



MULTIDISCIPLINARY PRELIMINARY DESIGN PROCESS OF HYBRID-ELECTRIC SEAPLANE

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Abstract

The growing sensitivity towards environmental sustainability in the aviation market drove, during last years, aircraft manufacturers, research centers and universities all over the world to put more effort on the development and analysis of disruptive aircraft concepts and configurations, leveraging the introduction of renewable energy sources as main technologies capable to achieve significant reduction in fuel consumption and pollutant emissions. The paper is framed in the context of the COLOSSUS project (Collaborative System of Systems Exploration of Aviation Products, Services & Business Models), funded by the European Union in the Work programme of Horizon Europe, that sees as one of its main technical objectives the capability of performing conceptual studies on an innovative multi-role seaplane that serves as transport platform into an European inter-modal mobility scenario. The aircraft design process is carried out through a multidisciplinary design and analysis framework with the objective to investigate how disruptive powertrain architectures can help improve the environmental sustainability of future seaplanes.

Keywords: Seaplane, Hybrid-Electric aircraft, Multidisciplinary Design and Analysis, Aircraft design process.

1. Introduction

Nowadays the aviation operations contribution to pollutant emissions in Europe is about 3% of the total greenhouse gaseous emissions and it is expected to grow every year by 5% for unit of passenger-kilometers [1]. The increasing sensitivity towards more efficient and sustainable products paved the way to a large number of research projects and activities with the objective to develop and integrate technologies that enable a fast and reliable transition to more eco-friendly air vehicles. Such necessity led to the analysis of different and more sustainable energy sources, starting from biofuels, such as sustainable aviation fuel (SAF), to more disruptive solutions like the application of propulsive batteries, fuel cells and distributed electric propulsion [2].

When considering such objectives, the COLOSSUS (Collaborative System of Systems Exploration of Aviation Products, Services & Business Models) project aims at developing environmentally friendly transport systems, specifically a seaplane and an advanced air mobility vehicle (AAM), that represent the initial points of the transition towards the climate neutrality of the air transportation system. In this context two seaplanes in the CS-23 category are presented, the first one with entry into service (EIS) in 2035 and a second one with EIS in 2050. Both vehicles feature a hybrid-electric propulsive system as key enabling technology capable achieving a significant reduction in fuel consumption with respect aircraft, in the same category, operating in 2020.

1.1 Paper Outline

Section 2. provides an overview on the design methodology and the main technological assumptions, specifically, subsection 2.1 provides a description on how requirements for the preliminary design process, Top-Level Aircraft Requirements (TLAR), have been derived from a short analysis of existing vehicles and from identified inter-modal mobility scenarios in the context of the COLOSSUS project.

Subsection 2.2 discusses the main features of those technologies that enable aforementioned environmental objectives, together with the choice of their configurations, while subsection 2.3 provides a description of the multidisciplinary design and analysis (MDA) framework implemented to perform sizing and design activities on vehicles of interests. Sections 3. and 4. provide an overview of the most important achieved results, finally, in Section 5. conclusions are provided.

2. Methodology and Assumptions

2.1 Analysis of Top-Level Aircraft Requirements

The preliminary design of a new aircraft starts with the identification of a feasible set of TLARs, such investigation is generally conducted from the analysis of the vehicle's operating scenarios, market analysis and performance evaluation of aircraft in the same category that represent competitors of the new product.

The seaplane market showed a strong reduction of production and sales of such vehicles, especially due to their drawbacks with respect equivalent land-based aircraft, the higher weight and aerodynamic drag induced by the geometry of the hull caused them to have poor performance and high fuel consumption, operations on water were also limited by safety considerations, causing them to be unavailable even in moderate sea state conditions [3]. However in the last years the improvement of manufacturing processes, development of new design solutions and the increasing demand of fast and reliable connections near coastal areas and islands enable a constant growth of feasibility studies of such vehicle type. In addition, the possibility to use a seaplane designed aircraft as a multi-role platform (such as firefighting, search and rescue) has increased the attention towards such aircraft category.

Derivation of TLARs has been performed extracting from identified inter-modal mobility scenarios three different operating environments and from those the most demanding typical mission has been sized in terms of required in-flight and on-ground performances.

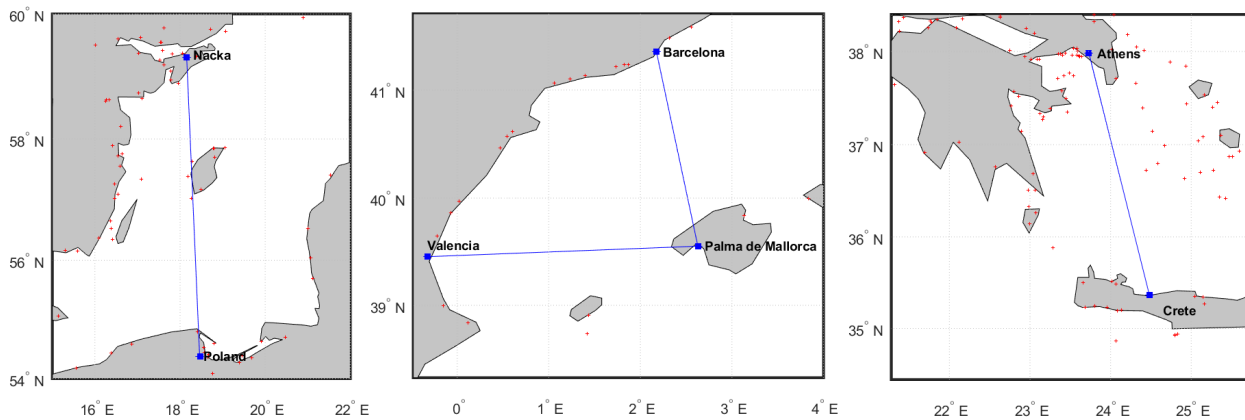


Figure 1 – Typical mission routes

Figure 1 illustrates three different routes, in the first application case, the seaplane could serve as mean to connect the city of Nacka to the city of Gdansk in Poland on the Baltic Sea, the second route Palma de Mallorca island to the main Spanish's ports on the Mediterranean Sea, while in the last use case from and towards the main islands of Greece. Table 1 summarizes proposed operating scenarios together with the description of typical ranges the seaplane should cover for each of them.

Route	Typical Range	Unit
Nacka - Gdansk	300.0	nmi
Barcelona - Palma de Mallorca	108.0	nmi
Valencia - Palma de Mallorca	140.0	nmi
Athens - Crete	162.0	nmi

Table 1 – Seaplane operating routes

According to Table 1, the most demanding mission is the one connecting regions in the Baltic Sea, a proper vehicle sizing on that route would enable a two stage journey, without refueling, on the other proposed alternatives. Travel time required to perform the mission should satisfy requirements coming from stakeholders that want fast point-to-point connections and goals of the European commission that aims at reducing door-to-door connection times down to four hours [4]. Payload requirements are selected according to limitations prescribed by regulation authorities and considering the effectiveness towards a given objective. For passenger transport aircraft regulated under the CS-23 the payload is driven by the rules and so by the maximum take-off mass (MTOM), that according to the CS-23 shall not exceed 19000 lb. Table 2 illustrates a summary of TLARs selected for the block mission, while Table 3 provides TLARs for the sizing of the fuel reserve.

Parameter	Value	Unit
MTOM	≤ 19000.0	lbm
Number of passengers	15	-
Design Cruise Range	≥ 500.0	nmi
Typical Cruise Range	300.0	nmi
Cruise Altitude	10000.0	ft
Cruise Mach Number	0.30	-
Take-Off Distance	≤ 3280.0	ft
Landing Distance	≤ 3280.0	ft

Table 2 – Block Mission TLARs

Parameter	Value	Unit
Alternate Range	100.0	nmi
Alternate Mach Number	0.22	-
Holding Time	30.0	min
Holding Mach Number	0.22	-

Table 3 – Reserve Mission TLARs

2.2 Technological Assumptions and Airframe Layout

The increasing sensitivity towards greener aviation operations, requiring lower fuel consumption and pollutant emissions, cannot avoid the integration of disruptive technologies, including the use of alternative energy sources. The design of new concepts that employ hybrid-electric propulsion architectures represents the most promising solution to the problem and it has been widely investigated in literature, Abu Salem et al. [5] performed a review on state-of-the-art of hybrid-electric configurations and technologies, illustrating how one of the major drawback of such configurations is represented by the technology readiness level (TRL) of the new components that form the powertrain in its entirety, Palaia et al. [6] performed a parametric analysis of the TRL of such configurations, specifically the battery energy density, showing how such factor affects the overall aircraft mass, the achievable mission range and the amount of power that can be drained from the electric storage. In the present work two different scenarios are investigated, a short-term horizon with an EIS year in 2035 and a long-term scenario with an EIS year in 2050.

Studies on disruptive powertrain architectures show that exist a large number of possible configurations [7, 31], that can be classified in three main groups, namely: turbo-electric, hybrid-electric and all-electric. Each category, or class, is characterized by specific intervals of so-called hybridization factors, in this context defined "supplied power ratio", representing the ratio between the power supplied by the batteries and the total power delivered by the powerplant in its entirety [7–9]. Equation (1) provides the mathematical definition of such supplied power ratios.

$$\Phi = \frac{P_{BAT}}{P_{BAT} + P_{FUEL}} \quad (1)$$

Higher the value of such ratio and higher will be the power delivered by the propulsive battery system, allowing this way a down-scaling of the thermal engine. Clearly as Φ increases also the mass of batteries increases leading to a higher necessary power to match defined TLARs and so to a greater aircraft's empty mass and maximum take-off mass.

Architecture	Φ
Turbo-Electric	0
Hybrid-Electric	< 1
All-Electric	1

Table 4 – Classes of hybrid and electric powertrain architectures

Table 4 summarizes hybridization factors for the three main class of possible configurations. For both horizons the hybrid architecture is chosen and sees a battery system and a conventional piston engine coupled in parallel in a so-called "parallel hybrid-electric" configuration. The total power delivered at the shaft of the propeller accounts for both contributions, this kind of hybrid-electric powertrain could allow, depending on the ratio of power supplied by the batteries, a downsizing of the thermal engine, leading to a lower take-off mass and fuel consumption. Figure 2 illustrates a simplified logic schema of selected powertrain architecture.

Batteries have been identified as one of those components enabling a fast decarbonisation of the aviation market, however their complete integration must face several challenges regarding safety aspects and performance [11]. The current state of the art of batteries is characterized by Lithium-Ion (Li-ion) batteries, for this reason they can be used as reference technology for the 2035 scenario, including proper projections of specific energy density and specific power density.

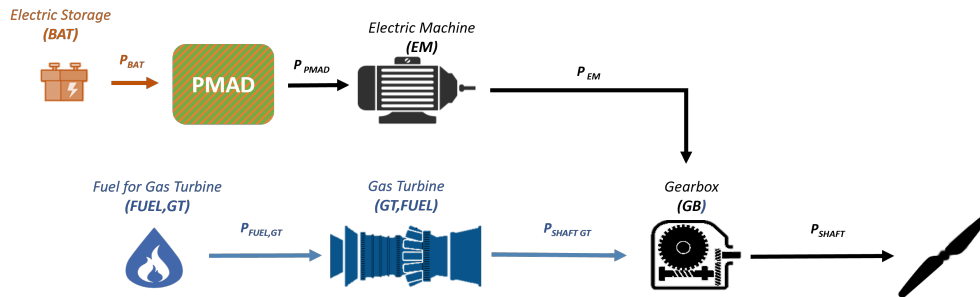


Figure 2 – Parallel Hybrid-Electric Architecture

Concerning the long-term scenario solid-state batteries (SSB) are being developed and they represent an interesting alternative to Li-ion batteries, also considering that their working principle is very similar. Table 5 illustrate the main technological assumptions and projections for propulsive batteries, for both time horizons. Analysis of such parameters refers to the battery pack level and has been performed considering projections from the automotive sector [12]. Figure 3 illustrate characteristic curves of battery cells chosen for both time horizons. Such curves, representing the battery cell's voltage as function of the cell's state of charge (SOC), will be used to size propulsive batteries. Cells' voltage curves have been computed thanks to the open source python library PyBaMM [13–22].

Parameter	2035	2050
Battery Technology	Li-ion	SSB
Specific Energy Density [Wh/kg]	280.0	585.0
Specific Power Density [W/kg]	560.0	2340.0

Table 5 – Technological levels of batteries assumed for EIS 2035 and EIS 2050

The selection of the thermal unit shall consider that most small operating seaplanes, as well as commuter aircraft in the CS-23 category with a maximum number of passenger between 15 and

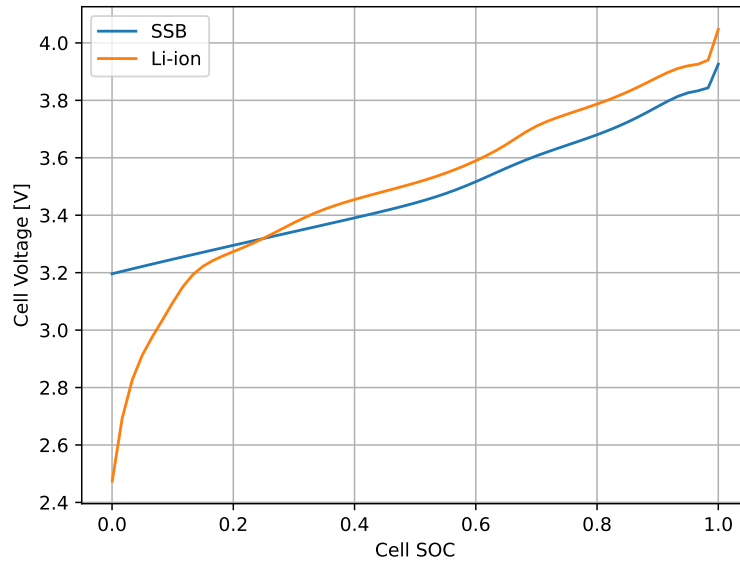


Figure 3 – Battery Cell Characteristic Curve

19, operate with turbo-propeller engines using Jet-A1 aviation fuel, however the call for an improved environmental and economical efficiency allows for the integration of novel diesel piston engines, enabling lower specific fuel consumption (SFC), certification for single pilot operations and a relatively simple aircraft. For each time horizons a different technological level has been assumed for the piston engine, in the 2035 scenario a conventional low-SFC turbocharged diesel engine is selected, while in the 2050 scenario a 20% blend of biofuels, specifically biodiesel, and pure diesel has been considered to account for the reduction in carbon monoxide (CO) and nitrogen oxides (NO_x) emission indices (EI), Table 6 illustrates the main technological assumptions for selected diesel engine, as well as their projections to the 2050 scenario [23].

Parameter	2035	2050
Fuel	Diesel	Biodiesel
SFC [kg/kW hr]	0.213	0.192
CO EI [g/kg]	11.9	4.76
NO _x EI [g/kg]	18.0	15.3

Table 6 – Technological levels of diesel engine assumed for EIS 2035 and EIS 2050

When dealing with a seaplane, the choice of the architectural layout of the vehicle shall account for additional constraints with respect their land-based counterparts, specifically for (1) manufacturing and corrosion induced by water operations, (2) maximum sea state operability and (3) weight and drag penalties. There are three kinds of seaplanes: floatplanes, flying boats, and amphibians [24]. A floatplane is a landplane that has had its landing gear replaced with pontoons that are partially submerged floats. A flying boat is a seaplane with a fuselage designed to function as a hull. An amphibian is an aircraft that features a hull-shaped fuselage for operations on water surfaces and retractable landing gear to also permit take-off and landing on land.

Float based aircraft enables manufacture to take advantage of the economy of scale by just a minor modification to the vehicle architecture. On the other hand, such vehicles provide limited on-ground and in-flight performance due to the increased weight, from floats and struts necessary to increase the stiffness of the structure, and drag. Take-off and landings are also limited to low sea state conditions. Amphibian architectures does not provide a strong weight saving but flight performance increase, also offering the possibility to operate at higher sea state levels. A seaplane has to avoid corrosion problems, one key aspect when designing a seaplane is to properly account for scheduled and non-scheduled maintenance costs, a solution could be the application and installation of composite materials on those surfaces more likely to face this problem, however regulation authorities

often impose strict safety margins on structures integrating composite materials, reducing this way their advantages in weight saving. For this class of aerial platform becomes then crucial the integration of novel technologies in the prediction and scheduling of maintenance to make the vehicle economically attractive, such as the emerging structural health monitoring technique, promising up to 5% reduction in direct operating costs (DOC) while preserving the same flying qualities and performance [25,26]. A different possibility that reduces the impact of saline water on airframe components is the adoption of a high wing and a T-Tail configuration, moving away lifting surfaces from water helps reducing degradation of aerodynamic characteristics induced by the water spray during take-off and landing on water.

2.3 Multidisciplinary Design and Analysis Process

Analysis have been performed leveraging multidisciplinary design and analysis (MDA) techniques, Figure 4 illustrates the eXtended Design Structure Matrix (XDSM) of the entire design workflow. Collaborative engineering and MDA processes require, by definition, the interaction between several disciplines, by consequence a heterogeneous team of specialist is needed in order to provide the necessary cooperation during aircraft design process. To properly enable collaborative analysis, competences integrated into the design framework must be able to feed-forward and feed-back state variables, output variables, parameters and constraints to others. Since each discipline requires its own set of design variables and constraints, then a multidisciplinary analysis framework may suffer from a poor data management between involved disciplines. To solve this problem is necessary the adoption of a well-structured data format for the sharing of information. Such data format should be able to capture not only the aircraft geometry but should also enable a simple parameterization of its components and should allow a simple and complete managing of data, or results, from each discipline involved in the design process, without ambiguity or redundancy. For these reasons, design activities on both seaplane concepts will be carried out leveraging the Common Parametric Aircraft Configuration Schema (CPACS), a data structure developed by the German Aerospace Center (DLR) [27].

According to Figure 4, the first step requires an initial sizing of the vehicle, satisfying the initial collection of Top-Level Aircraft Requirements (TLARs). Once the initial configuration is chosen, a Multi-disciplinary Feasible (MDF) formulation and a Gauss-Seidel algorithm ensure that each discipline is executed in turn and the convergence of the MDA framework [28]. The choice of such formulation, coupled with the low-fidelity nature of involved disciplines, enables a quick investigation of the design space and the identification of those most promising configurations.

In order to evaluate goodness and effectiveness of MDA outcomes proper performance metrics should be considered. Literature review on design of hybrid-electric vehicles shows a large number of key-performance indicators (KPIs), Brelje et al. [29] and Abu Salem et al. [30] propose a summary of the most used for both conventional and hybrid-electric configurations, including both flight performance indicators and economical performance indicators. For this work authors focused the attention on some specific flight performance indicators, KPIs, including:

- Block fuel for the design mission and the typical mission;
- Total energy consumption, considering both fuel and energy drained from batteries;
- Pollutant emissions, such as carbon oxides and nitrogen oxides;
- Maximum take-off mass of the vehicles.

The always increasing necessity in integrating high-fidelity methodologies also in the conceptual and preliminary stages of the aircraft design process represents a challenge due to typical computational times of such methodologies, like Computational Fluid Dynamic analysis on both conventional and unconventional vehicle and systems' architectures [31] and Finite Element analysis, and to the possible incompatibility between the large number of design variables required by high-fidelity tools and the smaller collection of design variables required for low-fidelity analysis, which are typical of the conceptual design level. State-of-the-art in multidisciplinary design analysis proposes two solutions to the

problem, (1) the use of surrogate models of costly disciplines, enabling this way the formal definition of surrogate-based optimization (SBO) problems and their implementation in a suitable multidisciplinary design and optimization (MDO) framework to maximize the effectiveness of the integration of disruptive powertrain architectures by optimizing those listed KPIs with respect design variables defined in the proposed MDA workflow; for instance Corcione et al. [32] performed surrogate-based aero-structural optimization on an innovative horizontal tailplane configuration of a jet vehicle to show its impact on the environmental footprint of the aircraft, and (2) the integration of machine learning and deep reinforcement learning techniques to properly catch non-linearities in the behaviour and performance of each discipline or system of interest [33].

For the scope of the present work only low-fidelity and medium-fidelity methodologies have been considered in the workflow. Design disciplines mostly affected by the architecture of the vehicle under investigation include aerodynamics, with the determination of the drag polar curve that must take into account additional contribution that may come from the presence of stabilizing wing tip floats or a hull-shaped fuselage; weight and balance, that shall into consideration weight penalties coming from hull-shaped fuselage or main floats that have to support the vehicle during operation on water and the effects on the balance of non-conventional components of the powertrain, such as batteries and electric machines. Other design competences affected by the vehicle's architecture are those connected to the sizing of the hybrid-powertrain, constrained to the already discussed parallel hybrid-electric, enabling power generators (i.e. thermal engines and electric machines) to be allocated in conventional wing-mounted nacelles, leading this way to smaller or negligible coupling effects with the aerodynamics [34], that could not be evaluated by proposed low-fidelity methodologies, and performance analysis, that have to implement dedicated methodologies for the analysis of take-off performance from water, specifically, among preliminary low-fidelity methodologies, a modified version of the method proposed by Savitsky [35] will be implemented to perform such take-off analysis.

3. Hybrid-Electric Concept 2035

Preliminary sizing activities have been performed considering payload and design mission requirements, statistical trends and semi-empirical models have been implemented to provide an initial layout of the 2035 concept. The application of a Multidisciplinary Design and Analysis (MDA) framework enabled a detailed analysis of the vehicle, sizing its powertrain and airframe components through a simulation-based analysis of the design mission. Figure 5 provides a simple illustration of the airframe layout of the 2035 concept, together with the position of nacelles that allocate both the thermal engines and electric machines.

Table 7 shows the breakdown of the main masses that affect the take-off weight of the vehicle on the design mission, according to the proposed MDA approach, masses are computed at each iteration to account for the snowball effect, variations on the required power and energy at mission level causes a scaling of the powertrain system, and consequently of the structure that allocates such components. The power distribution between the thermal engine and the batteries in a hybrid-electric powertrain, without distributed propulsion, is managed by a design parameter that is the supplied power ratio, which is a measure of the hybridization level and is defined accordingly to (1). As discussed in [36] a proper management of the power split should be carefully evaluated to avoid an unfavourable mass distribution that may lead to higher fuel consumption and to exceed limits imposed by regulation authorities.

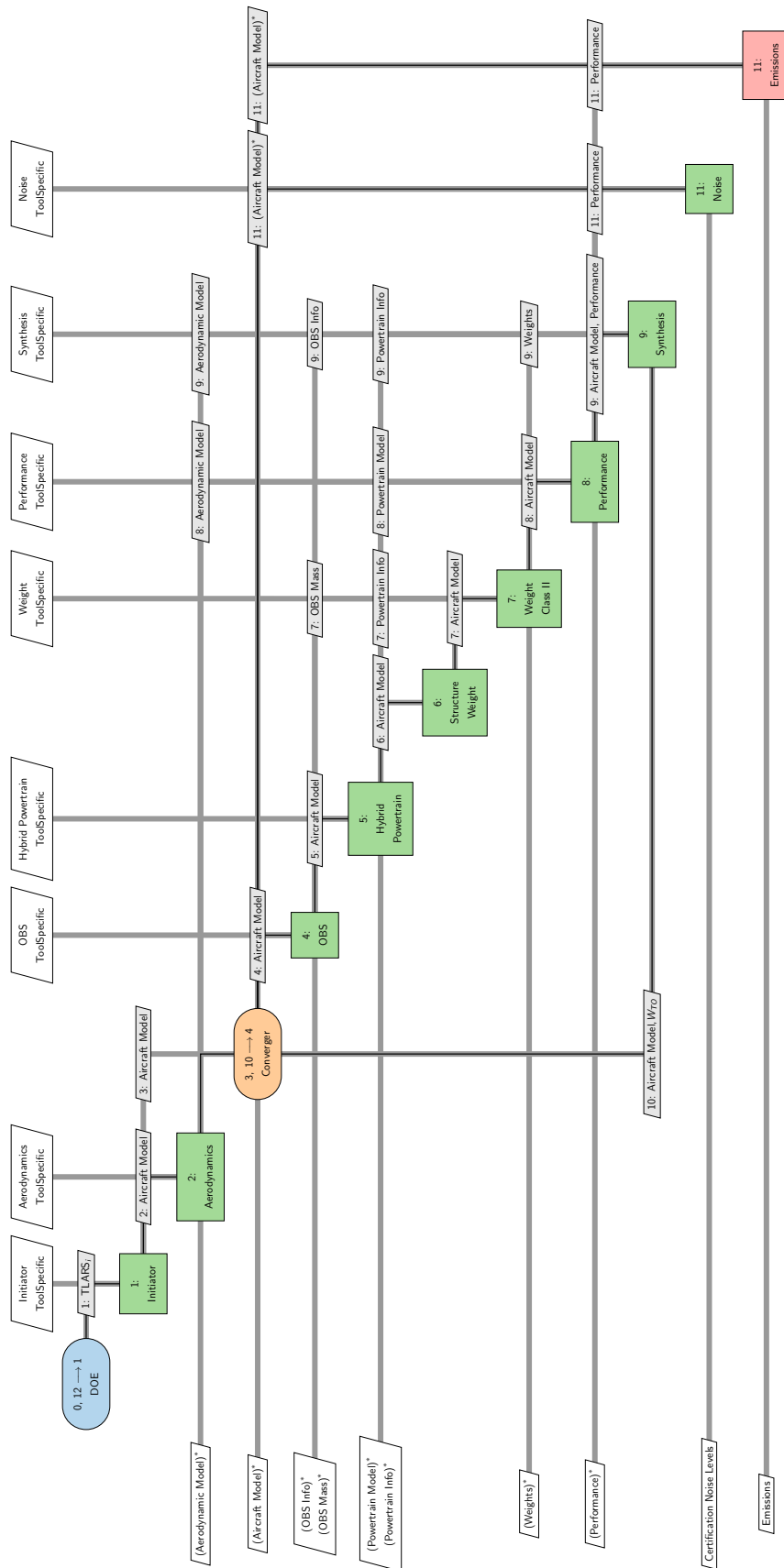


Figure 4 – XDSM - design and analysis workflow



Figure 5 – Seaplane concept 2035

	Value [kg]
Airframe	1948.04
Powertrain (incl. batteries)	1434.40
Systems	494.98
Payload	1425.0
Total Fuel	511.25
Operating Empty Mass	4998.69
Maximum Take-Off Mass	7024.46

Table 7 – Mass Breakdown Concept 2035

To properly select the hybridization level that lead to a significant reduction of fuel consumption and pollutant emissions, a DOE has been performed on such hybridization factors. Figure 6 shows the effect of changing hybridization strategy on the block mission's fuel consumption. To maximize fuel efficiency we chose as ideal hybridization level the one that minimize fuel consumption, still satisfying maximum take-off mass constraints imposed by CS-23.

In Figure 6 the hybridization level, " H " refers to the block mission only and is defined according to (2). A sweep between 0.0% and 10.0% has been performed, larger values have been excluded to avoid maximum take-off masses to exceed the limit imposed by current regulations.

A null value in the hybridization level means there is no contribution of batteries to the thrust generation process, increasing its value there will be an increasing contribution from batteries and a decreasing contribution from the thermal engine. It is possible to notice that a general increase in the hybridization level of the powertrain system is not always favorable in fuel saving; according to (2) there are different strategies in choosing hybridization factors to reach a desired global percentage of powertrain hybridization, affecting in different ways the sizing process of the powertrain itself.

$$H = \frac{\Phi_{TO} + \Phi_{CR} + \Phi_{CL} + \Phi_{DS}}{4} \quad (2)$$

Figure 6 shows that a global hybridization level of 0.073 (7.3%) allows to get the minimum fuel consumption, specifically, Table 8 illustrates the selected strategy for supplied power ratios in each flight phase for both the design mission and typical mission, that allow the proposed concept to satisfy the limit imposed by CS-23 regulatory rules. It is worth mentioning that supplied power ratios that minimize fuel reach their maximum value in the take-off and climb phases, while a value close to the minimum is registered for the cruise phase. In a parallel hybrid-electric architecture the power available at the propeller's shaft considers the contribution of all installed generators, a larger use of

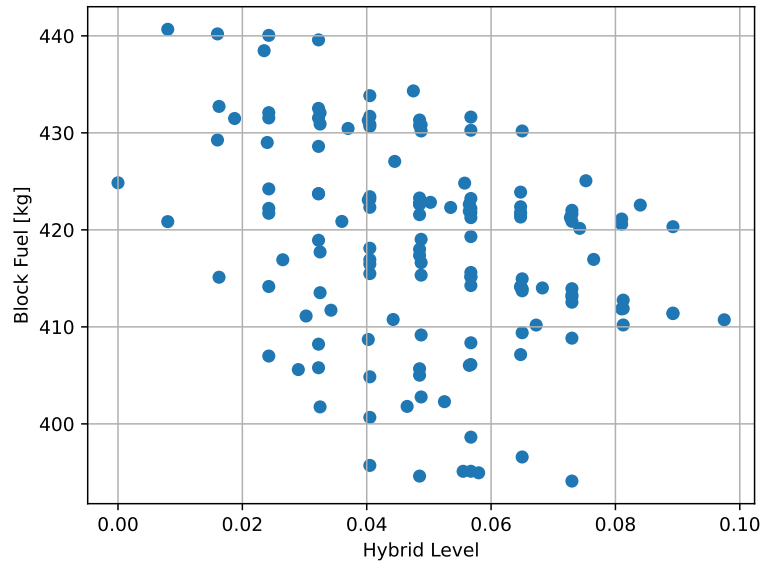


Figure 6 – Effects of Hybridization Level on Block Fuel - Scenario 2035

batteries, for a given required power, makes possible a downsizing of the thermal engines, leading, for a reciprocating engine, to lower fuel flows. The rated power of the battery becomes this way its sizing feature.

Figure 7 illustrates the effects of increasing the hybridization factors in the cruise phase, the larger such value and bigger will be the necessary energy to be stored in the batteries, in this case the battery capacity becomes the sizing feature of the battery. In a straight levelled flight the necessary thrust (equal to the aerodynamic drag) is proportional to the vehicle mass, a much heavier battery lead to a strong increase in the aircraft mass, requiring also a more powerful thermal engine to deliver the necessary thrust, keeping the cruise hybridization factor at very low levels prevents from weight and block fuel diverging induced by the snowball effect.

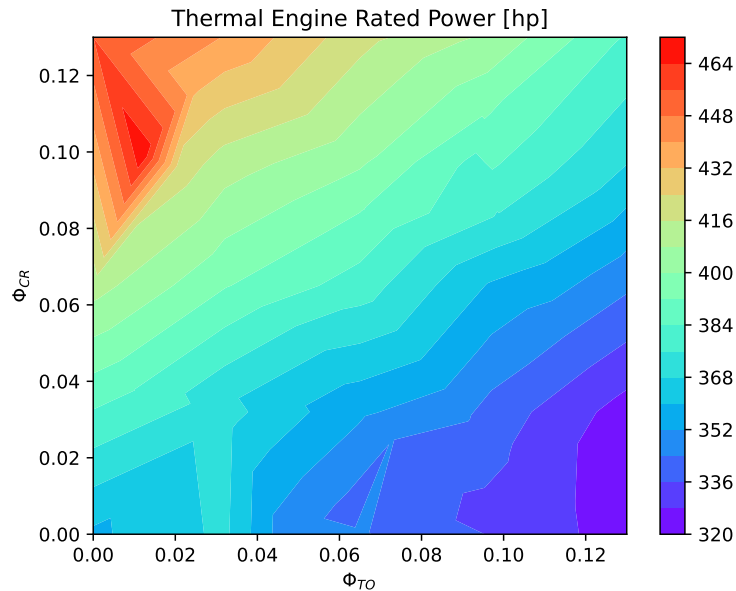


Figure 7 – Effects of hybridization factors on the thermal engine rated power

Table 9 provides a comparison of the fuel and energy consumption between the 2035 hybrid-electric concept and its conventional (powered only by thermal engines) version. The technological levels of selected Li-ion batteries shows how such concept can only achieve a 7.30% reduction in fuel consumption on the design mission and a 8.17% reduction on the typical mission.

	Value	Min.	Max.
Φ - Take-Off	0.13	0.0	0.13
Φ - Climb	0.13	0.0	0.13
Φ - Cruise	0.032	0.0	0.13
Φ - Descent	0.0	0.0	0.13
Φ - Landing	0.0	0.0	0.13

Table 8 – Supplied Power Ratio Distribution and boundaries - Scenario 2035

	Design Mission	Typical Mission
CONVENTIONAL		
Block Fuel [kg]	425.13	265.61
Block Energy [kWh]	5101.56	3187.32
CONCEPT 2035		
Block Fuel [kg]	394.09	243.91
Block Energy [kWh]	4825.26	3023.10

Table 9 – Block Fuel and Block Energy analysis concept 2035

Table 10 shows the total fuel burnt (excluding the trapped fuel), the NOx and CO emissions, for both the conventional and the hybrid-electric concepts.

	Design Mission	Typical Mission
CONVENTIONAL		
Total Fuel [kg]	545.32	386.70
NOx [kg]	8.917	6.028
CO [kg]	5.903	3.986
CONCEPT 2035		
Total Fuel [kg]	511.29	360.03
NOx [kg]	8.417	5.681
CO [kg]	5.556	3.750

Table 10 – Total Fuel and emissions. Concept 2035

When dealing with the design of seaplanes another key performance indicator is the take-off distance from water, for the scope of the present work a low-fidelity approach will be applied, leveraging methodologies proposed by Gudmundsson [24], for the numerical determination of the take-off distance through the integration of the equations of motion, and by Savitsky [35], for the determination of the hydrodynamic characteristics, such as hull trim angle and drag of wetted hull surface as function of the speed coefficient.

Specifically, the approach proposed by Savitsky has been modified to account for aerodynamic forces and moments coming from the two main lifting surfaces of the seaplane, the wing and the horizontal tailplane respectively, the hull trim angle will be such that to satisfy the equilibrium along the vertical axis and about the pitch axis, including effects of the aerodynamic forces.

Figure 8 shows a comparison between two main hydrodynamic figures of merit for the 2035 concept, the trim angle, labelled τ , and the hydrodynamic drag coefficient, C_R defined according to (3). It is possible to notice how the modified Savitsky method leads to a smaller trim angle, at high speed coefficients C_V , than the original methodology, such difference is a function of the pitching moment contribution coming from the wing and horizontal tailplane, which is negative (pitching down), requiring this way a smaller trim angle at equilibrium. Being, according to the Savitsky's method, the hydrodynamic drag a function of the hull's trim angle, then a reduction in the latter causes a reduction in the hydrodynamic drag.

$$C_R = \frac{R}{\rho_w B^3} \quad (3)$$

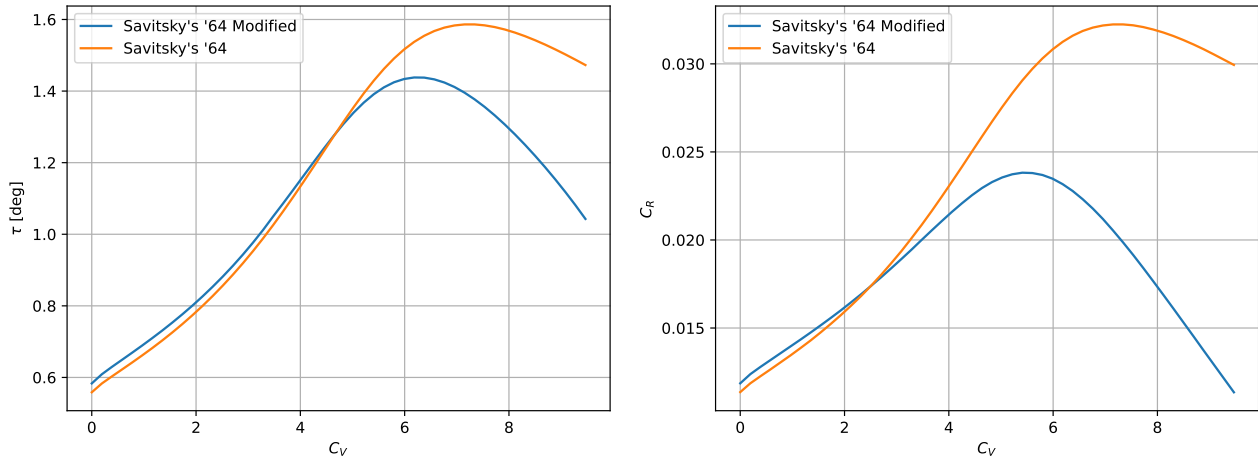


Figure 8 – Trim angle and water drag coefficient - 2035 concept

Finally, Table 11 compares take-off distances on land and on water for the 2035 hybrid-electric concept, the additional drag coming from hydrodynamic sources leads to a 10.35% increase in the take-off distance, still satisfying design requirements.

Take-Off Distance	Value	Unit
Land	586.46	m
Water	647.14	m

Table 11 – Take-off distance on land and on water - Concept 2035

4. Hybrid-Electric Concept 2050

The analysis performed on the 2050 concept sees the same geometrical configuration of the 2035 vehicle, used as hybrid-electric baseline to show how the technological improvement of the powertrain system allows for a reduction of block fuel, maximum take-off mass and emissions.

A DOE has been performed also for the 2050 concept, supplied power ratios have been chosen implementing the same approach of the 2035 concept, maximizing this way the effects of integrating SSB. As shown in Figure 9 also for the 2050 scenario an increase in the global hybridization level does not guarantee a reduction in fuel consumption, for the 2050 concept a minimum in fuel consumption is obtained for a global hybridization factor equal to 0.065, that is 6.5%.

As shown in Table 12 the optimal supplied power ratio for the 2050 hybrid-electric concept are quite similar to those chosen for the 2035 concept. The main difference is just about the supplied power ratio for the cruise phase, in this case shifted to zero, that is that no power or energy from the battery are used for the cruise phase. In the 2050 scenario the battery characteristic's curve causes the block fuel and the vehicle maximum take-off mass to be linear with the cruise hybridization factor, as shown in Figure 10, therefore the lower will be such factor and lower will be the fuel consumption.

Table 13 shows the mass breakdown for the 2050 seaplane concept, being the payload, the mission, the overall aircraft layout arrangement unchanged and assuming frozen the technological level of on-board systems, their overall mass is equal for both time horizons. A reduction in the aircraft empty weight and maximum take off mass is due to the technological improvement of the powertrain, that allows a 9.84% reduction in total fuel consumption (including the reserve fuel mass), with respect the 2035 concept, enabled by the downsizing of the powertrain.

The simulation of the design mission allows the determination of the fuel consumption of the block mission segment, as well as the block energetic consumption in the same block, Table 14 shows, for the design mission, a 13.65% reduction in the block fuel and a 14.98% reduction in the block

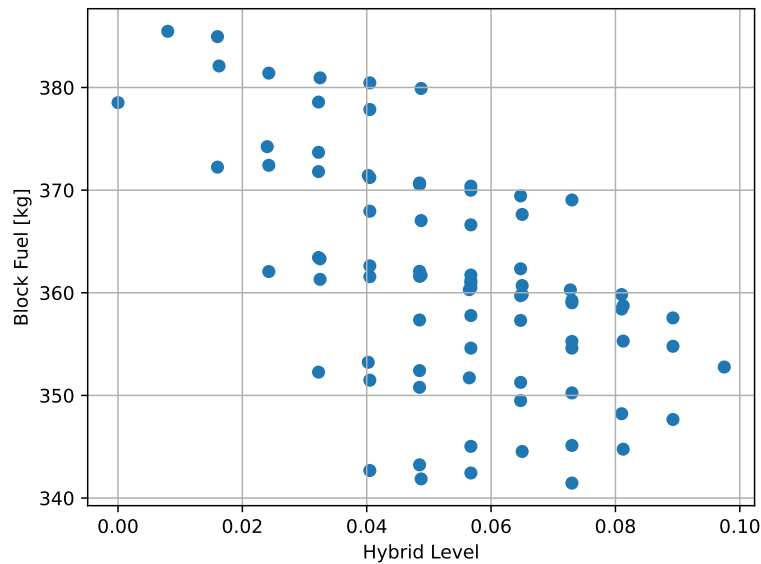


Figure 9 – Effects of Hybridization Level on Block Fuel - Scenario 2050

	Value	Min.	Max.
Φ - Take-Off	0.13	0.0	0.13
Φ - Climb	0.13	0.0	0.13
Φ - Cruise	0.0	0.0	0.13
Φ - Descent	0.0	0.0	0.13
Φ - Landing	0.0	0.0	0.13

Table 12 – Supplied Power Ratio Distribution and boundaries - Scenario 2050

energy consumption with respect the 2035 concept, while for the typical mission there is a 13.15% reduction in the block fuel and a 15.29% reduction in the block energy. Table 14 illustrates also the block fuel and energy consumption for a conventional aircraft, powered only by thermal engines, with the same EIS of the 2050 concept, so characterized by the same technological level. It shows how the hybrid-electric concept provides a 10.13% reduction in fuel consumption, for the design mission, with respect its thermal counterpart; a similar reduction, of about 10.50% is reached for the typical mission.

	Value [kg]
Airframe	1684.04
Powertrain (incl. batteries)	1119.22
Systems	494.98
Payload	1425.0
Total Fuel	460.95
Operating Empty Mass	4597.58
Maximum Take-Off Mass	6548.87

Table 13 – Mass Breakdown Concept 2050

Table 15 shows pollutant emissions and total fuel burnt (including reserve) for the 2050 hybrid-electric concept and its conventional version. It is immediate to notice how the use of biofuels enabled, even for the conventional version, a 23.05% reduction in NO_x emissions on the design mission and a 64.0% reduction in CO emissions. When comparing the 2050 hybrid-electric concept with the 2035 concept we get a 25.91% reduction in NO_x emissions and a 65.26% reduction in CO emissions. Also for the 2050 concept a preliminary investigation of water take-off distance has been performed leveraging the modified Savitsky method. Figure 11 illustrates a comparison for both trim angle and

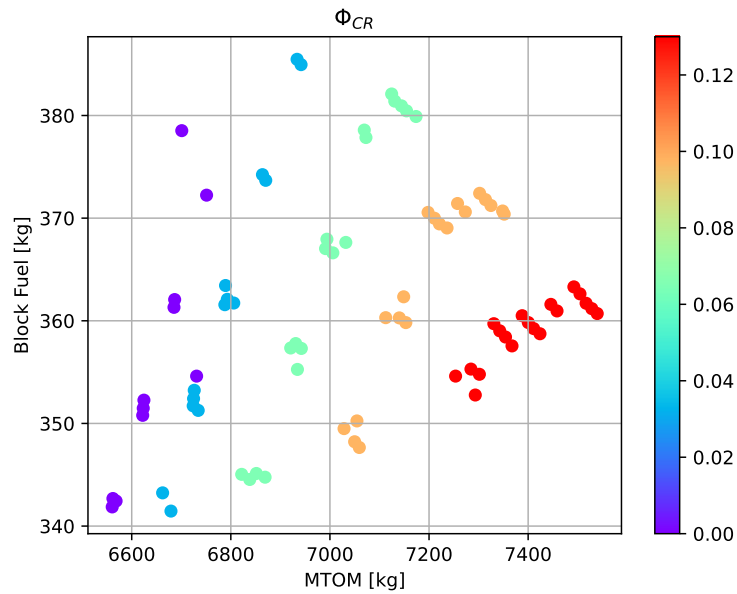


Figure 10 – Effects of cruise hybridization factor on block fuel and MTOM - Scenario 2050

	Design Mission	Typical Mission
CONVENTIONAL		
Block Fuel [kg]	378.66	236.66
Block Energy [kWh]	4543.92	2839.92
CONCEPT 2050		
Block Fuel [kg]	340.28	211.82
Block Energy [kWh]	4102.30	2560.78

Table 14 – Block Fuel and Block Energy analysis concept 2050

water resistance coefficient achieved with the classical approach developed by Savitsky and those obtained through the modified methodology. As it is possible to notice, the modified approach lead to a lower trim angles, especially at high speed coefficients where aerodynamic forces contribute with a stronger pitching down moment, leading this way to a lower hydrodynamic resistance coefficient.

Table 16 shows take-off distances on land and on water for the 2050 concept. Both distances have been calculated integrating the equations of motion, including additional sources of drag for the water distance, as proposed by Gudmundsoon. Results show a 9.54% increase in the distance when taking-off from water induced by the additional drag sources in both the displacement and planing regimes.

As already discussed a major drawback of seaplanes is represented by often poor take-off perfor-

	Design Mission	Typical Mission
CONVENTIONAL		
Total Fuel [kg]	505.60	356.42
NOx [kg]	6.861	4.667
CO [kg]	2.125	1.444
CONCEPT 2050		
Total Fuel [kg]	460.87	325.98
NOx [kg]	6.236	4.250
CO [kg]	1.930	1.319

Table 15 – Total Fuel and emissions. Concept 2050

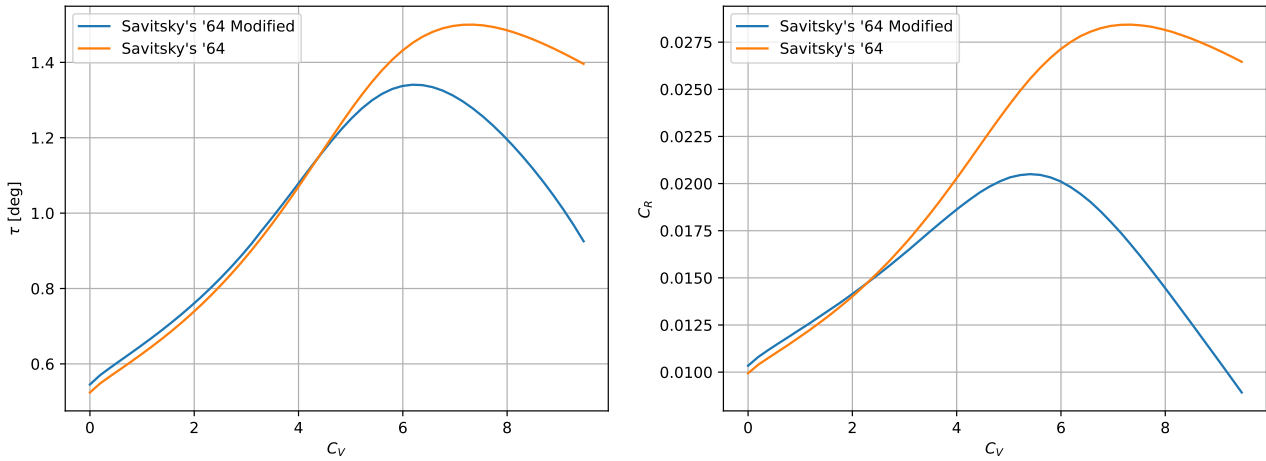


Figure 11 – Trim angle and water drag coefficient - 2050 concept

Take-Off Distance	Value	Unit
Land	537.20	m
Water	588.48	m

Table 16 – Take-off distance on land and on water - Concept 2050

mance from water, due to the nature of involved hydrodynamic and aerodynamic forces, future developments of such vehicle architectures may implement the optimization of the aerodynamic properties of the aircraft to overcome disadvantages induced by hydrodynamic forces, for example by integrating novel configuration of high-lift devices [31] or through a deep investigation of how ground effects may change the aerodynamic behaviour [37] in all segments of the take-off run.

5. Conclusions

This paper has presented new scenarios suitable for the development of the next generation of seaplanes, how MDA processes can be implemented to perform design and analysis of hybrid-electric vehicles and how the integration of new sources of energy can be used to achieve, at operational level, significant reductions in fuel consumption and pollutant emissions. However, it should be noted that such improvements in the vehicle's environmental performance have been achieved not only integrating disruptive powertrain solutions, but also improving between investigated time scenarios, their efficiency and performance levels, meaning that sustainability of flight operations should also carefully evaluate the technology readiness and performance levels of new promising systems.

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