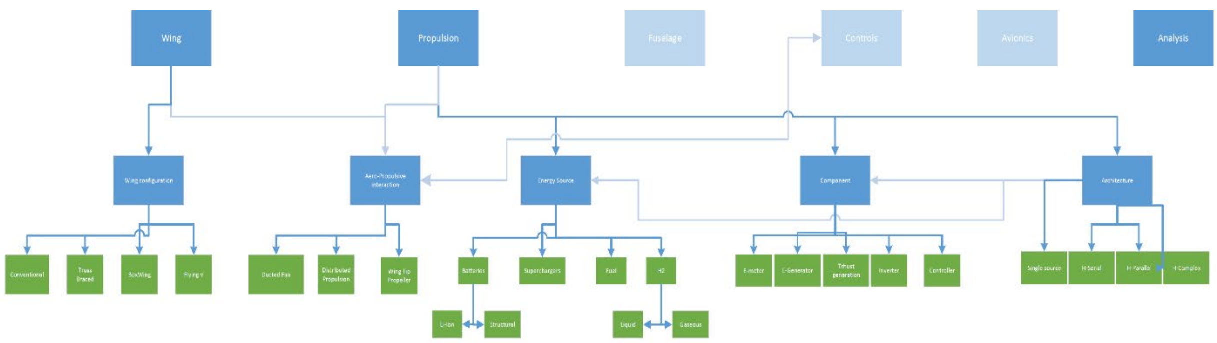

Figure 1 – Aircraft architecture option-tree diagram.

3. Initial Configuration Selection

The initial Concurrent Design Competition was carried out with the aim of exploring the aircraft configuration space at large, exploiting the in-house design procedures and tools developed by each consortium partner, as well as their experience in previous research efforts, such as the MAHEPA project [3-8]. The process was comprised of three stages. In the first one, a panoramic definition of the options regarding the layout of various major components of aircraft was established, to allow the maximum extension of the design configuration space, in the quest for the most favorable options. The following focuses on the work performed by the authors at the Politecnico di Milano research unit.

The chosen electric-driven propeller propulsion, with its higher scalability and ease of positioning with respect to conventional solutions, inherently provides a larger range of configuration solutions. Indeed, this provided numerous fairly "exotic" initial candidates by combining general configuration options (tube and wing, blended wing body), lifting configuration options (aft tail, canard, three-surface, tailless), wing structural arrangements (cantilever, truss-braced, box/joined wing), propulsive unit arrangement (nose, mid-wing, distributed, wing-tip, tail cone), propeller type (normal, contra-rotating, ducted), and other elements. The combination of these features results in a large number of possible permutations (notionally, over 200,000), arising from the option-tree diagram shown in Figure 1. Therefore, a first substantial reduction process was carried out, applying a qualitative judgement of the overall feasibility of the potential candidates. Removal of configurations deemed unfeasible or unable to provide any benefit, plus a number of preliminary assessments (also relying on hand-drawings to better define some particulars of less-intuitive solutions), helped to shrink the number of potential candidates to 45 for the initial list to be qualitatively assessed.

Table 2 – Intermediate list of candidate design configurations.

Score	Label	Definition		
		Layout	Wing	Propulsion
0.22759	C3	Canard with *"laminar flow fuselage"*, VIW and BLI		
0.20612	C12	Tailless	TBW	DEP, WTP and BLI
0.20415	C2	Canard PCA with DEP, WTP and BLI		
0.20373	C7	Aft Tail	TBW	DEP, WTP and BLI
0.19857	C15	TSA	TBW	DEP, WTP and BLI
0.19850	C6	Aft Tail	Cantilever	DEP, WTP and BLI
0.19420	C4	BWB with with asymmetric BLI-DEP		
0.19419	C9	Aft Tail	Box Wing	DEP and BLI
0.19399	C11	Tailless	Cantilever	DEP, WTP and BLI
0.19380	C10	Canard	Cantilever	DEP, WTP and BLI
0.19188	C5	BWA with DEP		
0.19121	C1	Aft Tail	TBW	DEP and WTP
0.18676	C14	TSA	Cantilever	DEP, WTP and BLI
0.18284	C13	Tailless	Cantilever	WTP and BLI
0.17913	C8	Aft Tail	Box Wing	DEP

Subsequently, a qualitative selection was performed by down-selecting the initial list based on a set of rational criteria and an accurate ranking of the surviving candidates. The criteria included the assessment of the presence of multiple critical innovations in each candidate, the degree of uncertainty of estimated performance, the relevance of expected benefits relative to the objective of the project, and others. Also, care for keeping at least one instance of an attractive technology/solution in the down-selected list was applied. This discussion led to an intermediate list including the 15 candidates shown in Table 2, where the following acronyms are used (in alphabetical order):

- BLI – Boundary layer ingestion
- BWA – Blended wing-body aircraft
- DEP – Distributed electric propulsion
- PCA – Propulsion-controlled aircraft
- TBW – Truss-braced wing
- TSA – Three-surface aircraft
- VIW – Variable-incidence wing
- Figure 4 WTP – Wing-tip propeller

It is remarked that configurations featuring BLI are endowed with a tail cone pusher propeller. DEP is considered only as a high-lift device, enhancing or even substituting flaps altogether, allowing to design a cruise-optimized wing, therefore all DEP configurations also have a separated cruise propeller (possibly in the tail). PCA identifies a case in which differential control of DEP/WTP permits a certain degree of maneuvering capability without primary control surface deflection.

The next step involved the application of a Multi-Criteria Decision Making (MCDM) process to rank the 15 configurations in relation to the following criteria:

1. Capability to capitalize interactions between the airframe and the propulsion system.
2. Aerodynamic efficiency (especially for high-lift generation).
3. Structural efficiency.
4. Noise emission.
5. Cost and design complexity.

The first two columns in Table 2 presents the results obtained with the application of the Analytic Hierarchy Process (AHP) method [9]. The histogram on the left side depicts the ratings attained by each of the 15 candidates at the end of the evaluation procedure. The rank is the result of the geometric mean among multiple different applications of the AHP, considered for robustness. Colours show the clustering inspired by discrete jumps in the score values.

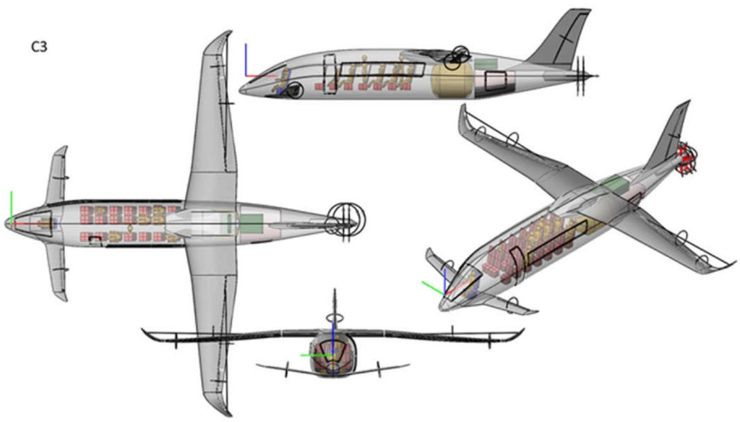

Figure 2 – The C3 candidate configuration.

The five top-ranking configurations emerged from the MCDM process are C3, C12, C2, C7, and C15. Configuration C3 (Figure 2) stands out thanks to its relatively simple design that ensure great aerodynamic and structural potential, while exploiting propulsion-airframe interaction. Configuration C2 is also a canard realization, with the added complexity of DEP. Concerning C12, C7 and C15, all representing TBW applications, it may be noted that they represent relatively similar solutions, ranked very close to each other, and the are expected to provide relatively similar performance.

A mid-fidelity modelling of a truss-braced wing was developed and integrated, to better evaluate the implications os such a solution for the wing structural arrangement. This showed that the effect of the enhancement in lift-to-drag ratio was not enough to offset the weight penalty associated. As a result, a decision was taken to consider a variant of C7, named C7A, with the same features of C7, but a cantilever wing, for further development.

4. Preliminary Sizing

The five candidates C2, C3, C7A, C12, and C15 have been subjected to a quantitative evaluation. This was carried out by application of the HYPERION preliminary sizing tool, which implements a general methodology dedicated to innovative fixed-wing aircraft conceptual design. General information on this methodology can be retrieved in Refs. 6, 11, as well as in a companion paper submitted to ICAS 2024 [12]. This methodology has been further improved by adding a subsequent preliminary design loop implementing the geometric sizing of the major aircraft subsystems, the static stability and control requirements, and the performance evaluation.

Assuming the technology parameters reported in Table 3, which correspond to a prevision for the year 2025 based on literature and market trends, the design configurations have been sized and design sensitivity studies have been carried out, including energy efficiency considerations.

Table 3 – Assumed technology parameters for 2025.

Battery mass energy density	260 Wh/kg
Battery volumetric energy density	600 Wh/m^3
Battery power density	1,670 W/kg
Fuel cell power density	2,130 W/kg

As an example of the results obtained in this phase, Figure 3 shows the sizing matrix (or performance-matching) plot for configuration C7A, where the design point is shown to match the take-off distance requirement and (asymptotically) the stalling speed requirement. Note that both the stalling speed and the landing distance requirement do not translate into vertical lines due to the blowing effect of DEP. Also, Figure 3 shows the C7A mass breakdown, where the pure airframe (*i.e.* devoid of propulsive system elements) accounts for 49% of maximum take-off mass (MTOM), while the sum of all propulsive system elements amounts to 21% MTOM. Note that the hydrogen tank mass, yielding a promising tank gravimetric index of 0.6, refers to a cryogenic vessel for liquid gas storage, sized according to Ref. 13. The MTOM amounts to somewhat less than 8,000 kg, which complies with the 8,618 kg limit of CS-23/FAR-23, leaving a very reasonable margin.

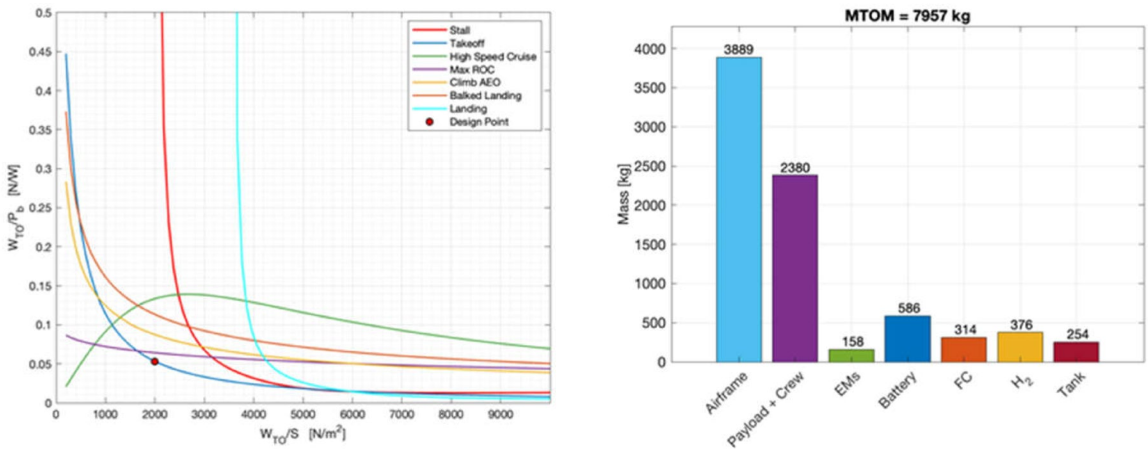

Figure 3 – Sizing matrix plot (left) and mass breakdown (right) of candidate C7A.

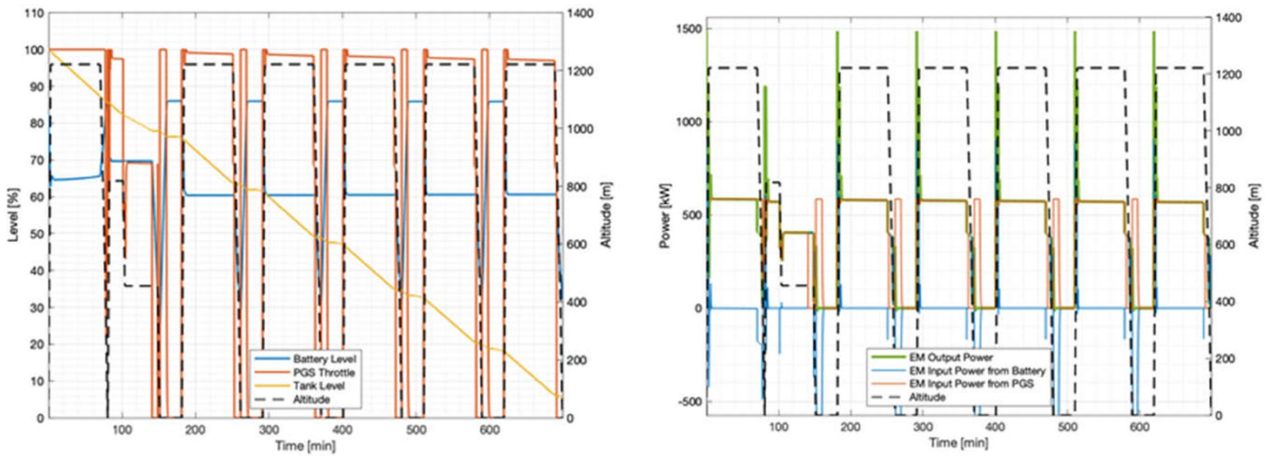

Figure 4 – Time histories during the sizing mission for candidate C7A.

Figure 4 shows the time histories of relevant quantities during the sizing mission for configuration C7A. On the left, the battery state of charge (blue), power generation system (PGS, *i.e.* the fuel cells) throttle percentage (red), and hydrogen tank level (yellow) are depicted. On the right, EM output power (green), EM input power from FC (red) and from batteries (blue) are depicted. In both cases, the altitude profile is contrasted in black dashed lines.

Sensitivity analyses have been carried out to characterize the candidate solutions and identify possible criticalities. Variation of several parameters belonging to three broad categories have been considered:

- Technology: battery mass-specific energy, battery mass-specific power, FC mass-specific power, EM mass-specific power.
- Performance: range, rate of climb, cruising speed.
- Operations: payload mass, airport altitude, turnaround time.

This study allows to evaluate, among other things, the optimality of energy utilization. An example of the obtained results is shown in Figure 5, where the energy-efficiency index f_{TOT} is plotted versus battery and FC mass-specific powers p_b and p_{FC}. The index f_{TOT} is defined as the total energy consumed divided by the mission range multiplied by the number of passengers.

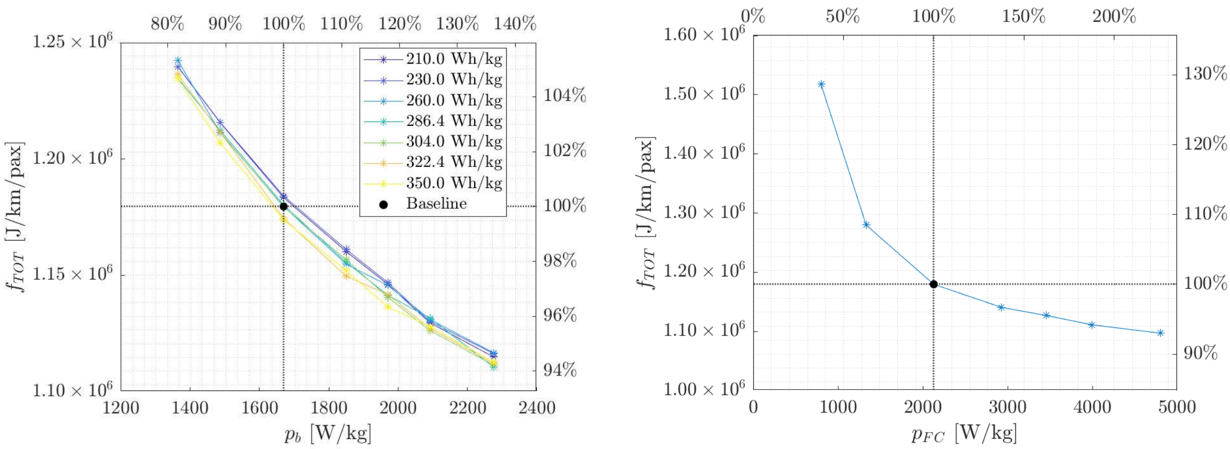

Figure 5 – Sensitivity of energy-efficiency index on battery specific power (left) and fuel-cell specific power (right) for candidate C7A.

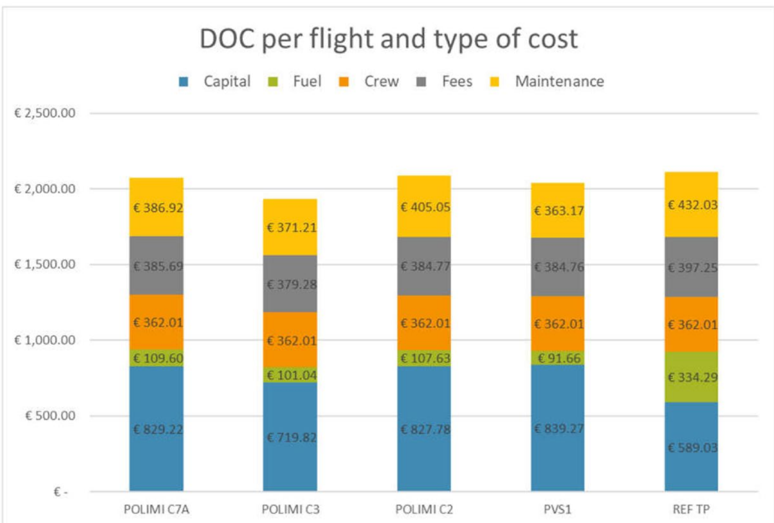

Figure 6 – Total direct operating cost estimation per flight.

Following the preliminary sizing and the sensitivity analysis, a thorough cross-check and validation was performed by Pipistrel Vertical Solutions, applying in-house preliminary tools, mid-fidelity aerodynamic and aeroacoustic tools, and cost analysis tools. For the latter, Figure 6 presents the results of three Politecnico di Milano candidates (C2, C3 and C7A) along with Pipistrel's own candidate solution (PVS1) and the reference (conventional) turboprop solution (REF TP). As shown, the comparison is favorable to configuration C3, while the others do not differ markedly from the reference configuration.

At the end of this process, configuration C3 was deemed less favorable, particularly in terms of noise emissions during take-off, which is alleviated when using distributed electric propulsion (DEP). Configurations C2 and C7A both fully met design requirements and offered more than adequate performance. However, configuration C2, with its canard design, faced challenges related to trim and stability – issues that are likely to be more pronounced when using DEP, due to the possible increase in propulsive pitching moment coefficient. After careful consideration, configuration C7A emerged as the preferred choice for further maturation in the preliminary design process.

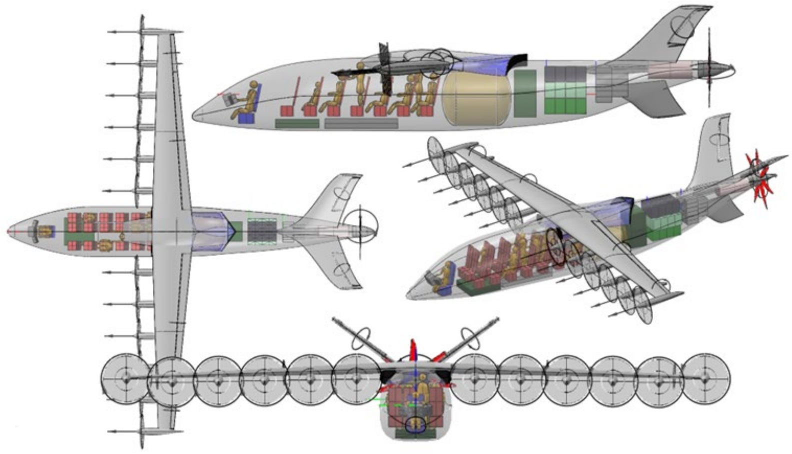

Figure 7 – The UNIFIER19 final configuration (C7A-HARW).

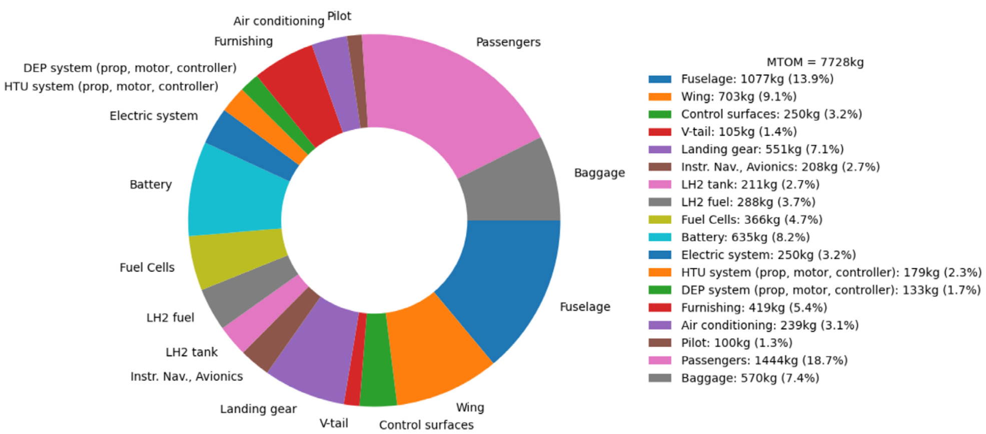

Figure 8 – Detailed mass breakdown of the UNIFIER19 final configuration (C7A-HARW).

Table 4 – UNIFIER19 main specifications.

Maximum take-off mass	7,728 kg
Hydrogen mass	288 kg
Length	18.5 m
Wingspan	20.1 m
Wing surface	28,9 m^2
Height	5.0 m
Take-off distance (CS-23)	605 m
Cruising speed	150 KTAS
Cruising L/D ratio	15.1

5. Further steps

The UNIFIER19 consortium, after a thorough verification and comparison of the candidate configurations provided by each partner, elected the C7A as the winner. Nevertheless, some modifications were proposed to optimize this configuration, the major one being the increase of the wing aspect ratio from 9 to 14, thereby enhancing the aircraft ability to leverage the benefits of DEP, particularly during the cruise phase when DEP propellers are inactive and their blades folded.

Another element in the configuration that underwent revision is the empennage assembly, which was defined as a V-tail supplemented by a pair of fins in the lower side of the tail cone. This was considered as a means to contain the disturbance in the inflow of the tail-cone propeller used in all phases of flight, seeking favorable effects in propeller efficiency and noise reduction. Figure 7 depicts the final C7A-HARW (high aspect-ratio wing) appearance and Figure 8 its detailed mass breakdown.

The final configuration underwent a complete preliminary design loop with the co-operation of all the UNIFIER19 consortium partners, including detailed aerodynamic, structural, propeller, and control system design, yielding the specifications shown in Table 4 and the full results disclosed in Ref. 2. This, based on the analysis of performance, stability and control, safety, environmental impact, life-cycle, and economics for the project, proved the viability of the proposed design solution as a means to improve the citizens' quality of life regarding short-haul travel within a future air transportation network exploiting small aerodromes in Europe.

6. Acknowledgements

The authors acknowledge the fruitful collaboration in the UNIFIER19 project matters discussed herein with the unit at Pipistrel Vertical Solutions led by David Eržen, as well as with colleague Fabrizio Oliviero, TU Delft.

7. Funding

This research was funded by the EU Horizon 2020 research and innovation program, under project UNIFIER19, GA N. 864901.

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