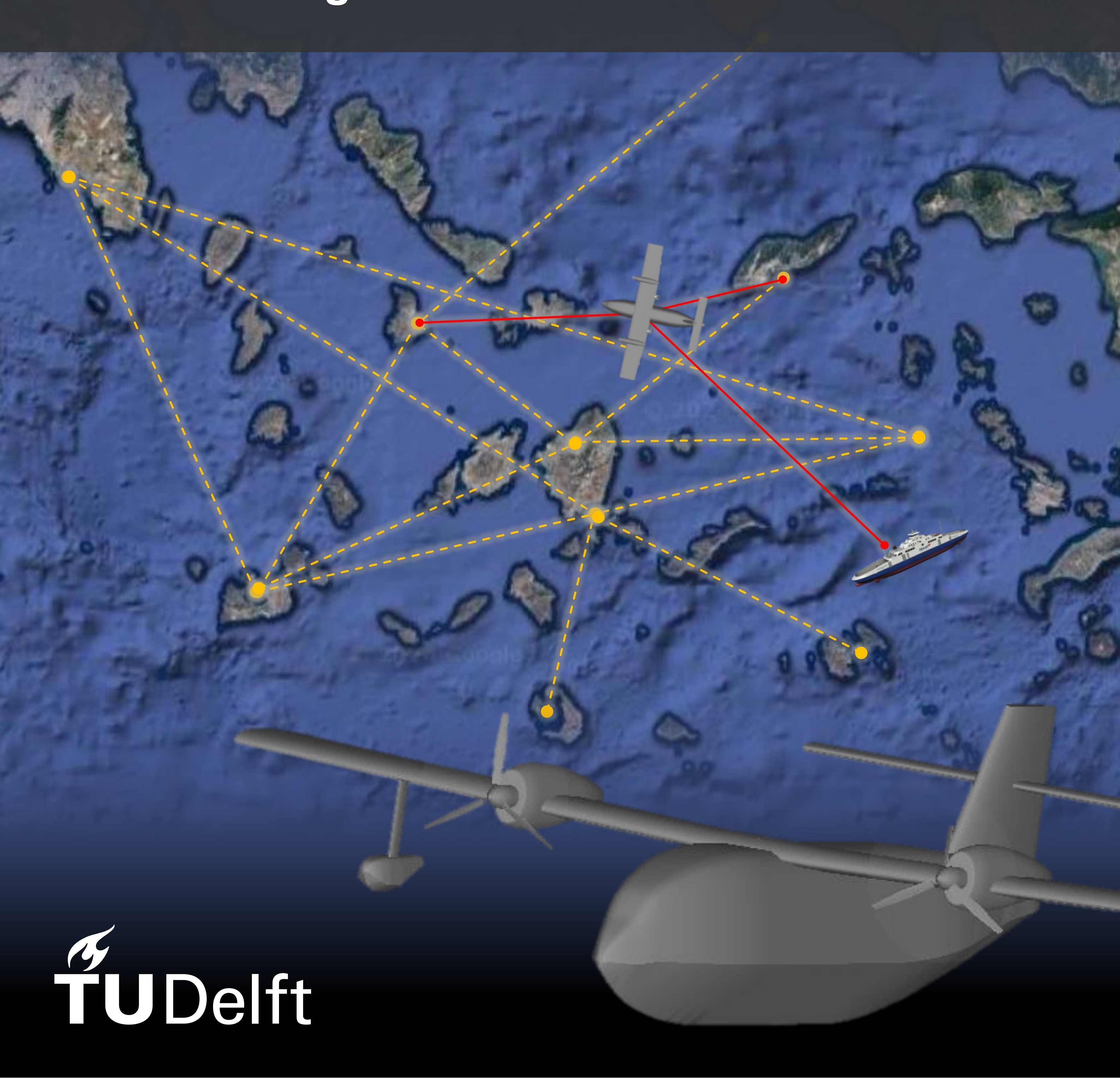
A System of Systems Aircraft Design Framework

Demonstration Using a Seaplane Transport Network in the Greek Islands

Vincenzo Nugnes



TU Delft

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by

Vincenzo Nugnes

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Vincenzo Nugnes
Delft, July 2022

Contents

1 Introduction

This Master's Thesis was conducted at German Aerospace Center (DLR), and it is presented in the form of a scientific paper which was submitted for publication at the Congress of the International Council of the Aeronautical Sciences ICAS to take place the the 09/09/2024 in Florence, Italy. The research endeavors undertaken and their outcomes are integral components of the European project COLOSSUS [1], a collaborative initiative aimed at advancing the frontiers of aviation through innovative methodologies and interdisciplinary approaches. Within this context, this thesis embarks on a journey to explore aircraft design methodologies, focusing particularly on the development of a novel System of Systems (SoS) approach. With a specific emphasis on seaplanes, this study aims to reposition them as a cornerstone of future Advanced Air Mobility systems, evaluating their potential to address contemporary transportation challenges.

Contemporary research in aircraft design is driven by the imperative to reduce emissions, leading to the exploration and implementation of innovative, highly efficient concepts. The adoption of new methodologies enhances the precision and efficiency of analyses and calculations. Coupled with the integration of innovative powertrain technologies, these advancements have contributed to the development of more efficient designs, resulting in reduced fuel consumption and emissions. Despite these efforts, recent contributions often exhibit a notable absence of a holistic view of the transportation system within the design process. Compatibility with airline operations, scenarios, and infrastructures is often overlooked, and a notable gap remains in considering how these aircraft configurations behave in the existing transportation system, which depends on a multitude of interconnected component systems to deliver services [1], [2].

This paper proposes a Systems of System Engineering (SoSE) perspective on aircraft design with the aim of including requirements of the operational environment in the design process [3]. The conceptual aircraft design is tailored to specific scenarios of operation using Agent-based Modeling and Simulation (ABMS). A System of Systems (SoS) can be simply defined as any other system: it "consists of parts, relationships and a whole that is greater than the sum of the parts". However, within a SoS the "parts" are independent systems themselves, and a majority of the following characteristics is present: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development [4], [5].

ABMS is believed to be one of the most suited techniques to model a SoS. It is defined as "a computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment" [6]. It can reveal qualitative and quantitative properties of real systems and it serves as a computational laboratory for testing hypotheses. More particularly, ABMS holds the potential for capturing the interactions among various stakeholders in transportation, such as airlines, air traffic control, passengers, and policymakers [6]. It also allows to model and investigate uncertainties related to travel demands, resources availability, and/or operational procedures that might be present in the system [7]. One relevant example of using ABMS to model a transportation

[1] https://cordis.europa.eu/project/id/101097120

system is provided by Prakasha et al. [2], who showed the importance of considering other systems than the aircraft to determine its effectiveness in fleet operations.

In a similar way, this paper introduces an aircraft design optimization process that is driven by an overall scenario analysis. For this purpose, conventional design disciplines were coupled with ABMS, defining a unique aircraft design optimization problem. To validate this methodology, we propose a proof of concept design framework in which the design of a seaplane is driven by the performance of a fleet operating in an on-demand transportation system serving the Greek islands.

Seaplanes have been considered in the study due to the recent interest researchers have showed in this configuration. Seaplanes played an important role in the aviation industry during the first half of the past century. Due to their ability to take-off and land from/on water bodies, these aircraft were widely employed in military operations as well as passenger transportation. However, as numerous runways were built worldwide during and after World War II, the relevance of seaplanes waned [8]. In recent times, a renewed interest in these vehicles has emerged. Nevertheless, contemporary contributions fail to implement modern design approaches and lack a holistic view of the transport system in the design process, as seen for aircraft design [9]–[11]. We think that these vehicles have the potential to improve connections in maritime and coastal areas. In particular, it is believed that the Greek islands would benefit from an on-demand seaplanes transport system due to the poor and slow ferry connections available at present day. The fixed schedule on which the ferry operation is based causes the trips with stopovers to be extremely time consuming.

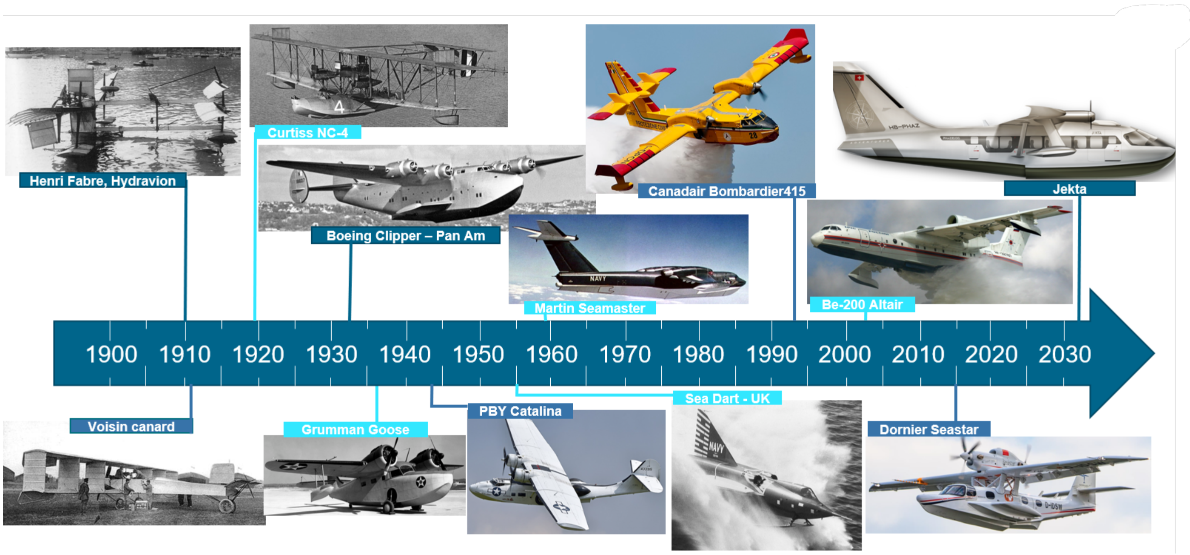

Figure 1.1: Caption

The proof of concept framework proposed in this paper has a dual purpose: on the one hand, it shows the impact of including ABMS in the aircraft design workflow, and on the other, it demonstrates the potential of seaplanes as an alternative mode of transportation. The first goal is achieved by investigating the sensitivity of seaplane design parameters with respect to scenario parameters such as fleet size, and incoming and outgoing travel demands at each seaport. The results of the framework are compared to conventionally designed seaplanes to establish the significance of the new approach. Secondly, in order to assess the effectiveness of seaplanes in enhancing the connections among Greek islands, several analyses are performed to estimate the average travel time, fuel efficiency, CO_2 emissions, and percentage of travellers choosing to fly on seaplanes in different conditions (scenarios). Finally, the design requirements for seaplanes to improve the transport productivity in the islands network are identified.

This report includes the scientific paper, main outcome of this research project, followed by the literature review performed during the defining stage of the project. In conclusion, additional material regarding the tools employed is provided to the reader.

2

Scientific paper

A SYSTEM OF SYSTEMS AIRCRAFT DESIGN FRAMEWORK: DEMONSTRATION USING A SEAPLANE TRANSPORT NETWORK IN THE GREEK ISLANDS

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Abstract

This paper presents a System of Systems Engineering approach to aircraft design. For this purpose, conventional design disciplines are coupled with Agent-Based Modeling and Simulation (ABMS) defining a unique optimization problem. The proposed methodology is applied to design seaplanes for an on-demand transportation system connecting the Greek islands. Within this network, diverse scenarios are analyzed by varying parameters of the model such as fleet size and travel demands at each seaport. The objective is to show the impact of including ABMS in the design workflow on the optimized seaplane design parameters. The optimum designs are evaluated on the basis of a number of classic performance metrics, to assess to what extent they can represent a competitive alternative to existent maritime means of transportation. The results reveal optimal fleet performance for seaplanes characterized by lower cruise speeds and passenger capacities, as compared to those derived from conventional methodologies and to existing designs.

Keywords: system of systems, conceptual aircraft design, agent-based modeling and simulation, seaplane

Nomenclature

D_{prop}	=	propeller diameter
m	=	mass
$\dot{m}$	=	mass flow
M_{CR}	=	cruise Mach number
n_{pax}	=	number of passengers
$\underline{P}$	=	array of motors rated powers
R_{des}	=	aircraft design range
$\underline{V}$	=	array of mission velocities
$\underline{\lambda}$	=	requests converted

Subscripts

0	=	initial value
CR	=	cruise
F	=	fuel
FF	=	fleet fuel
PT	=	powertrain
ref	=	reference value

Superscripts

$*$	=	optimal value

1 Introduction

Aircraft design is rapidly advancing through the adoption of new methodologies that enhance the precision and efficiency of analyses and calculations. The integration of innovative powertrain technologies allows researchers to develop more efficient designs, with reduced fuel consumption and emissions. Nevertheless, there remains a notable gap in considering how these aircraft configurations behave in the existing transportation system, which depends on a multitude of interconnected component systems to deliver services [1, 2]. This paper proposes a System of Systems Engineering (SoSE) perspective on aircraft design with the aim of including requirements of the operational environment in the design process [3]. The conceptual aircraft design is tailored to specific scenarios of operation using Agent-Based Modeling and Simulation (ABMS).

A System of Systems (SoS) can be simply defined as any other system: it “consists of parts, relationships and a whole that is greater than the sum of the parts” [4]. However, within a SoS the “parts” are independent systems themselves, and a majority of the following characteristics are present: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development [5].

ABMS is believed to be one of the most suited techniques to model a SoS, in particular for transportation [6]. It is defined as “a computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment” [7]. More particularly, ABMS holds the potential for capturing the interactions among various stakeholders in transportation, such as airlines, air traffic control, passengers, and policymakers [7]. It also allows for the modeling and investigation of uncertainties related to travel demands, resource availability, and/or operational procedures that might be present in the system [8]. One relevant example of using ABMS to model a transportation system is provided by Prakasha et al. [2], who showed the importance of considering other systems than the aircraft to determine the latter's effectiveness in fleet operations.

In a similar way, this paper introduces an aircraft design optimization process that is driven by an overall scenario analysis. For this purpose, conventional design disciplines are coupled with ABMS, defining a unique aircraft design optimization problem. To validate this methodology, we propose a proof of concept design framework in which the design of a seaplane is driven by the performance of a fleet operating in an on-demand transportation system serving the Greek islands.

Seaplanes have been considered in the study due to the recent interest researchers have shown in this configuration. Seaplanes played an important role in the aviation industry during the first half of the past century. Due to their ability to take-off and land on water bodies, these aircraft were widely employed in military operations as well as passenger transportation. However, as numerous runways were built worldwide during and after World War II, the relevance of seaplanes waned [9]. In recent times, a renewed interest in these vehicles has emerged. Nevertheless, contemporary contributions fail to implement modern design approaches and lack a holistic view of the transport system in the design process, as seen for aircraft design [10, 11, 12].

The proof of concept framework proposed in this paper has a dual purpose: on the one hand, it shows the impact of including ABMS in the aircraft design workflow, and on the other, it demonstrates the potential of seaplanes as an alternative mode of transportation. The first goal is achieved by investigating the sensitivity of the optimized seaplane design parameters with respect to scenario parameters such as fleet size and travel demands at each seaport. The results of the framework are compared to conventionally designed seaplanes to establish the significance of the new approach. Secondly, in order to assess the effectiveness of seaplanes in enhancing the connections among Greek islands, several analyses are performed to estimate the average travel time, fuel efficiency, CO_2 emissions, and percentage of travellers choosing to fly on seaplanes in different conditions (scenarios). Finally, the design requirements for seaplanes to improve the transport quality in the islands' network are identified.

The paper is structured as follows: in the next section, the SoS design framework is introduced. The proof of concept used to demonstrate it, and the tools composing it, are illustrated in the same section. There, some space is also dedicated to explaining the development needed to adapt these tools into the framework. In Section 3, the scenarios modelled in the ABMS, and the assumptions they are based upon, are specified. The results are shown in Section 4. Finally, the conclusion can be found in Section 5.

2 Methodology

Fig. 1 depicts a flowchart representation of the methodology and it shows how the composing blocks are connected together. At the start of an optimization, a set of predefined Top Level Aircraft Requirements (TLARs) is input in the aircraft design block of the framework. The main goal for this first part is to design the vehicle that will be simulated in the ABMS. The design can be performed at any level of fidelity as long as the input requirements for the ABMS are met. The aircraft design tool palette outputs the mission performance of the vehicle which can be used to evaluate the energy consumption and the travel time in the ABMS.

ABMS is then used to simulate the operation of a homogeneous fleet constituted by instances of the aircraft designed in the previous step. The environment of operation is a fixed scenario characterized by a certain demand distribution and a network of nodes to be connected by the above-mentioned fleet. The fidelity used to represent the scenario in the ABMS, and the assumptions adopted, play a pivotal role in the reliability of the design framework. The results of the simulation will then drive the choice of a new set of TLARs. The process is iterated until an optimum design, according to set criteria, is found.

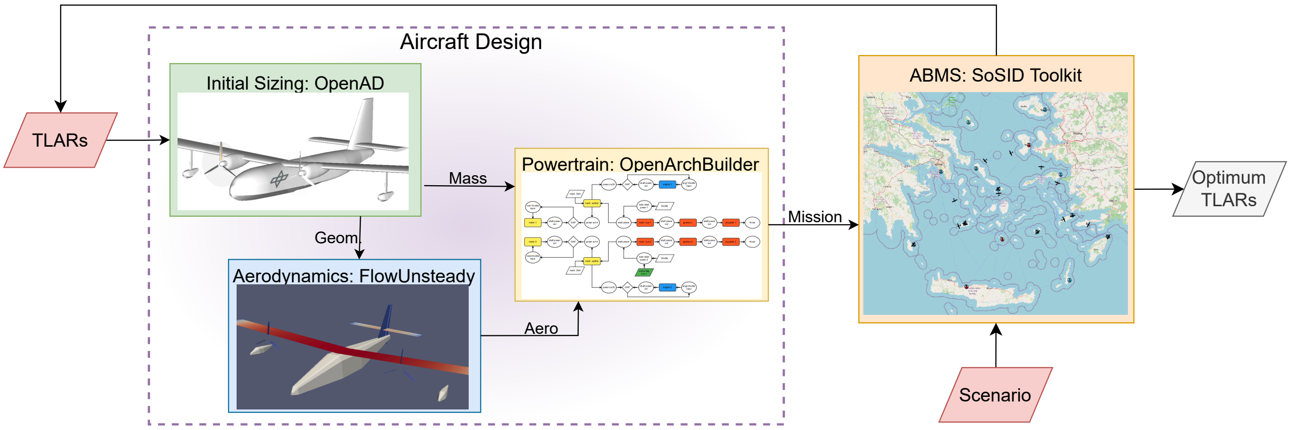


Figure 1 – System of Systems aircraft design framework flowchart

2.1 System of Systems seaplane design framework

The proof of concept encompasses a seaplane design framework where the aircraft is assessed within an on-demand transportation system connecting the Greek islands.

The seaplane design is kept at a conceptual stage to mitigate computational costs, and it is performed in three phases, as shown in the dashed box in Fig. 1. First, the entire vehicle is sized with the overall aircraft sizing tool OpenAD (OAD) [13]. The design is then refined with two additional tools: FlowUnsteady [14], to obtain a physics-based calculation of the drag polar of the vehicle, and OpenArchBuilder (OAB) [15], which retrofits a hybrid-electric powertrain on the initial design provided by OpenAD.

OpenAD is a software platform for conceptual aircraft design and sizing developed by DLR. It is based on publicly available textbook methods and DLR custom methods. It is used for seaplane geometry and mass sizing, and to provide an initial estimation of engine performance, aerodynamic polar, and mission analysis.

FlowUnsteady is an open-source solver based on the reformulated vortex particle method (rVPM). It is used to re-calculate the aerodynamic polar of the seaplane. The analyses are performed for cruise speed only, assuming the polar stays unchanged at climb and descent speeds. The vehicle is set in clean configuration and the solver to quasi-steady assumptions, allowing for a low computational effort, and better complements the geometry design fidelity (low). The steps taken to adapt the tool for seaplane geometries are described in Section 2.3.1

OpenArchBuilder is a tool for electric propulsion systems conceptual design. It makes use of the open source tool openconcept [16], and OpenAD, to optimize the propulsion system components and perform mission analysis. It is employed within this framework to retrofit a hybrid-electric powertrain on the seaplane as sized by OpenAD, and to re-calculate its fuel flow rate in the different mission phases. This process was already successfully performed by Bussemaker et al. [17]. The changes introduced to fit the tool in the methodology can be found in Section 2.3.2.

Lastly, the SoS Inverse Design (SoSID) Toolkit [18] (also referred to as Toolkit) is an agent-based model developed by DLR to simulate Urban Air Mobility (UAM) networks connected by fully electric vertical take-off and landing vehicles, and cars. In particular, it allows for the simulation of an on-demand transportation system over a predefined network of nodes and for a set demand distribution. The model has been adapted for the simulation of seaplanes and ferry fleets using a new agent performance model. This process is described in section 2.3.3. The Toolkit provides reports of all flight segments performed during one day of operation. These are used in the framework to obtain values of fleet and aircraft fuel consumption, flight time, passengers transported, and number of

missions performed. Moreover, three main types of uncertainties in fleet operation are modeled in the Toolkit: resources, timing, and demand uncertainties. In Section 3, one uncertainty parameter for each category is selected and varied to investigate their impact on the outputs of the framework. The results of this sensitivity analysis are shown in Section 4.
All tools presented above are connected and executed in the Remote Component Environment (RCE) platform [19], the DLR open-source integration environment. The Common Parametric Aircraft Configuration Schema (CPACS) [20], the open-source data format created by DLR, is used to guarantee standardization of tools inputs and outputs. The formal description of the optimization problem introduced above is provided in the next section.

2.2 Optimization problem set up

The eXtended Design Structure Matrix (XDSM) shown in Fig. 2 depicts the type and logic of information exchanged by the tools. An initial guess of the design vector (Eq. 1) is provided to the optimizer to start the optimization loop. The optimizer feeds the design variables to OpenAD, which performs an initial sizing of the seaplane. OpenAD forwards the aircraft geometry to FlowUnsteady, which analyzes the vehicle aerodynamics. Masses, geometry, and performance estimated by OpenAD, and the aerodynamic polar calculated by FlowUnsteady, are used in OpenArchBuilder to start a nested optimization loop, where the components of a hybrid electric powertrain are sized. Within this loop, the newly designed propulsion system is retrofitted on the seaplane designed by OpenAD, and masses and design mission are recalculated. At this point, the Maximum Take-Off Mass (MTOM) of the seaplane is compared to the initial estimation provided by OpenAD to check the consistency of the design (equality constraint in Eq. 2). The aircraft thus designed is provided as input to the SoSID Toolkit, together with the scenario of operation. The seaplane fleet operation is then simulated. Finally, the objective function (Eq. 3) is evaluated from the outputs of the ABMS. The objective value is fed back to the optimizer, which will then restart the loop with an updated design vector. The process is iterated until an optimum is found. The scenario is a constant input of the optimization loop, and it is defined in Section 3. The boxes on the leftmost column represent the optimal values that will be the final output of the optimization.

$$\vec{x} = [n_{pax}, M_{CR}, R_{DES}] \tag{1}$$

$$MTOM_{OAB} = MTOM_{OAD} \tag{2}$$

$$f = \frac{m_{FF}}{m_{FF-ref}} - \frac{\lambda}{\lambda_{ref}} \tag{3}$$

The design variables of this problem are: cruise Mach number, payload mass (expressed as number of seats), and design range of the aircraft (Eq. 1). Their choice was driven by the characteristics of the available design tools and by the fact that these aircraft parameters are also direct inputs of the ABMS. The objective function is a mixed objective that aims to minimise fleet fuel consumption while maximising the converted passengers' requests (the percentage of passengers choosing to travel with seaplanes) during one day of operation (Eq. 3). The problem is constrained to the bounds listed in Eq. 4. The bounds for the number of passengers are dictated by the choice of designing a seaplane in the CS23 class. The minimum cruise Mach number is imposed by OpenArchBuilder, while the maximum is defined according to values for aircraft in the CS23 class. The bounds for the design range are set to be the distance between the two furthest apart neighboring islands and the maximum distance between any two islands in the network. The latter is clarified in Section 3, where the islands' network is introduced.

$$\begin{aligned} 6 \leq n_{pax} \leq 19 \\ 0.20 \leq M_{CR} \leq 0.30 \\ 140 \leq R_{DES} \leq 500km \end{aligned} \tag{4}$$

Due to the nature of the optimization problem, where the gradient of the objective function is unknown, the optimizer selected for this optimisation is NOMAD, developed by Le Digabel [21] based on the Mesh Adaptive Direct Search (MADS) algorithm. NOMAD is designed for black-box optimization, where the objective function is a costly program, with no derivative information, and where some evaluations may return no values. In fact, NOMAD minimizes the number of evaluations needed to find the optimal solution and can handle discrete variables.

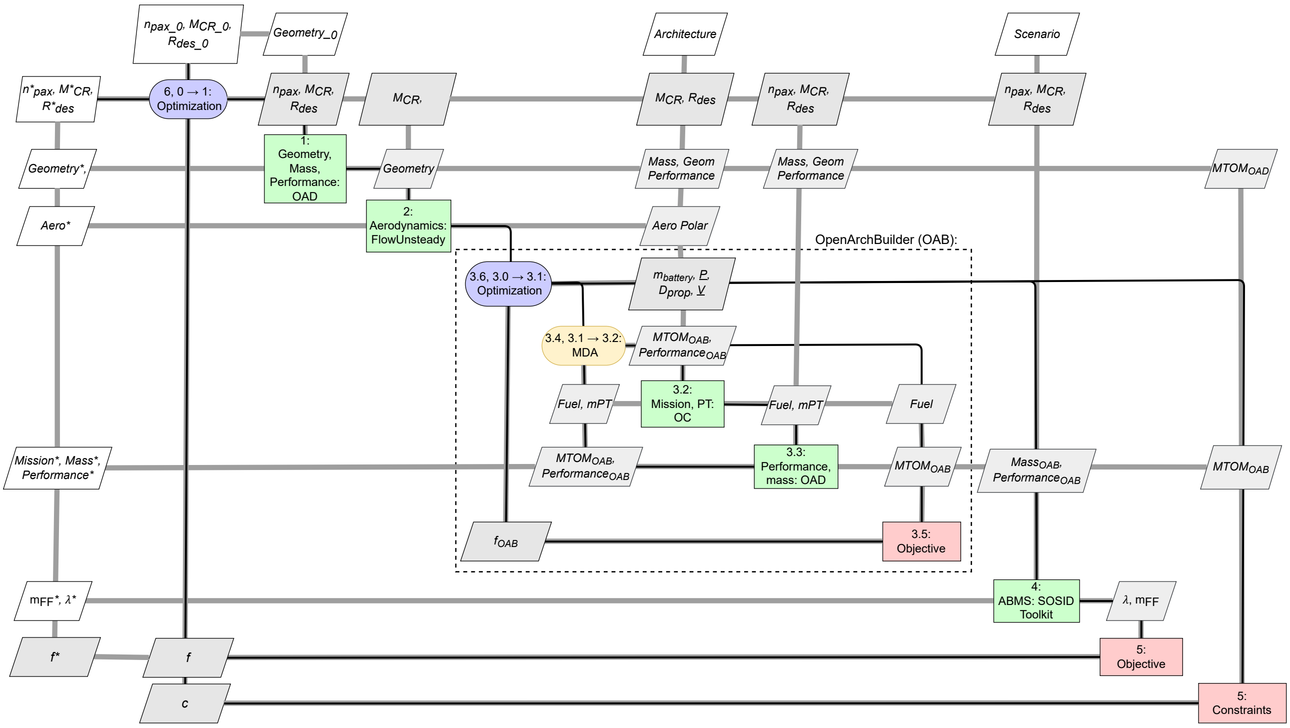


Figure 2 – XDSM diagram of the System of System-driven optimization problem

2.3 Tools development and adaptation to the framework

The most important modifications applied to the tools to make sure they could handle seaplane-specific data are explained in the following sections. All tools utilized in the framework communicate with each other thanks to pre-processing scripts created for each tool to read CPACS files in input. In the same way, post-processing scripts were created to convert outputs into CPACS files that could be interpreted as input by the following tool.

2.3.1 FlowUnsteady

FlowUnsteady offers a set of pre-built functions to describe wing and propeller geometries and to perform custom aerodynamics analyses. To represent a full seaplane, a function to define hull-shaped fuselages and tip-float components was introduced. This custom function takes the components' dimensions and cross-section as input from OpenAD, and it produces a loft surface over a sweep of seven cross-sections opportunely scaled.

The tool considers fuselage and tip-floats in the flow field but does not compute aerodynamic forces on them. The drag caused by these components is estimated in OpenAD with a semi-empirical method [22], and added to the total drag at each point of the polar.

2.3.2 OpenArchBuilder

The tool is used to set up a second (nested) optimization loop at the vehicle level which aims to size the hybrid-electric powertrain components, most importantly the battery, and to calculate the seaplane mission performance, as shown in Fig. 2. In this application, the input powertrain architecture is fixed to a parallel hybrid-electric configuration. The choice is based on the fact that this configuration performs better in terms of weight and fuel consumption over a wide range of degrees of hybridization [15, 17].

To adapt the tool to the framework, the cruise horizontal speed is fixed at the value dictated by the design variable M_{CR} passed by the main loop optimizer. The vertical speed at cruise is set to zero to ensure cruise at constant altitude. The Degree of Hybridization (DoH) with respect to power is considered to be zero during descent and the entire reserve segment [23], while optimized for climb and cruise. Thus, DoH_{CR} and DoH_{climb} were added to the design vector [15]. The objective function aims to minimize MTOM and fuel mass [15].
The battery pack specifications chosen by Fouda et al. [15] were considered to be too optimistic for a 2030+ time frame. Thus, Li-ion batteries with a specific power of 1 kW/kg and a specific energy of 350 Wh/kg were considered instead [24, 23, 25, 26]. The most relevant assumptions are listed in Table 1.

Table 1 – Technological assumptions for powertrain sizing

Component	Specific Power $(\mathrm{kW/kg})$	Efficiency (%)	PSFC $\mathrm{lb/(hp/h)}$
Battery	1	97	-
Motor	5	97	-
Generator	5	97	-
Converter	10	97	-
Turboshaft	7.15	-	0.6
Bus	-	95	-

2.3.3 SoSID Toolkit

The aircraft agents' behavior was adapted for the simulation of seaplanes by implementing a mission profile including taxi, take-off, climb, cruise, descent, loiter, and landing phases. Moreover, the agent performance model used to monitor the aircraft energy consumption has been updated in the following way. Taxi, take-off, and landing fuel consumption are considered constant. These values are estimated once for every seaplane in the aircraft design block of the framework. In the ABMS, seaplanes are required to fly a variety of missions often differing from the design one, therefore mission performance (for climb, cruise, and descent phases) are actively modeled in the simulation. In particular, fuel consumption during climb, cruise, and descent are calculated at every time step starting from the values of fuel mass flow for the design mission. The aircraft mass is updated at every time step by subtracting the instantaneous fuel consumption.
In Fig. 3, fuel mass flow against mass is plotted for the design mission and a representative simulated mission of a placeholder seaplane design. Note that OpenArchBuilder assumes linear dependency between the two quantities during each flight phase. The fuel mass flow for the simulated mission climb phase is obtained by linear translation, starting from the line representing the design mission climb phase. This is achieved by employing Eq. 5, which describes a grid of parallel lines.

$$y = ax + qk \tag{5}$$

Where a is the slope and q is the y-intercept of the design mission climb line. k is a constant that determines the spacing between the two lines and it is defined for each simulated mission as a function of the Take-Off Mass (TOM) (Eq. 6).

$$k = \frac{\dot{m}_F^0 - a \cdot TOM}{q} \tag{6}$$

Where $\dot{m}_F^0$ is the design mission initial fuel mass flow value.

The fuel mass flow during cruise is assumed to vary linearly across different missions. Therefore, the fuel mass flow for the simulated cruise is obtained directly from the line equation describing the cruise phase of the design mission. The loiter phase is considered a continuation of cruise and is thus modelled in the same way. Finally, the fuel mass flow during descent for the simulated mission is obtained in an analogous way as for the climb phase.

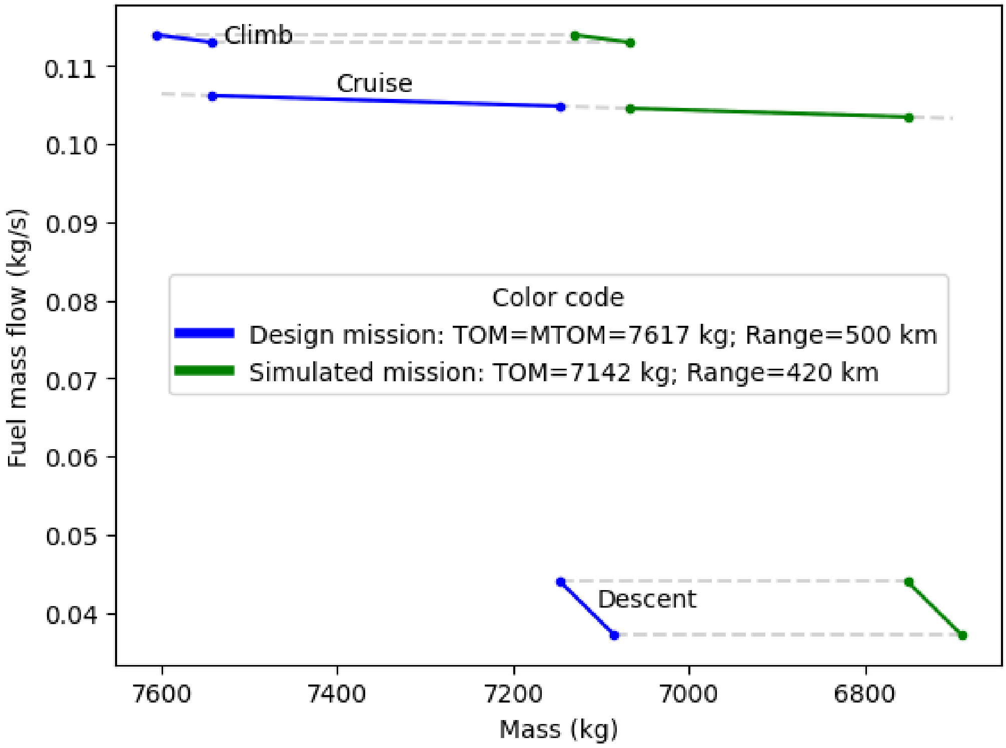


Figure 3 – Aircraft agents performance modeling

One of the objectives of this work is to evaluate to what extent seaplanes can represent a competitive alternative to existing maritime means of transportation in the Greek islands. For this reason, ferry connections have been modelled in the SoSID Toolkit. An average ferry for such an operation was selected [27], and its main features are summarized in Table 2. A fixed schedule, with departure and arrival times to the ports considered was assembled on the basis of information from the main service providers in the Aegean Sea (gathered on Ferryhopper[1], Seajets[2], and Blue Star Ferries[3] websites). For every travel request, the Toolkit reads direct routes from the schedule, and it computes possible connecting routes by considering a stopover in each of the other islands in the network. A maximum of one stop is allowed. The earliest possible arrival time by ferry is thus computed. The latter, together with the estimated arrival time by seaplane, is provided to the traveler, who will choose the fastest mode of transportation. (For information regarding the Toolkit models and logic please refer to Kilkis et al. [18]).
The above-mentioned islands network, as well as further assumptions posed for the simulation scenario definition, are described in the following section.

Table 2 – Ferry assumptions

Parameter	Assumed value
Pax capacity	250
Fuel consumption	$658.76\,\mathrm{kg/h}$

3 Scenario definition and assumptions

The input scenario is a network composed of 15 islands and the port of Athens, the Piraeus (Fig. 4). The choice of these seaports stems from the study carried out by Ilopoulou et al. [28], where the authors selected 31 islands and identified the most important travel routes in the Aegean. However,

[1] https://www.ferryhopper.com/en/ accessed on 10/23
[2] https://www.seajets.com/ accessed on 10/23
[3] https://www.bluestarferries.com/en-gb accessed on 10/23

in this paper, we reduced the number of ports to 16 to ease the computational power required by the simulation. The iterative selection process discarded the island with the shortest distance to its neighboring one until a set of 16 was obtained. "Neighboring islands" are any two islands directly adjacent, for which the distance between each other is the minimum among all pairs they can form with other islands. It is important to highlight the maximum distance among all neighboring islands as the minimum distance a seaplane should be able to fly to make sure no islands are unreachable. Data from the Hellenic Statistical Authority ELSTAT [4] was used to model the travel requests (demand distribution) in the network. This data, reporting the total number of passengers embarking and disembarking in each of the selected ports every 4 months, allows for the estimation of an average amount of travelers per day. The demand was assumed to be normally distributed throughout the day.

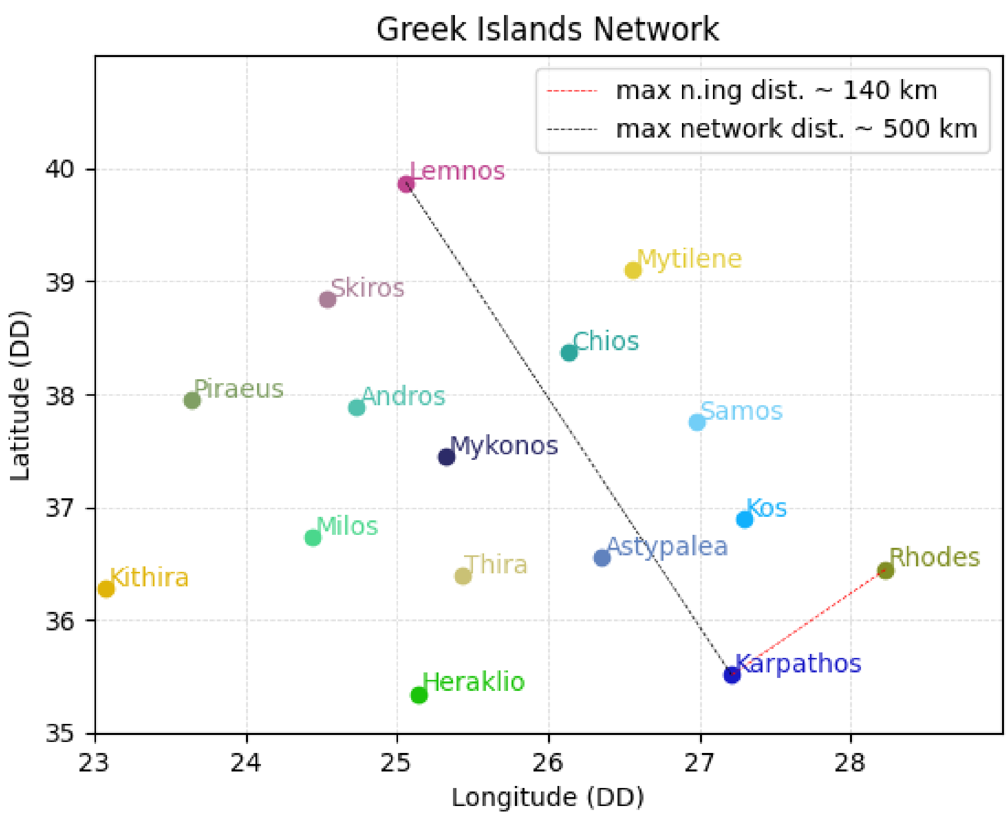


Figure 4 – Greek islands network representation

In order to investigate the effects of resources, timing, and demand uncertainties in the simulation on the outputs of the framework, the fleet size, grouping time window, and demand volume parameters are used to perform a Design of Experiments (DoE). Three fleet sizes are considered in the study: 16, 32, and 48 aircraft. The grouping time window (gw) is the time period during which the aircraft expects additional travel requests (after the first one) to be grouped together for a joint departure. For example, if there is a travel request at time T, the aircraft will wait for additional travel requests until time $T+gw$ before departing. One short and one long grouping windows are considered: 15 and 60 minutes, respectively. Lastly, two travel demand cases are analyzed. The first one considers a low demand case which is representative of the winter season, modelled with data from the first quarter of 2023. The second case considers data collected for the second quarter of 2022, representative of the summer season. With these values, a full factorial DoE was defined, for a total of 12 scenarios (Table 3).

More uncertainty parameters modeled in the Toolkit are listed in Table 4, and are fixed on the basis of the following assumptions. The seaport size is limited to one runway, and the fleet is split into an equal number of aircraft among the ports at the beginning of each simulation. The turnaround time

[4]ELSTAT website: https://www.statistics.gr/en/statistics/ind, accessed on 10/23

Table 3 – Scenarios considered

	Summer						Winter					
Scenario	S.1.1	S.1.2	S.2.1	S.2.2	S.3.1	S.3.2	W.1.1	W.1.2	W.2.1	W.2.2	W.3.1	W.3.2
Demand $(\frac{n_{pax}}{day})$	$\approx$ 3000						$\approx$ 880					
Fleet size (-)	16		32		48		16		32		48	
gw (min)	15	60	15	60	15	60	15	60	15	60	15	60

was broken down into three components: boarding, disembarking, and deployment time. A total time of 15 minutes is applied to all flights in the simulation independently of the number of passengers [1, 29, 30].

Table 4 – Uncertainties parameters assumptions

Parameter	Assumed value
Battery specific energy	$350\,\mathrm{kWh/kg}$
Battery specific power	$1\,\mathrm{kW/kg}$
Charging power	$450\,\mathrm{kW}$
Seaport size	1 runway
Turnaround time	$15\,\mathrm{min}$
Refueling rate	$7.7\,\mathrm{L/s}$

This time also includes battery recharging and refueling. Indeed, considering a recharging power of $450\,\mathrm{kW}$ [31], with the relatively small battery size noted in the design phase (maximally $300\,\mathrm{kg}$), the battery can be fully recharged in maximally 15 minutes. In addition, assuming that the seaports are equipped with a pressure pump, the refueling rate is conservatively estimated to be $7.7\,\mathrm{L/s}$ [32, 33]. At this rate, seaplanes with tank capacity up to $7000\,\mathrm{L}$ can be refilled in $15\,\mathrm{min}$. A similar study performed on UAM showed that the turnaround time does not have a significant impact on the simulation results [34]. Lastly, taxi time and fuel consumption were also considered to be fixed for each simulation. The values are estimated by OpenAD at every iteration and kept constant during each Toolkit run.

4 Results

Aircraft design problems and ABMS are recognized as challenging to validate. In the context of SoS, theory and experimentation are intertwined within the simulation itself, thereby complicating the validation of results [7]. Although the tools used to build the proof of concept are singularly validated ([13, 14, 15, 18]), the analysis and sensitivity study presented in this section play a pivotal role in the results validation process.

Twelve optimizations were performed on the basis of the scenarios set up in Section 3. The outcomes are shown in the following sections. The impact of introducing ABMS in the aircraft design framework on the design variable values is discussed in Section 4.1. The sensitivity of the design variables to changes in the simulation scenario is studied in Section 4.2. In Section 4.3, seaplanes are assessed as a potential innovative mode of transport in comparison to maritime connections in the Greek islands.

Seaplanes designed with the framework introduced in this paper are represented in blue for winter scenarios and red for summer scenarios. The notations “W.x.y” and “S.x.y” are used to identify both scenarios and the seaplane designed for the corresponding scenario. (For example: scenario W.1.1 refers to the first case described in Table 3, and seaplane W.1.1 refers to the seaplane designed with the ABMS-driven methodology in scenario W.1.1)

4.1 Impact of ABMS on seaplane design parameters

To investigate the potential of the newly introduced design methodology, and the effects of adding ABMS in an aircraft design process,the seaplanes designed using the SoS-driven design framework are compared to conventionally designed seaplanes.

In Fig. 5, seaplanes W.1.1 and S.1.1 are compared to seaplanes designed with the same aircraft design tools, yet with design choices driven by standard methodologies, instead of ABMS. In other words, the TLARs were not output of the SoS-driven optimization, but were deliberately selected according to the following methodologies. The design approach proposed by Patterson et al. [35] was adopted to size seaplane “C1”. The design range was set to the maximum distance in the network, and passenger capacity to the maximum for the CS23 class (19 seats), while the cruise speed was sized by OpenAD. The TLARs of design “C2” were chosen by aligning them with those of existing innovative concepts, such as the Viceroy by REGENT[5]. C1 and C2 are represented in yellow and green, respectively. Note that the values in Fig. 5c are dimensionless, they are scaled by the values of the top bounds introduced in Section 2.2.

From Fig. 5, it appears that seaplanes C1 and C2 are oversized with respect to the designs outputted by the SoS-driven framework (W.1.1 and S.1.1). According to the simulation results, the number of seats needed in scenarios W.1.1 and S.1.1 is approximately half of the estimated one for C2 and a third of C1 (6 and 7 against 12 and 19, respectively). As a consequence, the design MTOM is lower, which coupled with the fact that the aircraft fly at a lower cruise speed, provides noticeable savings in fuel consumption.

To give an overview of the performance of all seaplanes designed for the different scenarios, fuel consumed and requests converted by the respective fleets are plotted in Fig. 6. For this, and all subsequent plots the color code introduced above is maintained. Moreover, two different line styles are adopted to distinguish scenarios characterized by grouping time windows of $15\,\mathrm{min}$ and $60\,\mathrm{min}$.

The conventionally designed seaplane C1 obtains the highest number of requests converted in every scenario thanks to the high speed, and long range. However, C1 is also the seaplane consuming by far the most fuel, with a fleet fuel consumption over two times larger than the second least efficient design: C2. Seaplane C2 performs poorly both in terms of fleet fuel consumption and requests converted. Finally, all seaplanes designed with the newly introduced methodology score better than the conventional designs when considering both metrics at the same time, which constitutes the value of the objective function introduced earlier.

An almost linear trend is identified for both fleet fuel and requests converted against fleet size. On the other hand, the effect of the grouping window appears to be less relevant. Note, however, that for ABMS-driven designs, the higher grouping window causes a loss of converted travel requests in the majority of cases. This is due to the fact that the higher grouping window is slowing down the seaplane service, thus more passengers prefer ferries.

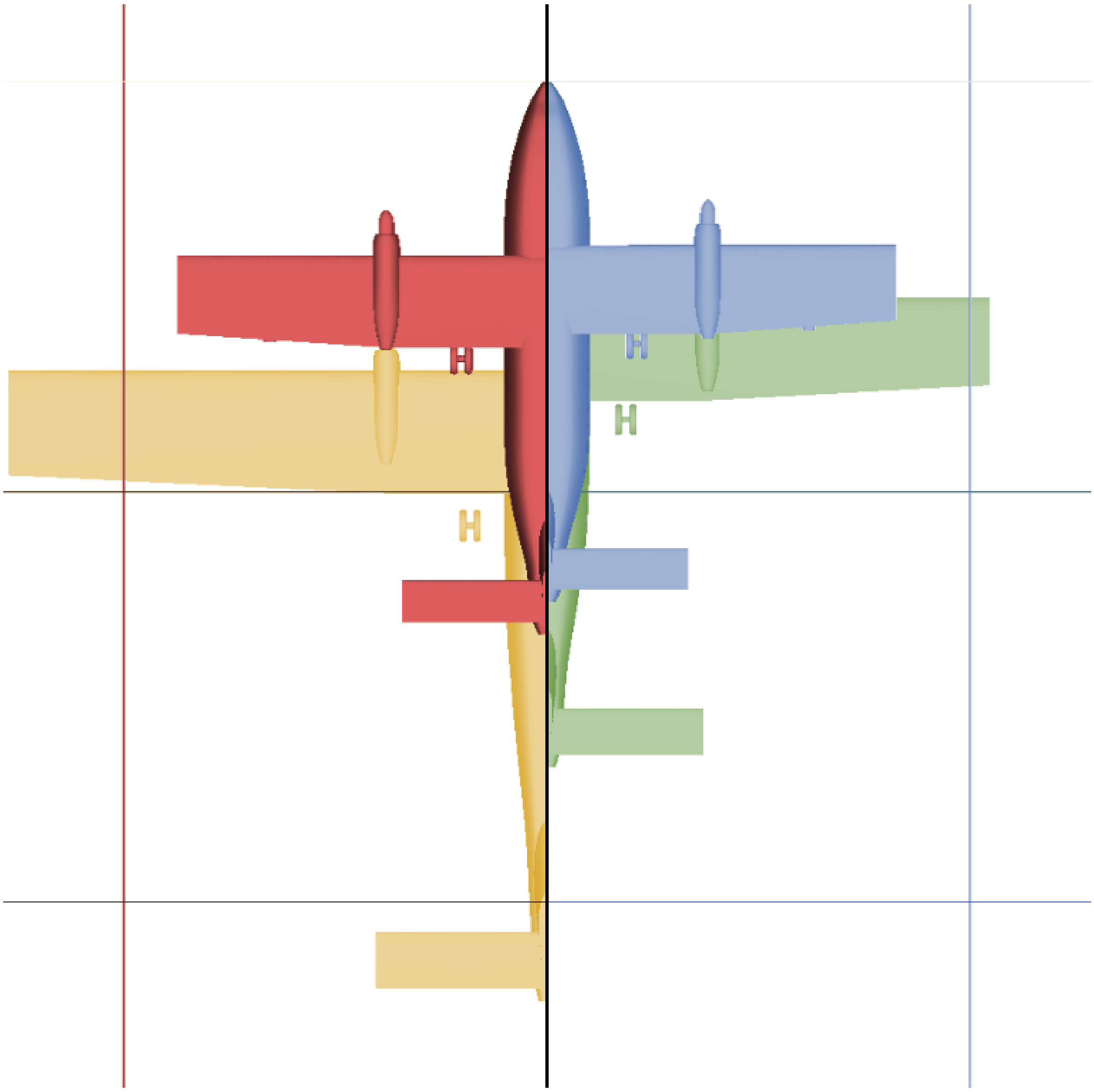
4.2 Sensitivity of seaplane design variables to scenario parameters

The sensitivity of seaplane design parameters to scenario parameters is investigated in this section. Fig. 7 illustrates the variations in optimal design parameters across the different scenarios.

In winter scenarios, the optimum design range does not present any clear correlation with fleet size. On the other hand, the high grouping window ($60\,\mathrm{min}$) causes the design range to be lower with respect to the values registered for $gw = 15\,\mathrm{min}$. From these considerations, and from the performance metrics in Fig. 6, it can be concluded that designs with longer ranges score higher travel request converted, while shorter ranges are enforced by the optimizer to reduce the fuel consumption. The optimum cruise Mach number grows with fleet size for $gw = 60\,\mathrm{min}$. Designs with lower ranges are characterized by higher cruise speed. Regarding optimum passenger capacity, contrary to expectations, high gw results in a lower number of seats. This is again correlated to the requests converted for the two grouping windows: when fewer passengers are served, smaller capacities are needed.

In summer scenarios, the optimum design parameters are not strongly affected by fleet size and grouping time window. Comparing the winter and summer scenarios, the optimum design range and cruise Mach number are in general higher in winter, while as expected, the opposite is true for passenger capacity. Overall, the optimum design vector is found close to the lower bounds of the design domain for all scenarios considered. Low values of design range, cruise Mach number, and passenger capacity are a consequence of the optimization enforcing a reduction in fuel consumption.

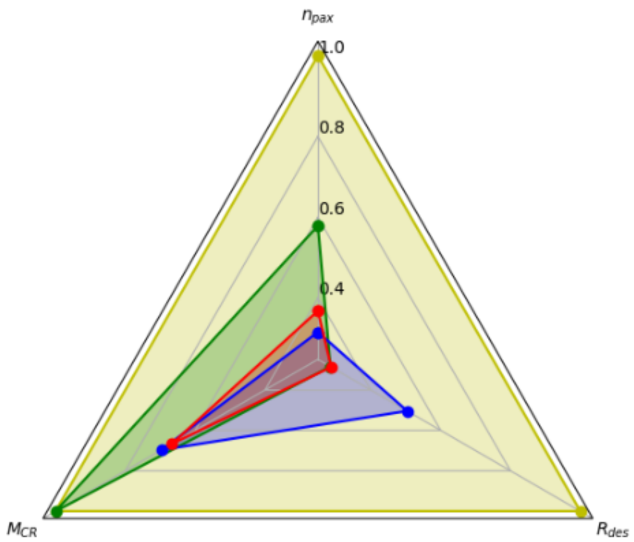
[5] https://www.regentcraft.com/seagliders/viceroy accessed on 11/2023



(a) Geometry comparison

	W.1.1	S.1.1	C1	C2
$MTOM$(kg)	3249	3564	7493	4931
$m_{battery}$(kg)	240	100	730	100
$m_{fuel}(kg)$	270	255	975	340
$m_{\text{payload}}(kg)$	665	760	1805	1140

(b) Masses comparison



(c) TLARs comparison

Figure 5 – Comparison seaplane designs W.1.1, S.1.1, C1, C2

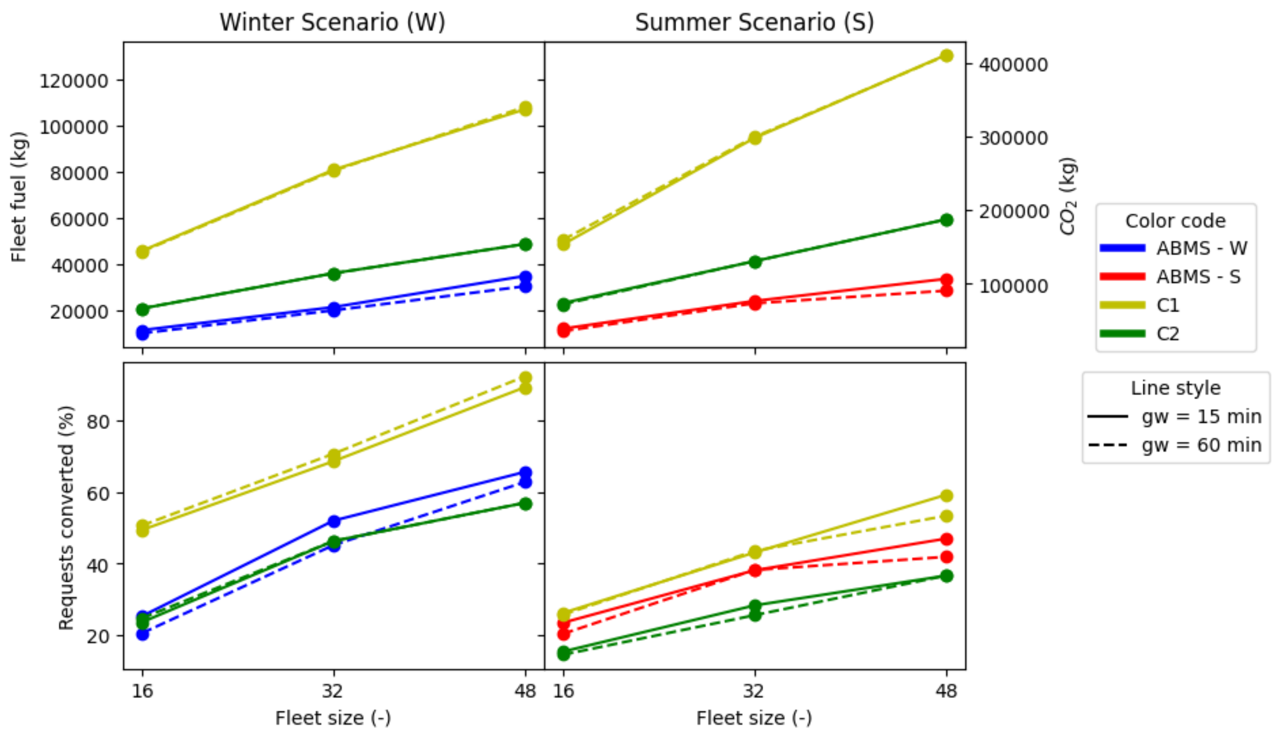


Figure 6 – Fleet performance of conventional designs against ABMS designs in different scenarios

In addition, this implies that minimizing the fuel consumption outweighs maximizing the requests converted in the scope of minimizing the objective function f.

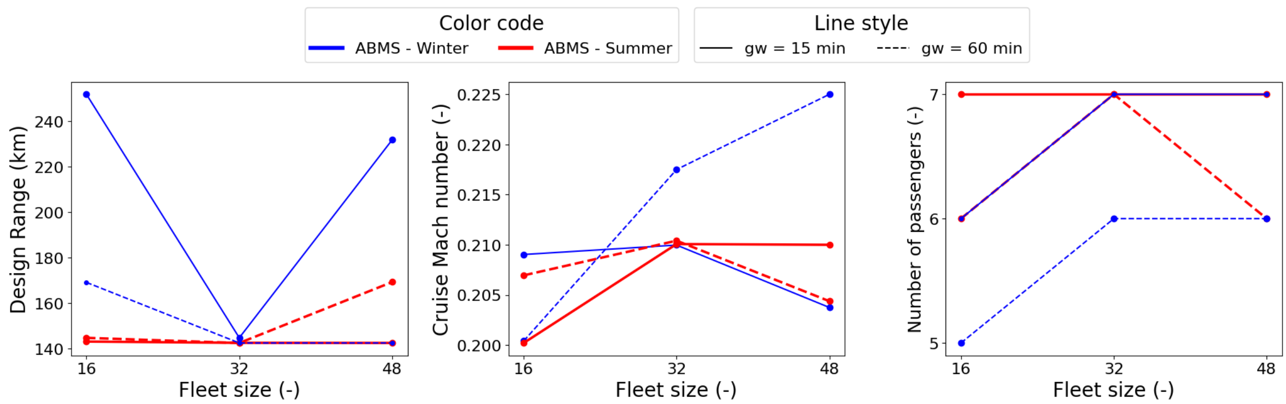


Figure 7 – Optimum seaplane design parameters in the different scenarios

4.3 Impact of seaplanes on the Greek maritime transportation system

In an attempt to assess the effect of introducing seaplanes into the Greek maritime transport system, we look at two main indicators: service quality and sustainability. The service quality is measured in terms of the frequency and duration (travel time) of the connections. The sustainability aspect refers to both environmental sustainability, assessed considering the fuel efficiency of the vehicles, and economic sustainability, evaluated on the basis of the average load of the vehicles. Note that the data for the ferries is obtained by considering the total amount of travellers. This is done in order to obtain an absolute comparison between the two modes of transportation. Moreover, the ferry schedule is fixed over the different scenarios.

The top two charts in Fig. 8 depict the average service frequency per route in the network for both seaplanes and ferries. The ferry fleet's average frequency per route is approximately two, meaning that each route is connected on average once in both directions every day.

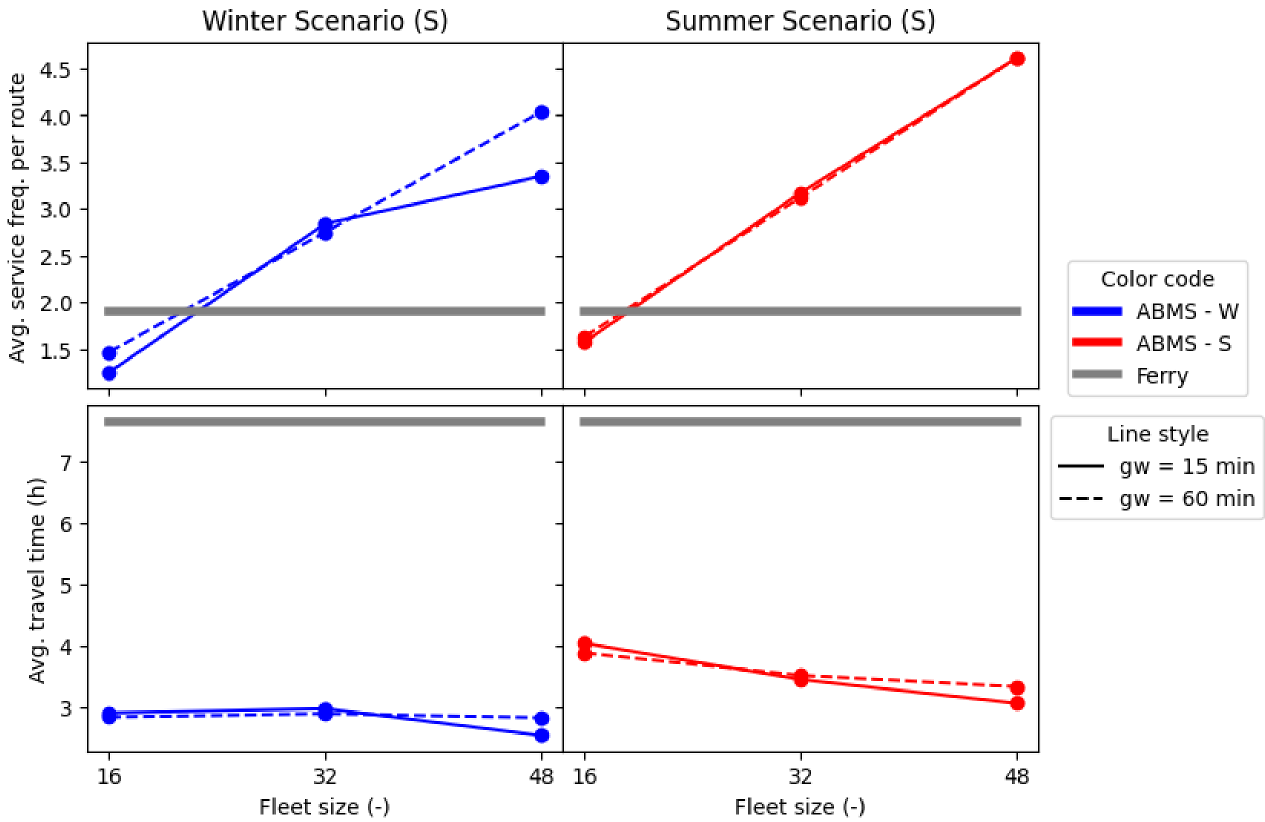


Figure 8 – Comparison of seaplanes and ferries service quality in different scenarios

In winter scenarios, the average frequency of fleets of 16 aircraft is lower than that of the ferry fleet. Therefore, in these scenarios, not all islands are well connected by seaplanes. With increasing fleet size, the average frequency of seaplanes increases until a peak of approximately twice the ferry one for $gw = 60\,\mathrm{min}$. The high grouping window has a positive effect on the service frequency in the majority of scenarios. The same considerations regarding fleet size are valid for summer scenarios, while the effect of the grouping time window is negligible in this case. Comparing winter and summer scenarios, the frequency of the seaplanes increases in summer with the increased demands.
The bottom two plots in Fig. 8 show the average travel time for seaplanes and ferries. In winter scenarios, the high discrepancy between the two means of transportation is eye-catching. In addition to the already large gap, the travel time of the seaplanes also includes waiting time: from the time the travel is requested until the flight departs. The true average flight time does not surpass an hour in most scenarios. The high travel time of ferries is due first of all to the slower speed of the vehicles, and secondly to the lack of direct connections for some routes. Regarding the dependency of seaplanes average travel time on the grouping time window, $gw = 15\,\mathrm{min}$ allows for faster connections in scenarios characterized by fleet size 48. The opposite is true for fleet sizes of 16 aircraft. The same applies for summer scenarios. Here the dependency of seaplanes average travel time to fleet size is stronger, and compared to the winter ones, the seaplane connections are slower.
In passenger transportation, Available Seats Kilometers (ASK) is often used to measure the passenger carrying capacity of a vehicle. In this paper, an average ASK is considered: it is calculated by multiplying seats available on one vehicle by the average distance (in kilometers) traveled in the network. In Fig. 9, one can clearly see the low average ASK of the seaplanes compared to ferries, resulting from the seaplanes' limited seat capacity. The disadvantage of low ASK vehicles is the need to operate in larger fleets and the requirement for more trips to transport the same number of people. However, the low ASK can have different effects on the fleet performance based on the type of transportation system operated. Indeed, having small vehicles is beneficial for an on-demand transportation system, where travel requests are scattered throughout the day. In contrast, for a scheduled transportation system it is more convenient to have high vehicle capacities and small fleets.

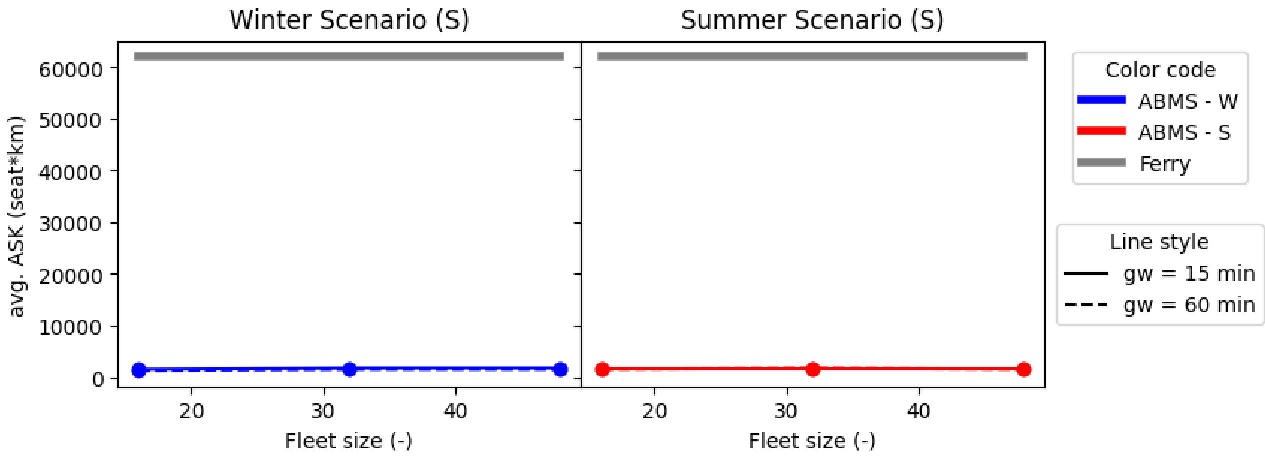


Figure 9 – Comparison of seaplanes and ferries average Available Seats Kilometers (ASK) in different scenarios

At last, the sustainability metrics are discussed for the various scenarios. Starting from the fuel efficiency, defined in Fig. 10 as mass of fuel consumed per passenger. In winter scenarios, comparing seaplanes and ferries, the gap on fuel efficiency of the two is substantial: ferries need circa 20 times higher amount of fuel per passenger transported than seaplanes. Despite the fact that total fleet fuel consumption grows with larger fleet size, the seaplanes fuel efficiency stays approximately constant. This is because larger fleets can also transport more passengers. In scenarios where $gw = 60\,\text{min}$ and fleet size is smaller than 48, the fuel consumption per passenger is higher.
In summer scenarios, the same considerations apply, with the only difference that the effect of the grouping time windows is tamed. Comparing winter and summer scenarios, the optimum seaplanes consumes approximately three times less fuel per passenger in the latter case. The same difference is seen in the ferry fleet. In both cases, the seaplane fleets outperform the ferry connections.

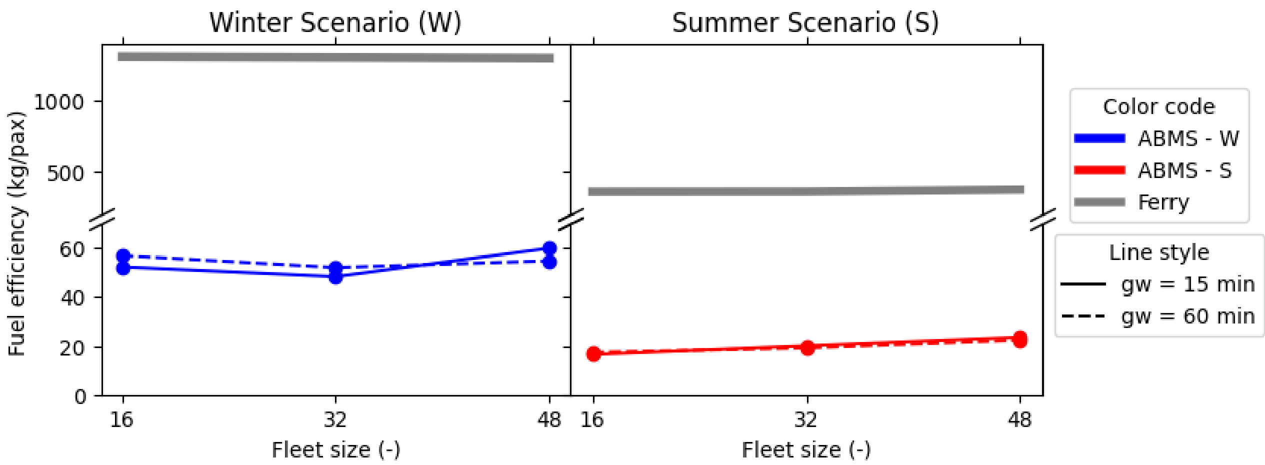


Figure 10 – Comparison of seaplanes and ferries service fuel efficiency in different scenarios

In Fig. 11, the average load factor indicates the average number of passengers on board a vehicle with respect to the total capacity. In winter scenarios, the average load factor of seaplanes is not clearly correlated to fleet size. As expected, high grouping time windows cause higher load factors (w.r.t. low grouping time windows). Moreover, it is interesting to highlight that for fleet sizes 16 and 32, the higher average load factors of scenarios characterized by $gw = 60\,\text{min}$ do not correspond to reduced fuel consumption per passenger. Lastly, compared to the summer scenarios, average load factors in winter are lower, despite the smaller seating capacity of the vehicles noted in Fig. 7.
In general, the average load factor of ferries is extremely low when compared to seaplanes. On the one hand, this shows that ferries offer room to accommodate future demand growth, making

the business more sustainable from this point of view. On the other hand, the high load factors characterizing seaplanes indicates a potential for covering operator costs and generating revenue.

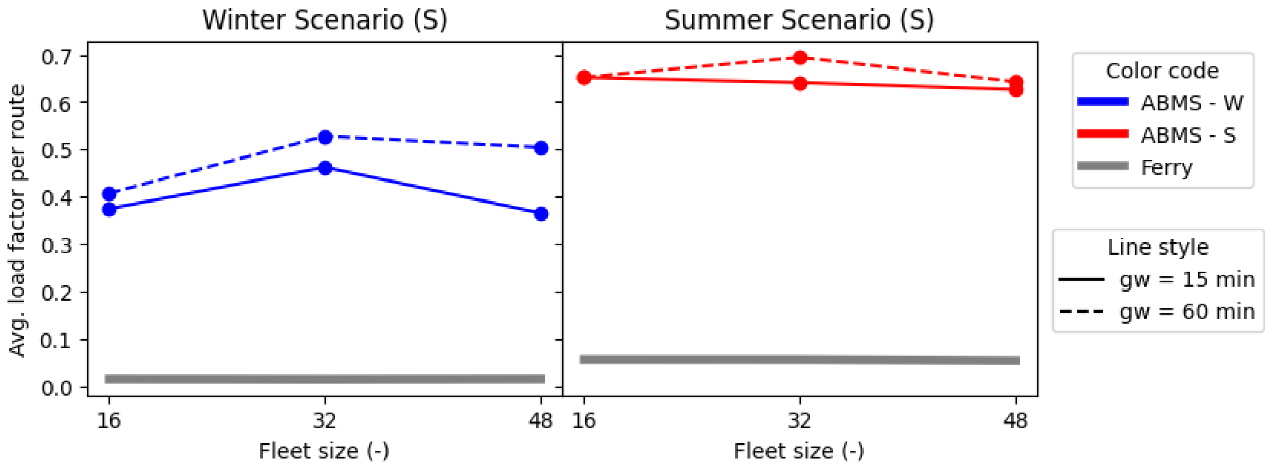


Figure 11 – Comparison of seaplanes and ferries average load factor in different scenarios

5 Conclusion

In conclusion, the SoS-driven aircraft design framework paves the way for new possibilities and insights in the discipline of aircraft design. For the first time, considerations about operational aspects are introduced in a methodical way in the aircraft design process, by combining a set of design tools with ABMS. The designs outputted by the optimization appeared to be different from expectations set by experience and conventional design approaches, as highlighted in Section 4.1. The framework demonstration showed the effects of adding ABMS to an aircraft design framework. The studies carried out in Section 4.2 unveiled trends and dependencies that can help improve the operational effectiveness of a conceptual design. Moreover, seaplanes proved to be a valid alternative to maritime connections in the Greek islands, providing relevant time savings to a large portion of travellers (Section 4.3).

The results shown for the number of travel requests converted by the seaplane fleets demonstrate that a significant percentage of travellers is captured starting from fleets composed of approximately 32 vehicles. In addition, the comparison performed with the service frequency of the ferry fleet shows that the two modes of transportation offer similar performance for a fleet of seaplanes with close to 16 vehicles. Therefore, from the data available, it can be concluded that for seaplanes to be a competitive alternative to ferries, and to eventually outperform them in terms of service quality, the minimum fleet size should be approximately 24.

From the considerations on the average Available Seats Kilometers (ASK) presented in Section 4.3, it can be concluded that an on-demand seaplane transportation system is most effective with a low ASK. This conclusion is supported by the results obtained for fleet fuel consumption and efficiency of seaplanes compared to the considered ferry fleet. In fact, these metrics show concrete possibilities to reduce the emissions for connecting the Greek islands. Another possibility is to boost the network with the addition of a seaplane fleet (on top of the ferry one), achieving much lower travel times with a minimal increase in emissions.

The disparity noted between ferries and seaplanes in terms of average ASK, load factor, and fuel efficiency, seeds doubts about the fairness of the comparison between seaplanes sized for an on-demand transport system and a ferry fleet thought for a scheduled system. Future work will need to focus on clarifying this aspect, by proposing a different comparison and metrics of evaluation, and above all, exploring different assumptions regarding the ferry schedule, and their passenger capacity. Another focus for future work regards the dependencies identified between the optimum design parameters of the seaplanes and scenario uncertainty parameters. The conclusions could be strengthened by broadening the analysis of the fleet size parameter, collecting more data. At last, the study could be expanded to evaluate the impact of the most important assumptions regarding the scenario definition. Investigating different networks beyond the Greek islands (with different daily demand distribution) would be beneficial to better understand the framework's potential and limitations.

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3

Literature review

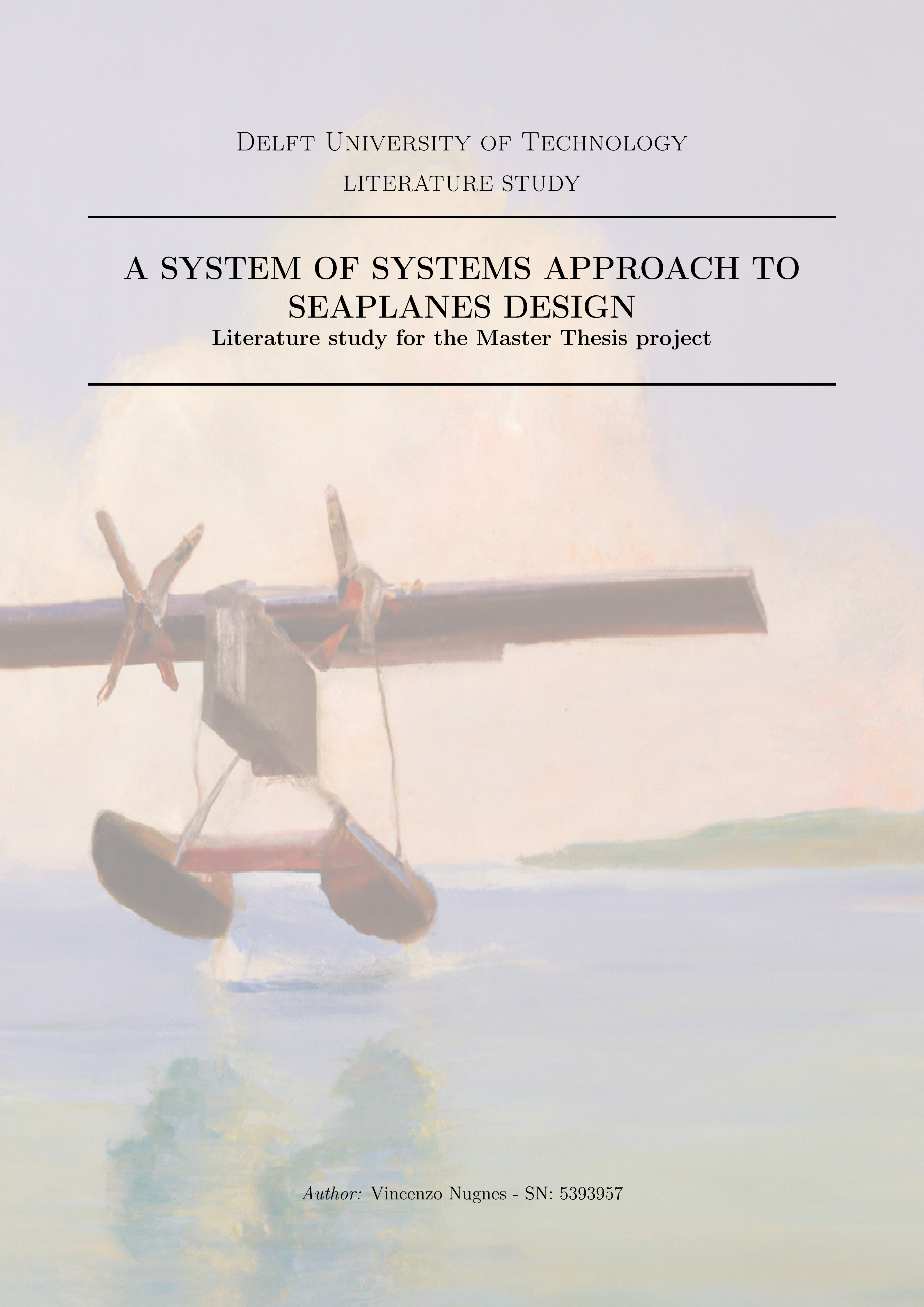
Note that the literature review here attached has been previously graded.

Delft University of Technology

literature study

A SYSTEM OF SYSTEMS APPROACH TO SEAPLANES DESIGN

Literature study for the Master Thesis project



Author: Vincenzo Nugnes - SN: 5393957

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Introduction

1.1 Introduction and Relevance of the Project

The literature study carried out in preparation for the MSc thesis project is outlined in this document. The general area of interest for the research is the seaplane System of Systems (SoS).

Seaplanes played an important role in the aviation industry during the first half of the past century. Their popularity grew thanks to their ability of taking-off and landing on water bodies. However, during and after World War II, numerous run-ways were built worldwide, and seaplanes' primary strength lost relevance. The flaws of seaplane designs became more apparent, outweighing their advantages and rendering them obsolete compared to conventional aircraft.

In order to understand the seaplane SoS, it is needed to describe the concept of SoS first. According to the ISO/IEC/IEEE International Standard [1], a System of Systems can be simply defined as any other system: it "consists of parts, relationships and a whole that is greater than the sum of the parts". With the peculiarity that the components of this system are independent systems themselves. With this definition in mind, the seaplane SoS can be introduced, where the seaplane, here considered as an aircraft, is the System of Interest (SoI), and systems such as meteorology, tourism, air and water traffic control, and many others, are component systems of the seaplane SoS.

During this research, a gap in the literature about seaplanes was found between 1960 and 2010 circa, which corroborates the decline in popularity of this configuration. Only recently, few scientists have shown renewed interest in seaplanes. However, even the latest contributions revealed to be lacking of modern approaches and above all of an holistic view of the seaplane system in the design process. The MSc Thesis project is intended to contribute to the new stream of interest towards these vehicles, and to adopt a System of Systems Engineering (SoSE) perspective in order to demonstrate the potential of seaplanes as a future sustainable means of transportation.

1.2 Purpose and main objectives of the literature study

This literature study was performed in order to gain understanding on the general area of interest of the MSc Thesis project. In particular, four main topic were identified, and for each, a set of "guiding questions" were formulated.

1. Background on Seaplanes
    (a) What are seaplanes?
    (b) What is their role in the history of aviation?
    (c) Which seaplane configurations exist?
    (d) Which missions can seaplanes fulfill?
    (e) Where do they operate?
2. The seaplane System of Systems
    (a) What is a System of Systems?
    (b) What are the main component systems of the seaplane SoS?

3. Seaplane design
   (a) What are the key parameters in seaplane design?
   (b) What unconventional (more sustainable) power train configuration can suit seaplanes?
4. System of Systems driven design
   (a) What is System of Systems driven design?
   (b) What is Agent Based Modeling?
   (c) How is Agent based modeling used in System of Systems driven design?

The questions were used as a guideline for the literature study which, as a result, is set to address each of them.

1.3 Report overview

The report is structured accordingly to the four areas of interest identified early on where, each chapter aims to answer one of the set of questions proposed above. Chapter 2 is dedicated to an investigation of seaplanes, including their role in history, and the different configurations available with respective strength and weaknesses. In Chapter 3, the concept of System-of-Systems is further elaborated, aiming to provide a comprehensive understanding of this discipline. In the same chapter, the seaplane SoS is introduced. The work of authors who provided valuable insights and perspectives on various aspects of seaplanes was analysed. in particular, the focus was posed on design methodologies, operation, and integration of seaplanes into different market sectors. The inputs from these studies were then synthesized and integrated to shape the concept of the seaplane SoS. The state-of-the-art of seaplane design methodologies is discussed in Chapter 4. Chapter 5 deals with SoS-driven design. An overview of the current SoS simulation methodologies is presented, and the role of Agent Based Modeling (ABM) in this field is illustrated. In Chapter 6, gaps in existing literature are highlighted and their significance in relation to the research topic is emphasized. Following, the research questions are developed based on these gaps in Chapter 7. In Chapter 8, the focus is on outlining the approach and methods that will be employed to address the research questions formulated in the previous chapter. Chapter 9 contains the estimated time-frame in which the project will be carried out, including major milestones and deliverables. Finally, the conclusions of the literature study are drawn in Chapter 10.

2

Background on Seaplanes

Seaplanes are a special aircraft configuration able to taxi, take-off and land on water. This capacity makes them suitable for unique types of missions, involving operation in unfavorable landscapes, where proper infrastructure is not available. The main advantage of seaplanes is indeed their versatility, the capacity of operating in diverse environments with minimal infrastructures.

2.1 Seaplanes in history

2.1.1 From the first flight to World War I

In the early 20th century, engineers recognized the potential of using water as a runway for aircraft take-off and landing. According to La Rocca [2], Henry Fabre achieved the first successful water take-off and landing with his "Hydraviation" in 1910. Only two years later, the Voisin brothers developed the first amphibian aircraft known as "The Canard Voisen", capable of operating on both water and land. This advancement caught the attention of the military, leading to a collaboration between Curtiss and the US Navy during World War I, when seaplanes were used in military missions. It was Curtiss'NC-4, an amphibian developed during his years at the US Navy, the first aircraft to ever cross the Atlantic Ocean (Figure 2.1).

2.1.2 From the first to the second World War

The first war showed the potential of seaplanes and encouraged their development. Boeing, produced 9 examples of the Clipper, a large passenger transport aircraft, operated by PanAm in the firsts transoceanic luxury travels. The private transportation sector also saw the involvement of seaplanes with the Grumman Goose. The first private charter seaplane was commissioned to Grumman by a group of wealthy business men from long island who needed a faster way to reach their work places in New York.

The hype around seaplanes grew faster and faster reaching a peak during WWII. The absence of paved runways on European soil, made the main characteristic of seaplanes, the ability to take-off and landing on water surfaces, a huge advantage during the war. The American bomber Catalina, employed by different factions, in few years became the most produced seaplane ever as reported by La Rocca [2].

2.1.3 From World War II to present days

However, the post-war period marked the decline of seaplanes. The construction of numerous airports and facilities for land-based planes worldwide reduced the relevance of seaplanes' primary strength. The flaws of seaplane designs became more apparent, outweighing their advantages and rendering them obsolete compared to conventional aircraft. Promising military programs such as Seamaster and Sea-Dart, advanced seaplane prototypes, were ultimately abandoned before they could be put into operation.

Surviving seaplanes found new roles, particularly in firefighting. Many Catalinas were converted into water-bombers, leading to the emergence of companies like Canadair (now Bombardier) specializing in manufacturing amphibian firefighting aircraft. Today, operating seaplanes are mainly found in North America, where small airlines use second-hand aircraft adapted with floats for passenger transportation. The Russian Beriev Be-200, a large flying boat equipped with turbofan engines, and Dornier's Seastar, a modern design in composite material, are notable seaplanes still in operation.

[1] Source of seaplanes pictures: Wikipedia `https://www.wikipedia.org/`

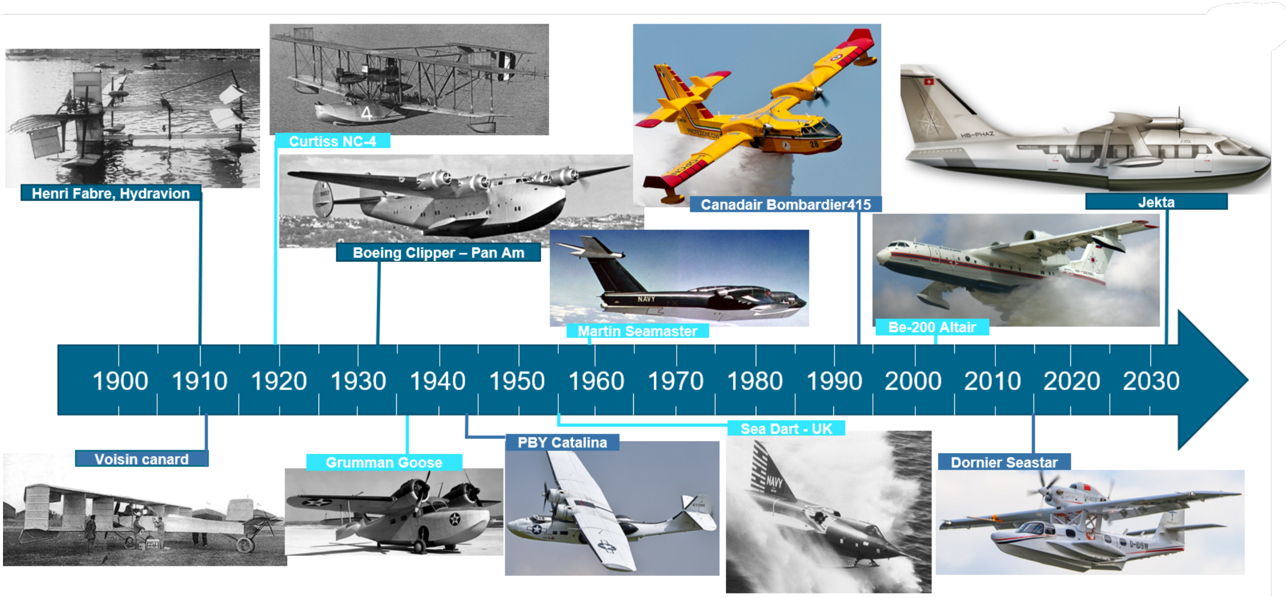


Figure 2.1: Seaplanes timeline [1].

New manufacturers, airlines and researchers are actively shaping the future of seaplane operations. Hellenic Seaplanes [2], for instance, on the lead of the research by Ilopoulou et Al. [3], envisions a network of connections in the Aegean Sea based on seaplanes, while Jekta [3], among other companies, is developing fully electric passenger transport flying boats. Worth mentioning that the latest seaplanes developed, as well as the next generation of seaplanes, are exclusively flying-boats (Figure 2.1).

2.2 Seaplane configurations

There are two primary configurations of seaplanes: float-planes and flying-boats, each available in standard and amphibian versions (Figure 2.2).

2.2.1 Float planes

Float-planes are the simpler configuration of seaplanes. La Rocca [2] describes them as conventional aircraft mounted with floats which provide the necessary buoyancy for water operations.

The simplicity of float-planes is the key to their success over flying-boats in the passenger transport market today. They represent a relatively cheap solution as floats can be adapted for existing aircraft. Moreover, the floats provide good water stability, and no other feature is needed for an aircraft to safely navigate, take off or land on water surfaces.

On the other hand, the floats highly compromise the aerodynamics of the aircraft. The bulky structures affect in particular the overall drag of the vehicle, and thus its efficiency. In addition, this design implies an high position of the center of gravity, making float-planes susceptible to capsizing in rough sea conditions.

2.2.2 Flying boats

Flying-boats utilize their own fuselage as a buoyant hull, optimized for water performance while maintaining high aerodynamic efficiency. This design choice ensures a lower center of gravity, enhancing the seaplane's handling capabilities in water. The reinforced hull also adds an extra safety factor during emergency landings.

However, the extra reinforcement comes with a weight penalty, graving on the payload capacity of seaplanes. One more disadvantage is due to the vicinity of the aircraft to the water, increasing the risk of spray ingestion in the propulsion system. The hull design must also feature an additional device to guarantee roll stability in water.

[2]HELLENIC SEAPLANES S.A. https://www.hellenic-seaplanes.com/en/
[3]JEKTA https://jekta.swiss/

Figure 2.2: Seaplane main configurations: (a) A float-plane (de Havilland Beaver); (b) an amphibious float-plane (de Havilland Twin Otter); (c) a pure flying-boat (Martin PBM-5 Mariner); (d) an amphibious flying-boat (Grumman Mallard) [2].

2.2.3 Float-planes and flying-boats in comparison

It emerges from the previous paragraphs that both float-planes and flying-boats can be employed for water landing and take-off operations, but their configurations offer unique characteristics that make each more suitable for specific scenarios and missions. The main comparison points are presented below and summarized in Table 2.1.

- Float-planes generally have a lower purchasing cost compared to flying-boats, whereas operational costs tend to be similar for both configurations. This makes the former often the preferred choice for airliners operating in the tourism sector.
- Complexity goes along with the cost analysis. Flying-boats have an high degree of complexity due to the hull design and the roll stabilization requirements in water.
- When considering missions such as rescue or firefighting, reliability is a crucial factor. The superior water handling capabilities of flying boats make them the preferred choice for these types of missions.
- Flying-boats currently offer higher aerodynamic efficiency compared to float planes, thanks to their streamlined shape.
- Payloads capability are generally higher for flying boats due to the limited buoyancy the floats are able to provide.

2.2.4 Standard and amphibian configurations in comparison

As mentioned above, seaplanes are available in standard as well as amphibious versions. Amphibian is any vehicle able to operate on both water and land surfaces. For this purpose, seaplanes can be adapted with retractable landing gears. Both float-planes and flying-boats are often proposed in amphibian versions which possess all the advantages of a seaplane, with the possibility of also taking-off and landing on conventional runways as well as not paved terrains. The main comparison points are presented below and summarized in Table 2.2.

	Float Plane	Flying Boat
Cost	++	-
Complexity	+	-
Reliability	- -	+
Efficiency	-	++
Payload	-	+

Table 2.1: Configurations comparison.

- The standard configuration has lower purchasing cost compared to the amphibian, while again operational costs tend to be similar for both. Also in this case, cost is often a priority for airliners operating in the tourism sector which prefer the first version.
- The addition of retractable landing gears makes amphibian more complex than standard configuration both in terms of manufacturing and operation.
- Another important factor when considering missions such as rescue or firefighting is versatility (or flexibility). In this aspect, amphibians have all advantages of standard seaplanes with the extra degrees of freedom granted by the landing gear.
- Payloads capacity are lower for amphibians (when considering the same aircraft) due to the additional weight of landing gear.
- Amphibians are easily dry-docked, which implies that operations of loading, maintenance and refueling are simpler than for the standard version.

	Standard	Amphibian
Cost	+	-
Complexity	+	- -
Versatility	+	++
Payload	+	-
Accessibility	- -	+

Table 2.2: Configurations comparison.

2.2.5 Special configurations

There are special configuration of seaplane that are treated outside of the classification introduced above. This choice is due to the fact that their distinctive traits make them stand out from the category flying-boats which they could be considered in.

Ground effect aircraft

Ground effect aircraft take advantage of the ground effect by flying low, close to the ground, to increase their lift capabilities. Ground effect phenomena for seaplanes is investigated by Arumugham-Achari et al. [4]. The authors show the possibility of exploiting this effect when flying over water bodies. Computational Fluid-Dynamics (CFD) methods were used to predict the ground effect over a deformable surface (water) for a range of ground clearances. The results provide insight regarding the altitude at which seaplanes could benefit the most of the ground effect.

The U.S. Defense Advanced Research Projects Agency (DARPA) is working to develop a new concept of seaplane designed to fly in ground effect: the program Liberty Lifter [4]. At the same time, the company REGENT [5] seems to be even closer to the goal. A prototype of their Viceroy Seaglider was built this year (2023), and it is planned to enter service in 2025. The Seaglider is not only going to fly in ground effect, it is also going to feature skies and hydrofoil to improve the take-off and taxi phases.

[4]DARPA, Liberty Lifter `https://www.darpa.mil/program/liberty-lifter`
[5]REGENT, Viceroy Seaglider `https://www.regentcraft.com/seagliders/viceroy`

Hydrofoil seaplane

Another special configuration consists of the addition of skies or hydrofoil to the hull of a flying boat. This technology dates back to the first half of the past century, and it was for sometime forgotten. More recently, skies were used in marine transportation, and hydrofoil came back in fashion when they were featured on the sail boats competing in the America‘s cup. Skies and hydrofoil allow the vehicle to reach planing phase without the need of a planing hull. In this way, the hull can be designed for better sea handling rather than for lifting the aircraft from the water as much as possible. This is achieved thanks to their particular shape which, similarly to a wing, lift partly or entirely the aircraft from the water, reducing drag during take-off and taxi.

This concept is explored by Seth and Liem [5]. The authors perform a conceptual design and optimization of a strut based hydrofoil mounted on a small flying-boat. The hydrofoil was firstly sized with semi-empirical formulae, and successively modified with two optimization algorithms. The first one aimed to optimize the span and incidence angle of the hydrofoil for the minimum take-off distance. The second one was set to find the optimal position of the hydrofoil along the hull in order to minimize the stabilizer force of the aircraft. Both were carried out using a CFD surrogate model the authors developed in order to avoid high computational costs. The conclusions show that the addition of the hydrofoil decreases the take-off length of 3% circa and the stabilizer force of 28% circa w.r.t. the standard flying-boat.

An example of this application on a modern seaplane is again the Viceroy Seaglider by REGENT, which is currently in testing phase. The aircraft mounts a retractable hydrofoil at the tail, and skies at the nose. The combination of the two allows for smooth water taxiing and take-off operations, as the company claims. Moreover, the presence of these devices allows for a deep V shaped hull which is ideal for reducing the impact in landing.

3

System of Systems Engineering

In this chapter, the concept of System of Systems (SoS) is introduced (Section 3.1), and its application to the seaplane system is investigated (Section 3.2). Therefore, the seaplane SoS is defined, and some of its main component system are introduced in Section 3.3. In the latter section, the main focus is posed on the passenger and cargo transportation sector, which will be at the core of the MSc thesis research.

3.1 System of Systems: definition and architecting principles

According to the ISO/IEC/IEEE International Standard [1], a System of Systems can be simply defined as any other system: it "consists of parts, relationships and a whole that is greater than the sum of the parts". With the peculiarity that the components of this system are independent systems themselves.

Gorod et Al. [6] carried out an in depth review of SoS engineering history and identified the main contributions from the academic and industry worlds as shown in Figure 3.1. The work of the authors is summarized in a table in which they managed to efficiently present the characterizing features of System Engineering (SE) and SoS Engineering (SoSE). The table is reported in Figure 3.2.

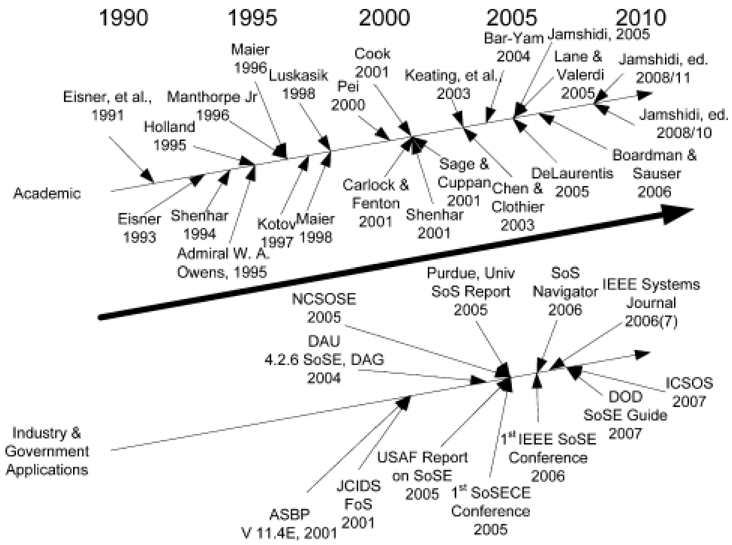


Figure 3.1: Modern history of SoS [6].

Following, more light is brought on the work of the main contributors identified by Gorod et Al. [6], whose work is believed to best explain the nature of SoS, the key traits, and challenges still present in this developing field.

Maier is considered as one of the fathers of of SoS engineering. He was the first one to adopt the characterization approach to distinguish "monolithic" systems from SoS. In his first publication on the topic [7], he introduced two properties that a system should possess in order to be considered a SoS:

- Operational independence of component systems

	SE	SoSE
Focus	Single Complex System	Multiple Integrated Complex Systems
Objective	Optimization	Satisficing, Sustainment
Boundaries	Static	Dynamic
Problem	Defined	Emergent
Structure	Hierarchical	Network
Goals	Unitary	Pluralistic
Approach	Process	Methodology
Timeframe	System Life Cycle	Continuous
Centricity	Platform	Network
Tools	Many	Few
Management Framework	Established	?

Figure 3.2: Major drivers of SE and SoSE [6].

- Managerial independence of component systems

Moreover, in the same article, the author refers to additional characteristics of SoS:

- Geographical distribution of component systems
- Emergent behavior of component systems
- Evolutionary development processes of component systems

The definition formulated by Maier was then re-used and re-elaborated by many researchers in the SoS field. One above the others is Jamshidi, who contributed to the field with the first two books entirely dedicated to SoS. In 2005, he proposed his own definition of SoS based on Maier's work: "System of Systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development." [8].

Moreover, in 2008, the author identified the lack of management and implementation techniques for SoS engineering [9]. While he tried to bring clarity on many aspect, in this review the focus is posed on two key issues: SoS architecture and simulation.

Regarding SoS architecting, the author argues that the dynamic nature of modern environments and operational conditions necessitates system architectures that effectively support the scenario to be represented while also being able to evolve and adapt to changes that might occur. Moreover, the component systems and their architectural constraints impact the SoS capabilities, and this further complicates the task of developing a SoS architecture. Components and functions should be added, removed, and modified as the owners of the SoS gain experience and use the system. The concept of meta-architectures is then introduced as proposed solution to the problem. Meta-architectures are constituted by collections of different system architectures.

When it comes to simulating a SoS, the author highlights the need of a common language for the different systems to communicate. He brings an example where Extensible Markup Language (XML) is used in an SoS architecture to wrap data from different systems in a standardized format. He emphasizes the benefits of XML in representing data and providing additional information for improved decision-making within the SoS. The case study mentioned involves the DEVS platform and a master-scout rover architecture, showcasing the practical application of the XML-based SoS architecture.

Another important name in the field of SoS is the one of Dan Delaurentis. In 2005, the author shifts the focus from the definition of SoS to the analysis of the key features identified by other contributors. To do so, he proposes a lexicon and a method for SoS design [10]. The author identifies the need for an effective language to allow efficient communication over the topic of SoS. As shown in Figure 3.3, this is based on two structures: categories of systems and level of organization. Four levels and four categories are shown as an example, but there could be in any number depending on the problem. Each category has a hierarchical structure based on the levels. Greek letters are used to represent each level. Level α represents the most simple entities which combined can construct a β level network and so on. The pyramids in Figure 3.3 are an attempt of the author to graphically represent the organizational idea introduced. This representation conveys the idea that the structure and organization of higher levels dominate the SoS behavior, not the characteristics of the α level entities.

Categories	Descriptions
Resources	The entities (systems) that give physical manifestation to the system-of-systems
Economics	The non-physical entities (stakeholders) that give intent to the SoS operation
Operations	The application of intent to direct the activity of physical & non-physical entities
Policies	The external forcing functions that impact the operation of physical & non-physical entities
Levels	**Descriptions**
Alpha (α)	The base level of entities, for which further decomposition will not take place. α-level components can be thought of as building blocks.
Beta (β)	Collections of α-level systems, organized in a network.
Gamma (γ)	Collections of β-level systems organized in a network.
Delta (δ)	Collections of γ-level systems organized in a network.

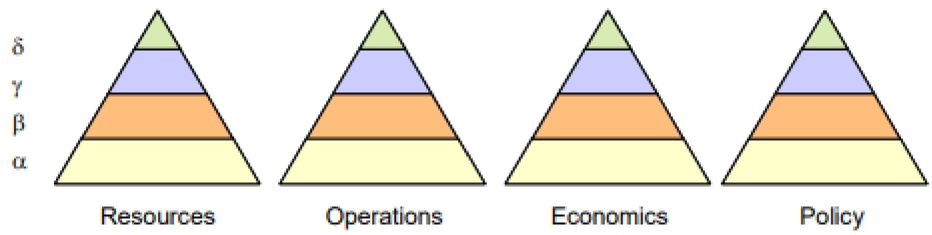


Figure 3.3: Example of SoS lexicon [10].

The approach to SoS architecting proposed by Delaurentis [10] is more practical than the one earlier presented from Jamshidi. The author formulated the so called "Proto-Method", which provides a three steps procedure to represent and simulate a SoS. The first phase, "Definition phase", is one of understanding. Here, the SoS obejct of study needs to be defined with its different categories and levels. One example is provided for the transportation SoS in Figure 3.4.

In the second phase, "Abstraction phase", the goal is to organize and categorize entities and their relationships within the SoS. The author introduces two pairs of entity descriptors: explicit-implicit and endogenous-exogenous. These descriptors are not meant to break down entities into separate pieces but rather to articulate their inherent natures. Based on these descriptors, four entity categories are identified: resources, stakeholders, drivers, and disruptors. These entities are interconnected by networks that define their linkages and relationships. To better understand these concepts, the example of the transportation SoS is continued, and the second phase is developed. Resources, such as vehicles and infrastructure, are explicit entities that consumers physically experience during travel. They are also considered endogenous since they are partially or fully controlled by the architect of the transportation system. Stakeholders, on the other hand, are implicit entities that desire to exert influence on the architecture for their own interests. They can be individuals or organizations involved in the transportation ecosystem, each having their own objectives. The transportation environment also encompasses exogenous entities that are beyond the architect's control. Driver entities are influenced by economic, societal, and psychological circumstances, indirectly affecting the stakeholder network. Disruptor entities, on the other hand, explicitly impact the resource network by reducing its efficiency or disabling specific nodes or links.

The concept of networks plays a crucial role in both the Definition Phase and the Abstraction Phase. Networks define the connectivity between entities, with nodes representing entities and links representing their relationships. In transportation, networks exist within both the resource domain (e.g., air transportation resource networks) and the stakeholder domain.

In the last phase, "Implementation phase", the network drawn in the abstraction phase is implemented in a simulation. The author outlines alternative system views with respective simulation methods, and possible schemes for effective implementation.

Four system views and related methods are proposed: Systems of Hierarchical Mappings with Decomposition Methods; Systems of Uncertain State Equations with Control Theory; Systems of Discontinuous Nonlinear Models with Chaos Theory and Networks; Systems of Autonomous Agents with Agent Based Modeling (ABM). System dynamics and ABM differ from traditional aerospace vehicle design approaches and address important

Level	Resources	Operations	Economics	Policy
α (9 10^6)	Vehicles & Infrastructure (e.g. aircraft, truck, runway)	Operating a Resource (Aircraft, truck, etc.)	Economics of building/operating/buying/selling /leasing a single resource	Policies relating to single resource use (e.g. type certification, flight procedures, etc.)
β (9 10^4)	Collection of resources for a common function (an airport, etc)	Operating resource networks for common function (e.g. airline)	Economics of operating/buying/selling /leasing resource networks	Policies relating to multiple vehicle use (e.g. airport traffic mangt, noise policies, etc.)
γ (9 10^2)	Resources in a Transport Sector (e.g. air transportation)	Operating collection of resource networks (e.g. ; commercial air Ops)	Economics of a Business sector (e.g. Airline Industry)	Policies relating to sectors using multiple vehicles. (safety, accessibility, etc.)
δ (9 10^1)	Multiple, interwoven sectors (resources for a national transportation system)	Operations of Multiple Business Sectors (i.e. Operators of total national transportation system)	Economics of total national transportation system (All Transportation Companies)	Policies relating national transportation policy
ε (9 10^0)	Global transportation system	Global Operations in the world transportation system	Global Economics of the world transportation system	Policies relating to the global transportation system

Figure 3.4: Transportation SoS lexicon matrix [10].

aspects of SoS problems: evolutionary and emergent behaviors.

Regarding possible schemes for SoS implementation, Delaurentis focuses on the instantiation of networks and entity models into an effective, flexible, comprehensive, and verifiable simulation architecture. To test various hypotheses, especially at the upper levels of organization, the chosen system views, associated methods, and data from different levels need to be combined. The text suggests that an Object-Oriented (OO) approach is well-suited for this task. In an OO approach, objects are constructs that are responsible for themselves and can be called by other objects to solve specific problems. When a computer program representing the problem is run, objects utilize their methods and data in a self-contained manner.

The author argues that an OO implementation paradigm is necessary to achieve the desired objectives in a SoS problem. Although the OO approach is now standard in many domains, there are still areas, such as aircraft design, where this shift is in its early stages. The use of generalized and abstract objects with attributes and methods that modify those attributes is believed to generate the holistic views required for system-of-systems analysis. Additionally, OO constructs facilitate the rapid exchange of model entities and networks within a transportation system analysis environment.

3.2 Seaplane System of Systems

In this section Delaurentis' approach [10] to SoS is used to outline the Seaplane SoS. Looking at the structure proposed by the author, it is possible to say that a SoS could be extended to increasingly higher levels. For this reason, the seaplane SoS can be identified as a related system to the larger transport SoS, therefore the work of Delaurentis [10] on applying a SoS framework to the National Transport System can be used as guideline in shaping the seaplane SoS.

In the definition phase, the lexicon matrix introduced by the author can be used to identify and classify component systems of the seaplane SoS. In Table 3.1, the main levels and entities within each level of the seaplane SoS were identified. At α level, there are the most basic components of the SoS: seaplanes intended as aircraft, runways, docks are good examples. At the same level, operations of the single entities, the economics behind this operations, and the low level rules and procedures that apply to building and operating the single resources are found. Going up one level, the first "systems" are defined. Here, the resources are collection of the basic entities earlier defined which "collaborate" in a common function. Moreover, at β level, the operations of these resource networks, their economy and policies are considered. In the third level, γ, resources for an entire sector are considered. An example is the entirety of the resources needed for passenger transportation operations, which again can be seen as networks of lower level resources. Following the example of the passenger transportation sector, it could be said that the resources at this level are the ensemble of seaports, airports, pilots, and many others. Moreover, operations, economy and policies regarding an entire sector are discussed at this level. Level γ is the higher level of the seaplane SoS where different sectors interact with each other. To get a clearer picture of this level, it is possible to think at the interaction of the tourism, passenger transportation, and meteorology sectors (systems). For example, when a week of good/bad weather is forecast, tourism will be affected, and as a consequence the passenger transportation sector might see higher/lower demand.

The structure introduced with Delaurentis' lexicon for the seaplane SoS will be used as a starting point for further exploration of the different entities and systems involved in Section 3.3.

Level	**Resources**	**Operations**	**Economics**	**Policy**
α	Seaplane, runway, dock, etc.	Operating single resources	Construction, sell, rent, etc.	Certifications, procedures, etc.
β	Seaport, etc.	airline, mission, etc.	Service operation, sell, lease, etc.	Air traffic, water traffic, noise etc.
γ	Resources for transportation, firefighting, etc	Passenger/cargo transportation, wild fire suppression, etc.	Seaplane industry, tourism, etc.	Safety, accessibility, etc.
δ	Interwoven sectors	Operation of interwoven sectors	Economics of overall system	Overall policies

Table 3.1: Seaplane SoS lexicon matrix.

Following the definition phase, there are enough elements to verify the nature of the seaplane system, and to assess its traits in order to be defined a SoS. For this purpose, the five characteristics identified by Jamshidi [8] will be investigated for the seaplane system, and according to the author, in case the presence of the majority of them is identified, the seaplane SoS can be formally recognised. In Table 3.2, the SoS traits are discussed for the seaplane system. Operational and managerial independence are treated together.

SoS Trait	Seaplane SoS mapping
Operational and managerial independence	Although interconnection at high level was highlighted earlier, component systems operates completely independently to each other; e.g. "Meteorology" and "Tourism" function as stand-alone system.
Geographic distribution	Looking at the different resources identified before, it is easy to picture the geographic distribution of component systems; e.g. the location of infrastructures
Evolutionary behavior	This trait can be recognised when looking at the history of seaplanes: their role has been changing over time, and it will probably continue to do so.
Emergent behavior	Identifying the trait of emergence is difficult [10], however it is possible to say that in this case the “whole is greater than the sum of the parts” [10], therefore emergent behavior can be present.

Table 3.2: Mapping of SoS traits to the Seaplane SoS.

In conclusion, it is possible to state the existence of the seaplane SoS, and the goal is to fully describe it within this literature survey. The second and third phases, abstraction and implementation of the SoS, are out of the scope of this study. They will be briefly discussed in Chapter 8, but they will only be tackled in the MSc thesis project.

3.3 Component systems

In this section, a deeper exploration of the most influential component systems of the seaplane SoS is carried out.

Through the research conducted by various authors in the past, different perspectives on the seaplane system have been explored. These perspectives have allowed for the identification of several component systems that are involved in the seaplane System of Systems. The study of Odedra et Al. [11] highlights the close relationship between the operation of seaplanes and the infrastructure supporting a seamless and efficient flying experience. According to their research, this infrastructure encompasses various services, facilities, and organizations involved in seaport operations. According to Smethers et Al. [12], the operation of seaplanes also necessitates consideration of meteorology, oceanography, and ecosystem preservation and wildlife protection rules. Another important system to be considered in this review is the one of airliners as it became evident during the studies performed in the project FUSETRA [13]. In addition, to complete the picture of the seaplane SoS, an overview of the different missions is needed to identify more stakeholders. Indeed, seaplanes have diverse applications beyond passenger transportation. They can be utilized for cargo transportation, firefighting, search and rescue, military operations, and sport and leisure.

The entities and systems considered relevant will be discussed following the structure of the lexicon matrix presented in Table 3.1. Starting from level γ, the main sectors involved in the seaplane SoS will be tackled separately. For each one, resources, operations, economics, and policy will be identified and decomposed in more basic entities if needed. The primary focus is posed on the "passenger and cargo transportation" sector. In particular, the objective is to gain understanding of resources and operational dynamics of this sector. For completeness, other systems were also analysed with the intent of bringing light on possible features overlaps, compatibility and dependencies within the different sectors in the seaplanes SoS.

Figure 3.5: Seaplane System of Systems.

3.3.1 Passenger and cargo transportation

Passenger and cargo transportation sectors are addressed together in this section. This choice was due to the high commonalities of the two sectors.

Resources

At the γ level of the matrix (Table 3.1) there are the collection of resources (networks) that form sectors. The sectors can be decomposed into an ensemble of basic functions (β level), and from there, the single entities can be detailed (α level). For the passenger and cargo transportation sector, the main functions are listed and commented below.

- Seaports are probably the most obvious function when talking about seaplane transportation. A seaport is a particular kind of airport based on a water body, equipped for seaplanes operations. Specific entities for this special -port configuration are:
  - Float planes dominates over flying boats thanks to their accessible cost.

  - Docking facilities, which differ for amphibian and standard seaplane configurations. The firsts occur ramps for moving from water to ground. The seconds make use of floating or fixed docks to allow accessibility to the cabin.
  - Hangars, or equivalent facilities. While amphibian seaplanes can be displaced in conventional hangars, for standard seaplanes is not as easy. Mooring at a buoy is an option some airliners adopt. However, the problem of corrosion, especially in sea water is something to take into account. Another possibility is dry docking, in this case the seaplane would not be always ready to operate as the maneuvers for dry-docking are slow and expensive. It can be done with cranes, cradles or winch systems. [11]
  - Refueling stations are again conventional for amphibian seaplanes. However, it requires special equipment to refuel aircraft from the water. A system similar to the one used for ships could be adopted, and refuel at the dock, or a more complex system could be installed to refuel at a buoy, in order to decrease traffic at the dock [11]. A similar approach can be considered for battery charging in case of electric vehicles.
  - Pilots can be considered a resource part of seaports. The results of a survey performed during the FUSETRA project [13] show the scarce availability of pilots in Europe. However, it needs to be considered that the low demand might be cause of the low offer.
  - Marking and lighting of the water area [14].

- Conventional airport could be used by amphibian seaplanes.
- Hospitality structures such as restaurants, hotels, parking, should be provided in the surroundings of seaports for passengers and staff.
- Hydrometeorological stations for monitoring weather and water surface conditions are needed in proximity of seaports according to Voloshchenko [15]. This concept will be further elaborated in the sections dedicated to oceanographic and meteorology sectors.

Operations

After the resources of the passenger and cargo transport sectors were defined, it is possible to explore the related operations. Here, insight on airliners/operators of these sectors is provided. The work of Mohr and Shomann [13] was investigated, and cross checked with internet researches to verify the current state of information.

Today's air market is dominated by conventional aircraft and there is little space left for seaplanes. The few in circulation are mainly operated in the passenger transport sector, over the North American continent. Only few of these airliners provide scheduled flight connections, most operators are in the business of private charters and tours, sport, and adventure expeditions. The operators in this group often adopt float planes for their activities, in particular old De Havillands and Cessna aircraft featured with floats purchased from third parties, and assembled in house. Few operators boast brand new aircraft such as Tropic Ocean Airways, which has a partnership with Cessna (providing Cessna Caravan) and Wipline (providing the floats). More operators are found around the globe, Australia, Japan, Maldives, and different European countries above the others.

In Europe, the market of seaplanes is not flourishing. They are operated for excursions, flight schools and in very few cases as connections on passengers routs. In the last two decades, many small business opened, and as many closed, in particular in the United Kingdom and in the Scandinavian countries. Only one or two family business survive today in the UK, providing the only service of flight school and some touristic excursion on particular request. In Norway, few more airliners are active, and in some occasions scheduled connections are also provided there.

Economics

The "economics" category aims to represent the businesses and economic benefits developed around/in a certain sector. For the seaplane transportation sector four main market segments were identified.

First, the seaplanes market intended as construction, sell, leasing of the product seaplane. This segment can be further decomposed in float-planes and flying-boats markets. Float-planes are by far the dominant product of the transportation sector. However, no producer of float-planes could be identified in this study. It resulted that the large majority of aircraft in this sector are conventional land-planes later modified with floats. Many airliners work on this modifications in house, and also few companies are specialised on this service. Wipline for example works in collaboration with CESSNA, they build and assemble floats on different CESSNA vehicles.

On the other hand, a direct market exist around flying-boats. Dornier is currently the most advanced company in the field. Moreover, this segment is expanding with new companies and products being announced.

Regent has presented an innovative electric sea-glider based on hydrofoil technology, and Jekta is working on a full electric flying-boat.

The airliners market represents the operational side of the business. In this category fall the operators mentioned in the previous section which profit from providing seaplane services. Detailed investigations on the profitability of this segment were performed by Wagner et Al. [16].

Lastly, the pilot business, including pilot training and pilot service, and the maintenance segment. From the survey of project FUSETRA [13], it emerges that these businesses are small, the availability of pilots is defined as critical by the main European operators. Seaplane flight schools find their cut in this sector. Noteworthy the school on lake Como: Aero Club Como, and Loch Lomond Seaplanes in Scotland.

Policy

In this sub-section, the high level policies for the sector will be discussed. Safety and environmental impact were found to be the most relevant.

The safety issue is tackled by different authors under multiple perspectives: safety of vehicles, safety of operation in a seaport, sea traffic management in a multi use seaport.

Voloshchenko [15] focuses on the safety during take-off and landing operation. While procedures for operations on land are well defined, performing these maneuvers on water runways comes with complications. The author suggests a set of requirements that seaports should satisfy to guarantee safe water take-off and landing. These include a water space with sufficient size and depth, floating lighting system, a control and correction station of satellite navigation, a control station for communications, a hydrometeorological station providing air traffic control, and water surface and weather conditions monitoring. Moreover, the author suggests to install sonar and radars on the vehicles to inspect the water way before using it. This is proposed along with a visual inspection of the seaport runway in order to guarantee absence of floating objects which could damage the aircraft. Another means of water surveillance is a net of hydroacustics antenna coupled with shore equipment, of which the author propose a detailed technical explanation.

Levis [14] approaches the safety issues in a broader sense, touching both points of vehicle safety and sea traffic management. Regarding the first, he points out specific regulations: watertight compartments must be considered in a certain number to keep the aircraft afloat in case of a hull breach, emergency exit and flotation devices must be present onboard, the emergency exit should be designed to always be above the waterline, adjusted considering rough sea conditions and flooding of the hull. Moreover, floating escape chutes, similar to those used on current aircraft in case of ditching, can be used as life rafts. The author suggest to use conventional land-plane requirements as a guideline, and to develop for seaplane specific issues.

Contrary to Voloshchenko, Levis states that it is preferred to have unmarked sea lanes for take-off and landing in order to have the possibility of freely adjusting the orientation according to waves and wind, but he recognise the challenge this would bring in seaports operations. Additional requirements for water ways are identified: the water current must be less than 5.5 km/h, maximum wind coverage, and the height and location of potential obstacles to air navigation should be regulated according to ICAO norms. The separation of parallel water ways should be such that waves and turbulence caused by one aircraft do not affect the other. Use of water breakers is suggested for this purpose.

Moreover, regarding sea traffic control, the easier solution would be to isolate the sea base area from the rest of the sea using an offshore breakwater. In this way, the seaplane base would be not accessible to other vessels. To avoid issues from colliding with whales or other animals, the use of submerged netting or repellents to keep such species away may also have to be considered.

Wagner et Al. [16] further detailed the vehicle policies in the certification requirements. They carried out an investigation for vehicles falling into the EASA CS23 category, up to 19 passengers. Requirements for take-off speed, landing distance, stability and control in water, water handling capabilities w.r.t. wave energy are proposed, as well as buoyancy requirements and many others.

In addition, the authors investigated operation regulations and pilot licenses. From a survey, they realised the complexity and high cost of certification procedures for seaport and pilots, with many different authorities being involved in the process. Moreover, they identified and reported key weaknesses in the existent regulation, in particular regarding training and licensing of pilots, flight time limitations, training of dock operating crews and others.

Another important aspect of policies needed for seaplane operations is the environmental one. Protection of the ecosystem, including wild life in water and on the coast should be a priority.

Levis [14] raises awareness on the impact of environmental concerns on design and operation of civil aircraft. He identifies aircraft noise and harassment of bird populations around airports as the main consequences of standard land-planes operations. In seaports operation, noise would not only affect surrounding inhabited areas, but also marine and coastal wildlife. The author argues that the amplitude of the noise is expected to

Noise	dBA	Example
Military jet	120+	
Jet ski	110	e.g. watersports on lake
Chainsaw	100-104	e.g. tree felling/forestry/logging
Grass Cutting	88-100	Golf courses
Tractors	95	e.g. general operations
All terrain vehicles	85	
Speedboat	65-95	e.g. watersports on lake
Seaplane	75	on take-off only @ 300m (20 sec)
Inside car – 30 mph	68-73	
Normal conversation	65	

Figure 3.6: Noise levels for various products [17].

be less than that for boats which use submerged propellers for propulsion. Potentially, by reducing traffic in airports seaplane could contribute reducing the impact of noise emissions of aviation. In this regard, a study performed during the project FUSETRA [17] revealed the low noise emissions of seaplanes Figure 3.6.

Levis also poses light on the fact that seaplanes operating in different locations could be transport non-native/invasive marine organism. In addition, the possibility of fuel and oils as well as other seaplanes emissions contaminating water and air is another concern. In particular when in sea water, where the presence of salt in the combustion process inside thermal engines could release a dioxin known to be carcinogen.

3.3.2 Firefighting and search and rescue

Seaplanes are commonly used as water bomber together with helicopters for wildfire suppression, and deployed in search and rescue missions in open sea. Most of the water bombers are flying boats which store water in a tank in their hull/fuselage. The main advantages of seaplanes operated as water bombers are the possibility of scooping water from the sea to fill their thanks, and their high speed (w.r.t. helicopter).

In this section, the main resources, operations, economics and policies around the firefighting and search and rescue sectors are presented together due to the high commonalities.

Resources

Seaplanes used in the firefighting sector are mainly flying-boats, and only a few examples of float-planes. These are mounted with a water (or other fire extinguishing substances) tank. Among the requirements for wildfire suppression and search and rescue missions, rapid intervention is priority. Due to the complexity of dry docking operations for standard seaplanes, the aircraft employed in these missions are often amphibian. Moreover, firefighters are often featured with scooping mechanism, and equipped with high power to weight ratios to guarantee high climb rate for steep climbing during water dropping operations.

In the search and rescue maritime sector, Brown [18] suggests that short takeoff and landing performance are important requirements. For this purpose, seaplanes operated in this sector such as the Japanese Shin Meywa, mount leading and trailing edge high lift devices. In addition, hydrodynamically efficient deep-V hulls and long length-to-beam ratios are needed for good sea handling. The possibility to operate even in rough seas is a strict requirement. The Shin Meywa single step hull design and spray skirt add to the quick planning ability of the craft. This design permits landings and takeoffs in high sea states with waves running eight-to-thirteen-feet high. The flight deck is set high for good visibility.

More resources regards the special equipment needed on board of seaplanes for these missions. Search and rescue aircraft must carry floating devices such as an inflatable dinghy. A large sliding door or ramp is needed to deploy these and to allow easy access to the cabin. Litters and first aid medical equipment are also needed [18].

In both sectors, the use of amphibians ease the requirements on infrastructures: no special seaports facilities are used. The only resources in this regard are dedicated hangars and runways.

Concerning the man-power for these missions, special pilot/rescuers training is essential in both cases due to the special maneuvers involved.

Operations

Firefighting and search and rescue operations are in most cases managed by national entities. According to Gobbi et Al. [17] many countries in Europe (Italy, Croatia, Spain, France, etc.), as well as the European Union itself, dispose of a fleet of seaplanes, mostly Canadairs CL 215 and 415.

A noteworthy example of active operations in these sectors is the one of the Japanese Maritime Self-Defense Force (JMSDF). The Shin Meiwa US-JAs is a multipurpose flying-boat which is commonly operated in Japan for open-ocean search and rescue as well as support or evacuation of victims from remote islands which do not have runways [18].

In Figure 3.7, the location of offshore missions where the Japanese aircraft was successful (on the left), and its operating limits (on the right). The latter figure shows the operational limits of the US-JA (in light blue) against those of common flying-boats (in dark blue). The figure reveals a neat superiority of the Shin Meywa flying-boat in rough seas. This aspect is further investigated in the section dedicated to oceanographic.

Economics

Canadair, Beriev and Fire Boss are the most used seaplanes for firefighting, according to Gobbi et Al. [17]. This market segment is really small as only 1% circa of seaplanes in circulation operates in this sector [13]. However, Gobbi et Al. [17] recognised the market potential and they see the possibility of seaplanes dominating it if new designs with water payload capacity in the range of 4 tons are produced and purchasing and operating costs of the vehicles are reduced.

The biggest competitors of seaplanes in the firefighting and search and rescue sectors are helicopters. While they can easily be adapted for different missions, seaplanes, in particular when designed as water bomber, can hardly serve different purposes, meaning that a fleet of firefighting seaplanes would sit unused most of the time. To obviate this problem, Wagner et Al. [16] suggest flexible water tank equipment in order to have convertible aircraft able to serve the market more efficiently. In the same way, first aid packages and devices for ambulance transport could be installed in special racks using the seat rails.

On the other hand, the higher speed, the possibility of landing on water, the higher payload capacity, and possibility to spend more time on station thanks to higher fuel availability, make seaplanes better than helicopters especially for search and rescue missions [18].

Apart from the market leaders Canadair, Beriev and Fire Boss, only two companies were found to be profiting from these sectors. AVIALSA [1] is a Spanish company operating Fire Boss aircraft with low purchase and operating cost for an efficient private firefighting service. Babcock [2] is an international defence company which serves multiple countries as clients. It provides private services for firefighting as well as search and rescue.

Policy

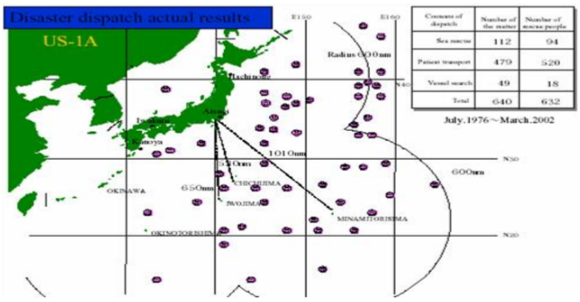
In the category "policy", for the sectors firefighting and search and rescue, the procedures and safety measures needed in this missions will be identified.

Mosov and Horskyi[19] perform a broad research of the current state of firefighting in different European and extra-European countries. It emerged that important policies regard the procedures of water scooping and dropping. In particular regarding water scooping in open sea, where the risk of causing accidents with other vessels is high.

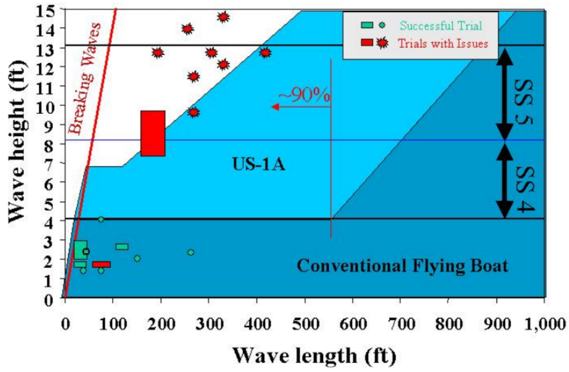
Moreover, regarding firefighting missions management, the authors highlighted the central role of fire detection strategies.

Environmental protection is an important topic which concerns the firefighting sector in particular. In this regard, it is needed to stress the compromise between the damages to the environment caused by a wild fire and those caused by the fire suppression mission. More in detail, one issue is to understand the drawbacks of sustainability policies in the firefighters design on the time needed to extinguish a fire (considering damages and emissions caused by the fire itself). Another problem concerns the means used to suppress wild fires: flat water against sea water or chemical fire retardant, and their effects on the ecosystem of the areas subject to the bombing.

[1] AVIALSA https://aerialfiremag.com/2018/08/26/at-802-firebomber-fleet-of-nine-in-spain/
[2] Babcock, emergency services https://www.babcockinternational.com/what-we-do/aviation/emergency-services/



(a) Operating limits in terms of range.



(b) Operating limits in terms of sea handling

Figure 3.7: Shin Meiwa successful missions and operating limits [11].

3.3.3 Military

Seaplanes were operated in the military sector since WWI, and their success continued during WWII as well. However, most fighters/bombers seaplanes were then converted to water bomber or dismissed [2]. According to Odedra et Al. [11], no seaplanes are currently operated by the US Navy or Coast Guard.

However, in the technical report "Seaplane Economics: A quantitative cost comparison of seaplanes and land planes for Sea Base operations" [20], the US Naval Surface Warfare Center investigates the Sea Base concept and propose the integration of seaplanes in its operations. Moreover, the Defence Advanced Research Project Agency (DARPA) is already working on a seaplane prototype.

Resources

In the military sector, the concept of seaplanes is often coupled with the one of Sea Base. The resources involved span from seaplane military technology to the component of Sea Bases.

Denz et Al. [20] define a Sea Base as a "collection of ships at a common location, typically 25 to 250 nautical miles off shore". The authors add that it might include innovative ships as well as floating platforms, which provide the great advantages of a mobile and safe base.

Regarding seaplane technology, the authors mention the primary scope of cargo transportation, which would set requirements for high payloads. Moreover, wing in ground effect and other innovative technology could be adopted thanks to the high budget in the military sector.

Smethers [12] points out more resources needed for military operated seaplanes: detection and communications equipment, defensive and offensive weapons, specialized crew. In addition, the author identifies technologies for the effective operation of seaplanes in military missions. Above all, an innovative hull design allowing rough sea handling while limiting the oscillations so that the crew is able to perform useful work while sea-sitting.

Operations

Four main military operations which seaplane could contribute to are identified by Denz et Al. [20].

- Force closure, which involves the transport of troops and equipment.
- In flight refueling, which means seaplanes could be used as tanker planes to refuel other aircraft at the combat zone.
- Maritime patrol is a mission profile similar to search and rescue earlier analyzed. Seaplanes would be employed for surveillance over an area and rescuing in open ocean.
- Casualty evacuation, it is a mission defined as rescuing troops from a casualty area and bringing them to the closest hospital.

Moreover, Smethers [12] suggested more specific mission profiles such as ship fleet re-supply, submarine crew evacuation, support for diving operations, mine-sweeping and convoy protection.

Economics

The economics behind the use of seaplanes in the military sector is analysed by Denz et Al. [20]. The authors evaluate the costs of Research and Development (R&D) as well as operating costs of seaplanes for the categories of missions listed in the previous paragraph. The costs per mission are then compared to the ones of conventional land-planes currently used in military operations.

From this analysis, it emerges that the use of seaplanes would be economically justifiable under certain circumstances. In particular, with an advantageous location of the Sea Base w.r.t. the mission location, operating seaplanes could be cost savings for the US Navy [20].

Policy

The lack of examples of seaplanes in use in the military sector makes it hard to identify specific policies. It is possible to assume that the development of the Sea Base concept will need to be integrated with regulation regarding constructions of platforms and procedures for their operations.

3.3.4 Meteorology

In this section, the importance of the sector meteorology within the seaplane SoS is highlighted. Meteorology will not be approached considering the categories presented by Delaurentis [10], as such a broad exploration was considered not relevant for the scope of this study.

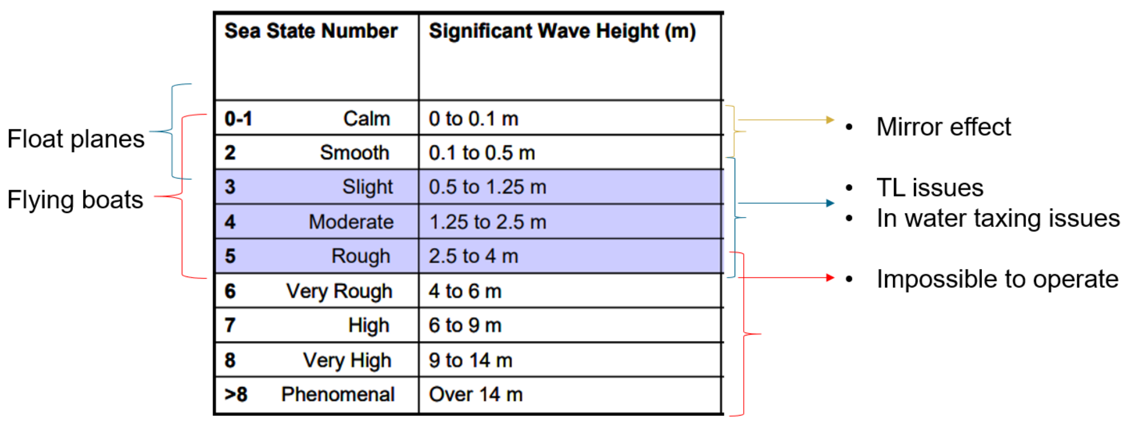
Weather conditions put concise limits on seaplane operations. While thunders and strong wind present blockers for any type of air vehicle, there are atmospheric phenomena affecting seaplanes in particular. Seaplanes can actually handle strong wind conditions well thanks to the flexibility of runways. Pilots can always adapt landing and take-off direction according to the wind. However, wind is a problem when it interacts with the water provoking high spray. Water entering the engines is one of the main causes of failure.

Moreover, icing is a considerable limiting factor for seaplane operations. The probability of such an event is higher for seaplanes than for conventional aircraft due to the water sprayed during take-off and landing [12]. Lastly, fog and darkness pose boundaries on operations as, of today, seaplanes operate under Visual Flight Rules.

3.3.5 Oceanographic

In this section, the same approach as for the sector meteorology is taken for oceanographic.

Sea state is one of the most important factors to be considered for seaplanes operation. The current technology allows float-planes to only operate in smooth and calm water (sea state lower than 2), while flying-boats can operate in sea state up to 5, in some occasions, with a maximum wave height of 3 or 4 meters as shown in Figure 3.8 [20].



Sea State Number		Significant Wave Height (m)
0-1	Calm	0 to 0.1 m
2	Smooth	0.1 to 0.5 m
3	Slight	0.5 to 1.25 m
4	Moderate	1.25 to 2.5 m
5	Rough	2.5 to 4 m
6	Very Rough	4 to 6 m
7	High	6 to 9 m
8	Very High	9 to 14 m
>8	Phenomenal	Over 14 m

Figure 3.8: Sea state overview [20].

The effect of waves and swells should also be addressed considering passenger/crew comfort, and not only in key of vehicle operating limits. Indeed, the fact that the aircraft is able to withstand some sea conditions, it does not imply that the crew and/or the passenger can do the same. Results of a research on the oscillation of seaplanes due to swells are presented by Odedra et al. [11]. In Figure 3.9, these results are depicted in a graph indicating the pitching motion of the aircraft as function of time in swells of 0.5 to 1 meter circa. Heavy oscillation can cause motion sickness, discomfort and can represent an obstacle to the crew operations.

In this regard, it is worth mentioning that Mediterranean, Baltic and North sea commonly experience waves higher than 2 meters in the winter times and occasionally during summer as well. Figure 3.10 by Oceanweather inc. [3] shows the sea state in the Mediterranean sea during a random winter day. As it emerges form the map, sea conditions are quite rough with waves often exceeding one meter height even in the coastal areas, making it almost impossible for float-planes to operate, and still challenging for flying-boats.

The case of the Shin Meywa flying-boat earlier introduced is used as an example to show the state of the art regarding sea handling performance. In Figure 3.7, it appears that the amphibian can land in sea state 4 and 5, but the wave length must be more than two hundred feet circa in length.

Studies were conducted by the JMSDF and Shin Meiwa to match the US-JAs' performance capability against the characteristics of the ocean waters surrounding Japan. Sea states and wave periods were measured and averaged in the Sea of Japan and the Northern Pacific. These studies indicated that the US-JA would be operable 77 % of the time [18].

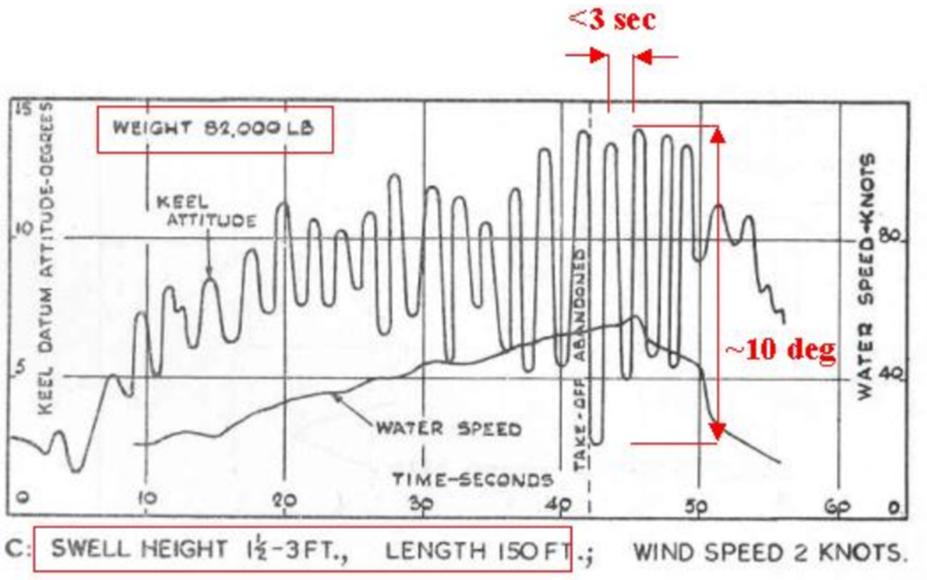


Figure 3.9: Effect of swell of length comparable or larger than aircraft length [11].

[3]Oceanweather inc. `https://www.oceanweather.com/`

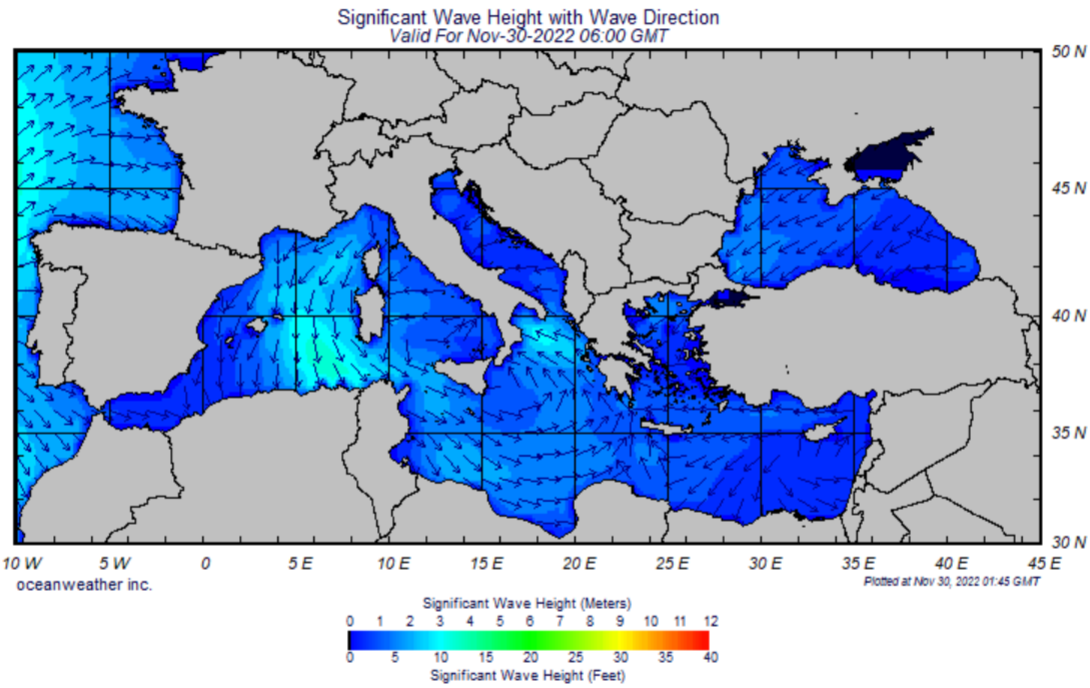


Figure 3.10: Marine data by Oceanweather.

4

Seaplane design

Seaplane design is considered by Elmar Wilczek a "forgotten art" mastered only by few still carrying the experience gained during the wars [21]. Most of the knowledge developed in the past was lost or put aside in the back of old archives, according to the author. The progress achieved in aircraft design did not involve seaplane design, and this literature study revealed the lack of modern approaches to this discipline. The most relevant research found on this topic were the ones from Canamar [22], Cary [23], and Levis [14]. The latter being the most advanced of the three in terms of complexity and completeness.

Levis [14] developed a conceptual design of a Blended Wing Body (BWB) seaplane. The author used semi-empirical methods for the geometry and mass sizing of the aircraft as well as for the hydrodynamic characteristic of the hull, and he worked out a Vortex Lattice Method for the aerodynamics analysis. The methods used were then synthesised in a tool written in FORTRAN, intended to allow for the analysis of parametric variant of the baseline configuration. The limitations of this tool include the fidelity of the aerodynamic model as well as the hydrodynamic performance estimation methods. In particular, the take-off and landing distances result to be much under-estimated according to Levis [14]. Moreover, the tool works with BWB seaplanes only, and it is limited by the choices made by the author in setting the baseline configuration.

Due to the scarcity of information regarding complete tools for overall seaplane design, it was decided to perform specific research in each of the most relevant design disciplines of seaplane design. Therefore, the following sections tackle separately the geometry and mass sizing of the vehicle, the aerodynamic and hydrodynamic analysis, and the power train design. At last, one section is dedicated to performance analysis.

4.1 Geometry and mass sizing

Sizing the overall geometry and masses of an aircraft is the very first step of conceptual design. Multiple methods exist in literature to estimate the main geometrical features and masses of a conventional land-plane, the most well known are those of Torenbeek [24] and Raymer [25]. However, due to their unique features, seaplanes need ad hoc methods.

In his PhD thesis, Chiken [26] explored seaplanes conceptual design, and he proposed new sizing methods based on a statistic study over a large database of seaplanes. The author focused on geometry and weight estimation of the buoyancy devices, including volume, area, and mass of floats and hull, as well as their position and orientation relative to the aircraft's center of gravity.

OpenAD [27] is a software platform for conceptual aircraft design and sizing developed by DLR. It is based on publicly available textbook methods and DLR custom methods. In particular, its extension OpenAD - Seaplane was programmed by putting together conventional methods with the ones introduced by Chiken for seaplanes. The software not only allows for seaplanes geometry and mass sizing, it is designed to facilitate the design of new aircraft configurations, including engine performance, basic aerodynamic analysis, systems, and mission analysis. The software is highly customizable, and the parameter attributes allow for simple and efficient manipulation of every parameter within the knowledge base. One of the key features of OpenAD is its ability to interpret CPACS tool-specific data as input, allowing users to easily define calculation settings and manipulate calculation parameters. OpenAD's parameter attributes include value, unit, factor, status, cpacsPath, and upper and lower bounds. The software provides an estimate run and a full calculation execution with convergence criteria and different parameter statuses.

4.2 Aerodynamics

Seaplane aerodynamics is heavily affected by the presence of hull and floats. With conventional aerodynamics methods, it is possible to try and catch the effects of the hull shaped fuselage and the floats. The most challenging part is to quantify the effects of hard chines and backward-facing steps which characterise the under-belly of flying-boats. While many authors neglected these factors and chose to use conventional semi-empirical models in their conceptual design workflow, few tried to tackle the issue with innovative approaches.

Hoerner [28] investigated aerodynamics of flying-boats hulls, and showed the impact of hard chines and steps. The latter were found to affect aerodynamic drag the most. The author proposed a method for two-dimensional steps in a turbulent boundary layer to assess the impact of hull steps. The method only applies for step heights smaller than 90 % of the boundary layer thickness at the step location. Moreover, when comparing the results to experimental data, the drag was found to be under-estimated by up to 50 % of the measured force.

Levis [14] approached the problem differently. The author decided to use a VLM solver for the estimation of aerodynamic pressure loads. Moreover, he introduced a novel method to account for the effect of the step on his flying-boat. The BWB flying-boat is approximated with lifting surfaces of zero thickness, and the viscous contribution to drag are estimated with the component buildup method presented by Raymer [25]. The step effects on drag were measured with an empirical expression based on the comparison between the results of CFD runs for stepped airfoils and a panel code coupled with an iterative viscous-inviscid matching algorithm. In this way, the drag increase on stepped section w.r.t. conventional section was estimated.

From Levis' analysis, it emerges that the key parameters affecting the aerodynamics of flying-boats are length to beam ratio, step depth, and afterbody angle.

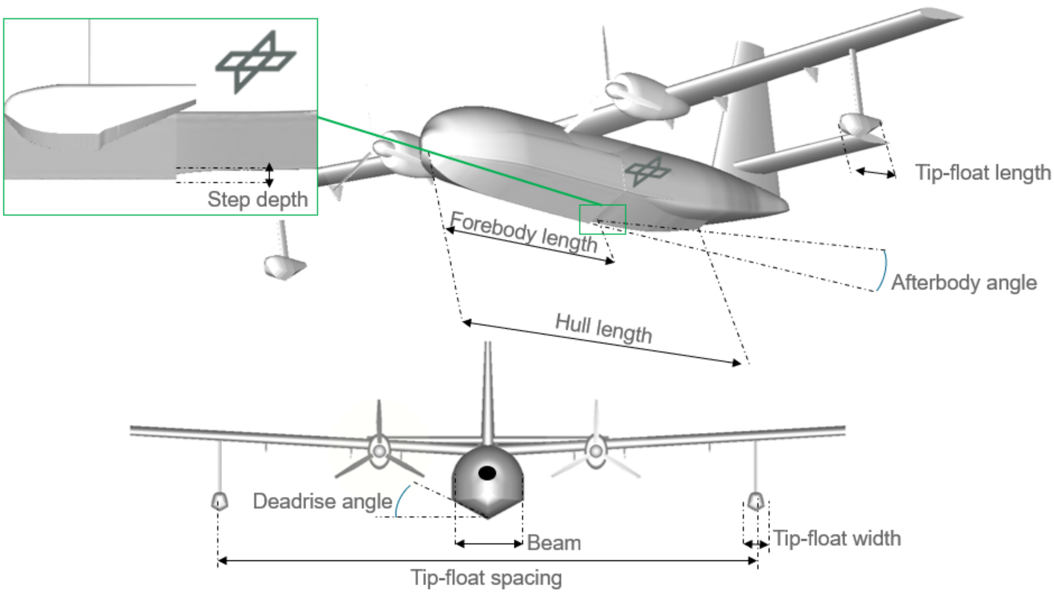


Figure 4.1: Flying-boats main geometrical parameters.

4.3 Hydrodynamics

The discipline of hydrodynamics studies the forces applied to a planing surface in water. There are two types of force which a hull is subject to when on water: hydrostatic force (buoyancy) described by Archimede's principle, and hydrodynamic force, which depends on the water density and viscosity, and the speed of the vehicle (proportional to the speed squared) [29].

Masri et Al. [29] define the fundamental parameters for planing hulls: speed, displacement, longitudinal length, beam length, trim angle, dead-rise angle and longitudinal centre of gravity. Moreover, the authors introduce a classification of the different hydrodynamic resistance prediction methods available: analytical, graphical, planing hull series, numerical, statistical, and experimental. These techniques are summarised in Figure 4.2.

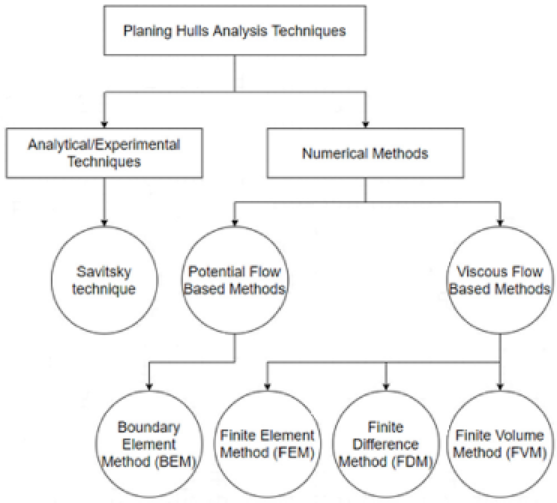


Figure 4.2: Performance prediction methods [29].

Yinggu et Al. [30] built off the well known Savitsky semi-empirical methods, and proposed some equations to estimate the hydrodynamic drag and lift forces and coefficients acting on a flying-boat hull. However, they do not attempt to estimate take-off and landing distances due to the complexity of the phenomena. Moreover, the method is based on Savitsky assumptions of constant speed, constant dead-rise angle along the hull, constant equilibrium trim angle, and and a constant beam length. The method does not perform well when the trim angle is larger than 4 deg and the dead-rise angle is higher than 50 deg. However, Yinggu et Al. proposed an equation to predict the whisker spray drag which was excluded from Savitsky approach.

Shuford method is also discussed by Masri et Al. [29]. This approach is similar to Savitsky's one therefore, it possesses the same limitations, with the exception of the trim angle one. Shuford approach is applicable to high trim angles (between 8 and 18 deg). Other methods investigated by Masri et Al. are those of Morabito, Payne, and the CAHI method. The authors concluded that "available analytical methods lack the ability of predicting the stability limits of the craft. Moreover, most of the methods discussed are valid under certain geometry and conditions." [29].

Simulating the hydrodynamics of a hull is extremely challenging and expensive. In the past, NACA performed numerous tank test in an attempt to predict the performance of specific hull shapes. Example of these tests are found in the reports from Davidson and Locke [31], and Hugli and Axt [32]. The issue with tank tests is represented by the high cost and the challenge in reproducing in such tests the planning motion of the hull, which is driven by the interaction of the hydrodynamic forces caused by the hull shape and the aerodynamic forces caused by the lifting surfaces.

Seth et Al. [5] predicted take-off length of an hydrofoil - seaplane making use of a CFD surrogate model. However, the authors focused the study on the effects of the hydrofoil on the seaplane rather than trying to explore and validate a performance prediction algorithm.

Chinvorarat et Al. [33] carried a take-off performance analysis of an amphibian making use of the relations defined by NACA between speed and hydrodynamic resistance of hulls in the experiments mentioned above. Moreover, the authors simulate the take-off run of the vehicle in a two phases CFD analysis. From the article, it emerges that the water resistance coefficient as function of speed coefficient and trim angle are two key parameters in the takeoff performance analysis of seaplanes.

4.4 Powertrain design

During the literature study on seaplanes design, no relevant research pertaining to seaplanes propulsion systems was identified. As a consequence, an exploration of innovative powertrain solutions applicable to various aircraft types was undertaken, with the intent of acquiring a broad understanding of the subject matter. This serves as a foundation upon which to build new knowledge in the discipline of seaplanes powertrain design in the course of the MSc thesis.

Bertram et Al. [34] analysed the impact of multiple architectures on Urban Air Mobility (UAM) vehicle concepts. This study revealed that currently there are 6 main generic architectures as shown in Figure 4.3. Although their research was focused on UAM, it is possible to generalize the evaluation criteria identified by the authors for the architecture choice. The first three criteria concern weights, three more regard required power, energy efficiency, and charging power. Figure 4.4 provides an overview of the relative weight of the different configurations (Φ indicates the hybridization factor).

Moreover, the authors developed a conceptual design methodology which allows to examine the power-train systems in the context of multi-rotor design. It was found that full electric and hydrogen fuel cell systems have the highest impact on weight. The latter also brings new requirements, e.g. for cooling and special tanks. However, fuel cells provide a continuous electrical energy output which guarantees high endurance, environmentally friendly and noiseless operations. Moreover, peak performances (e.g. during take-off and landing) where the system under-performs, could be satisfied by a battery system. Additionally, the authors state that "hybrid electrical architectures can be used as bridge technology [...] However, these in turn have the disadvantage of poorer energy efficiency" [34].

Viswanathan et Al. [35] investigated challenges and opportunities of electric flight. At the current state, battery technology is not ready to serve the aerospace market. The only applications in which fully electric flight is possible are UAM, with small drones designed to fly for few tens of minutes, and pilot training, with two seats training aircraft. Issues regarding energy requirements, weight, safety, and cost, make it impossible today to fly larger aircraft with battery power. However, in agreement with Bertram et Al., Viswanathan et Al. see hybrid solutions, in which thermal engines are used to extend the range over that possible with batteries alone, as viable solutions for commuters (less than 20 seats) and larger aircraft. Hybrid powertrains offer reduced carbon emissions and fuel savings over short ranges. [35]

An advantage of electric motors is that their efficiency and power density are scale invariant, meaning that a large number of small motors can be used instead of few large propulsion units (as for conventional combustion engines). Distributed propulsion (DP) reduces drag significantly, while electric motors are more efficient than thermal engines, resulting in higher overall efficiency for electric aircraft [36].

de Vries et Al. [37] studied DP and its application in hybrid-electric propulsion (HEP) systems. The authors show that "although HEP can be used with different propulsion-system layouts, it presents a synergistic benefit when combined with DP, due to the versatility that electrical systems offer when it comes to distributing power to the different locations on the airframe." [37]. In addition, in this paper, it is detailed a new conceptual design method to size wing, propulsion system, and maximum takeoff mass of aircraft with an hybrid electric distributed propulsion system.

From this study, important parameters for non conventional power-train systems emerged: overall efficiency, power to weight ratio, battery specific energy, disk-loading, efficiency and specific power of electric motors, and specifically for DP, number of propulsor, and their longitudinal and axial position.

4.5 Performance Analysis

Performance analysis is an important aspect of the design process as it allows to obtain flight mission parameters of an aircraft (such as range, flight time, etc.) starting from its aerodynamics, propulsive and weight characteristics [38].

Palaia and Salem [38] adopt a 2D point-mass dynamics model for performance analysis. This is based on the assumption that the aircraft can be simplified to its center of gravity, and as a consequence aircraft motions around it can be neglected in the overall performance estimation. With this simplification, only the force equations are considered, while the moments are ignored (Figure 4.5).

Moreover, in the 2D model, it is assumed that the aircraft can only move in the vertical plane, whereas turns are neglected, leaving only two degrees of freedom. The last assumption sees the aircraft thrust always aligned with its velocity. The system of aircraft dynamics equations under these assumptions is shown in Figure 4.6.

The mission is then split into phases (taxi, take-off, climb, cruise, etc.), and specific initial condition and flight programs are set for each segment. For a more complete and accurate analysis, the 2D constraints could be imposed only for selected phases, considering 3D flight for the others [39]. Following the definition of the equations of motion, the performance can be calculated by integrating them in time.

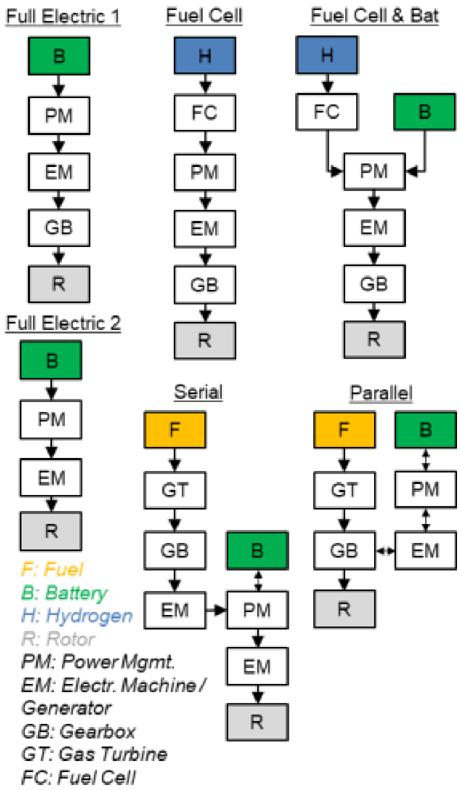


Figure 4.3: Simplified powertrain models [34].

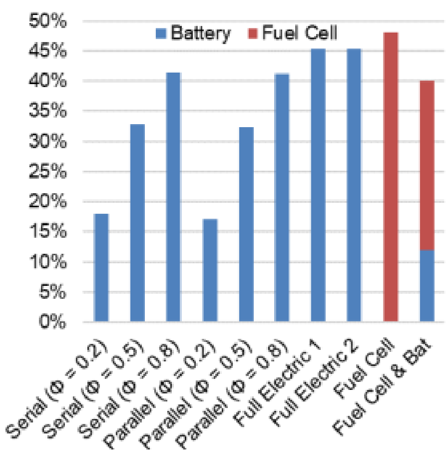


Figure 4.4: Battery and fuel cell mass fractions (w.r.t. MTOM) for UAM vehicles [34].

$$\dot{\sigma} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{h} \\ \dot{\chi} \\ \dot{V} \\ \dot{\gamma} \\ \dot{\mu} \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{m} \end{bmatrix} = \begin{bmatrix} V\cos\gamma\sin\chi \\ V\cos\gamma\cos\chi \\ V\sin\gamma \\ \frac{1}{mV\cos\gamma}\left\{T\cos\alpha\sin\beta + (N+L)\sin\mu + \left(F_{y_{ae}} + F_{y_{gd}}\right)\cos\mu\right\} \\ \frac{1}{m}\left\{T\cos\alpha\cos\beta - \left(D_{ae} + D_{gd}\right)\right\} - g\sin\gamma \\ \frac{1}{mV}\left\{T\sin\alpha + (N+L)\cos\mu - \left(F_{y_{ae}} + F_{y_{gd}}\right)\sin\mu - mg\cos\gamma\right\} \\ q\sin\beta + p\cos\alpha\cos\beta + r\sin\alpha\cos\beta \\ \frac{1}{\cos\beta}\left\{q\cos\alpha - p\sin\beta - \dot{\gamma}\right\} \\ \dot{\chi} + p\sin\alpha - r\cos\alpha \\ -T\cdot\mathrm{TSFC} \end{bmatrix}$$

Figure 4.5: Equations of motion under point-mass assumption (in vector format) [39].

$$\begin{cases} \frac{W}{g}\dot{V} = T - D - W\sin\gamma \\ \frac{W}{g}V\dot{\gamma} = L - W\cos\gamma \\ V_x = V\cos\gamma \\ V_z = -V\sin\gamma \\ \dot{W} = -k_c P_e \end{cases}$$

Figure 4.6: Simplified aircraft dynamics equations [38].

5

System of Systems driven design

Today, the design process is mainly driven by technical aspects and technological advancement. Meaning that when a new technology is introduced, a new design is created around it. This approach is limited as it does not take into account the effectiveness of the newly designed product in the operation environment. In a SoS perspective: the needs of the SoS are disregarded in favour of the SoI. System-of-systems driven design is a new approach to design which brings the SoS analysis into the process to increase success rate of the design, making it better fitting into its parent system. For example Levis [14] based his seaplane design on considerations coming from the performance analysis of the blended wing body (BWB) technology. This brought the author to narrow the scope of his tool to the design of BWB seaplanes. However, the author did not consider how this design would fit in the current transport system or aviation system.

Hu et Al. [40] recognise that aerospace engineers should pay high attention to SoS considerations at conceptual design stage. SoS engineering brings an holistic perspective and it helps designers gain understanding about demands and requirements of the actual operation environment during the design process.

As it was seen in Chapter 3, Delaurentis [10] presented a workflow for SoS engineering which saw three steps, with the last one being the simulation of the system. The author suggested different possible way to simulate a SoS behavior and elaborated on them in his book on the topic [41]. Particular focus is posed on two methods: System Dynamics and ABM.

System Dynamics, developed in the 1960s, focuses on understanding feedback mechanisms and developing policies that result in optimal outcomes over time. It uses causal loop diagrams and dynamic models to capture system behavior. System Dynamics can be applicable to analyzing future transportation service provider business models as they evolve alongside technology and regulations. However, one potential drawback is the difficulty in exploring emergent behavior.

ABM is a growing area that emphasizes the interactions and behaviors of individual components within a complex system. The global behavior of the system emerges from the interactions of autonomous agents and their environment. ABM is versatile and well-suited for studying complex non-linear systems. It can reveal qualitative and quantitative properties of real systems and serve as a computational laboratory for testing hypotheses. ABM holds potential for capturing the interactions among various stakeholders in transportation, such as airlines, air traffic control, passengers, and policymakers. However, a challenge in accepting ABM simulation results, as well as results from other modeling approaches, is validation. In the context of SoS, theory and experimentation are intertwined within the simulation itself.

5.1 Agent Based Modeling

In this section, the concept of ABM is further elaborated, and some example applications are explored.

Delaurentis [41] defines ABM as "a computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment". In other words, it is a complex model in which each individual component/system is programmed and their interaction is simulated in order to observe the effects on the whole system. ABM is considered extremely useful for modeling complex adaptive systems due to its dynamic nature, which allows to represent both the individual agents and their collective behavior. The authors emphasize that the goal of ABM is not to prove a concept, but to gain insight on the processes involved in a complex system. This analysis might bring light to unnoticed dynamics and consequences, and show emergent behaviors of the system.

There are really few applications of this methodology in literature, and some of the main contributions come from DLR. DLR developed the SoS Inverse Design (SoSID) toolkit [42] which is a model based on ABM that allows SoS simulations in a complex operational environment to capture emergent properties of a system. The SoSID toolkit was then validated with two use cases, on wildfire suppression and urban air mobility.

One example of application of the SoSID Toolkit is an exploration of Urban Air Mobility (UAM) from a system-of-systems perspective [43]. In this research, a SoS analysis is carried out in order to understand the impact of different UAM vehicles on the overall SoS capabilities. In this case, the authors developed a workflow combining aircraft design methods with an ABM (the SoSID Toolkit). Here, the focus is mainly posed on the ABM while the design is limited to the conceptual stage, and only used to generate inputs for the simulation.

6

Literature gaps

The main gaps emerged during this literature study are summarized in this chapter.

In Chapter 2 and Chapter 3, the strengths and limitations of seaplanes were highlighted. Here, the potential of flying-boats emerged due to their better water handling capabilities and higher payload capacity (w.r.t. float-planes). However, the study revealed that the only sectors where they are currently operated are those of firefighting, and search and rescue. No relevant scientific research was found regarding the use of flying-boats for passenger transportation.

From Chapter 4, the scarcity of modern conceptual design approaches for seaplanes became evident. The vehicle sizing techniques are limited to statistical methods lacking accuracy, and no semi-empirical approach was fund. The investigation of aerodynamics revealed the lack of methods specific to seaplanes. The few authors tackling seaplane aerodynamics limited their analysis to general semi-empirical methods. Only Levis [14] attempted to implement a correction to account for the hull step and afterbody angle. In addition, a lack of high fidelity analysis was registered in the field of seaplane aerodynamics.

The study of the hydrodynamics discipline had similar results. Although some physics based methods are mentioned by Masri et Al. [29] to simulate the hydro-static and -dynamic performance of seaplanes, only analytical methods were applied in literature. All semi-empirical methods analysed were fund to have strong limitations in representing the dynamics of seaplane take-off. Moreover, the most recent tank tests on flying-boats hull were performed by NACA in the first half of the past century, and only one example of high fidelity analysis on take-off performance was encountered.

Regarding power train system design, novel solutions such as full and hybrid-electric propulsion as well as hydrogen fuel cells have been widely investigated for conventional aircraft, but no scientific research in this direction was found for seaplanes. The concepts presented by Jekta and Regent both see distributed propulsion with full-electric power train systems. However, the companies do not provide any technical details or research material.

Lastly, current research fails to have a system view of the problem. In Chapter 5, SoS engineering revealed to be a new approach which still needs to be fully investigated. Seaplane design could benefit from SoS analysis and simulations. The examples brought in Chapter 5 show applications in the domains of UAM and firefighting. However, SoS engineering was always used as mean of results exploration, and it was never integrated in the vehicle design process, taking advantage of the insight provided by this analysis at the conceptual design stage.

7

Research Questions

Following the identification of the literature gaps, some questions rise. In this section, the main research questions are formulated and decomposed in sub-questions. Not all gaps could be tackled in this MSc thesis project, and for this reason it was decided to narrow down the scope to the application of SoS engineering to seaplanes conceptual design.

In order to address the possible interaction between aircraft design disciplines and SoS simulation (in the form of Agent Based Modeling), specific scenarios will be defined to restrict the research domain. One relevant example which is intended to be explored is the case of the Greek islands. Within this scenario, diverse sub-scenarios will be defined by varying parameters of the model such as: exact position of seaports on the map (travel segments), the incoming and outgoing demand of each seaport, and others.

The following questions are based on the above motioned scenario model. The first question aims to address the possible interaction between aircraft design disciplines and SoS simulation. The second question is meant to explore the results by analysing the impact of the newly designed seaplanes in the transport system. The last question focuses on the analysis of the seaplane design product of a design methodology based on SoS simulation. In this regard, the core of the investigation will concern the competitiveness of the design compared to other modes of transportation, in other words the frequency with which the agents chose to take the seaplane over other modes.

1. What is the impact of including Agent Based Modeling (ABM) in seaplane conceptual design on the main seaplane design parameters?

    1.1 What is the sensitivity of the design parameters to different scenarios and sub-scenarios (changes of the model parameters)?

    1.2 How do the values of design parameters change with respect to existent seaplanes when ABM is included in the design process?

2. What is the impact of the introduction of seaplanes in the transport system on its main characteristics?

    2.1 What is the impact on average traveling time and cost?

    2.2 What is the impact on average noise and CO_2 emissions? (Considering only emissions in operation)

    2.3 How does the position of seaports affect the competitiveness of seaplanes with respect to the current modes of transportation?

    2.4 What should the seaplane fleet size be to guarantee sufficient availability?

3. What are the design requirements for seaplanes to be a competitive alternative to other modes of transportation in the ABM?

    3.1 What should the main seaplane design parameters values be?

    3.2 Would an hybrid-electric seaplane be competitive? (Considering the known disadvantages of hybrid-electric propulsion w.r.t. conventional)

8

Proposed methodology and expected results

To answer the research questions, a SoS-driven design framework will be developed. An initial idea of the workflow is shown in Figure 8.1, where three main blocks can be distinguished.

In Figure 8.1, the design block is represented in blue. To assemble this block, different tools will be investigated and rearranged in order to form a new seaplane design loop. The latter will be able to estimate geometry and mass of the seaplane, its aerodynamic and hydrodynamic performance, noise emissions, and to size the power train system.

The second block (in green in Figure 8.1) represents the mission analysis and performance calculation that will be performed on the seaplane following the design phase. For this analysis a 2D point-mass dynamics model will be set up and solved for each mission segment, as shown in Section 4.5. The results obtained will then be input in SoS analysis tool.

In the SoS analysis block (in orange in Figure 8.1) the effectiveness of the seaplane operation in a SoS perspective is investigated. A similar approach as the one proposed by Delaurentis [41] for the national transport system will be applied to seaplanes in order to better define their role into the transportation system. Systems related to seaplane operations, and their impact on seaplane success/failure in serving predefined transportation networks will be investigated. This analysis will include the evaluation of seaplanes fleet operations, and it will be used to capture the main requirement for the design of these vehicle. In particular, Agent Based Modeling (ABM) will be applied following the example of [43] and [44] to simulate the SoS. The results of the simulation will be used to identify the Top Level Aircraft Requirements (TLARs) dictated by the needs of the SoS, which will be fed back into the design loop, starting an iterative process which aims to further improve the seaplane design.

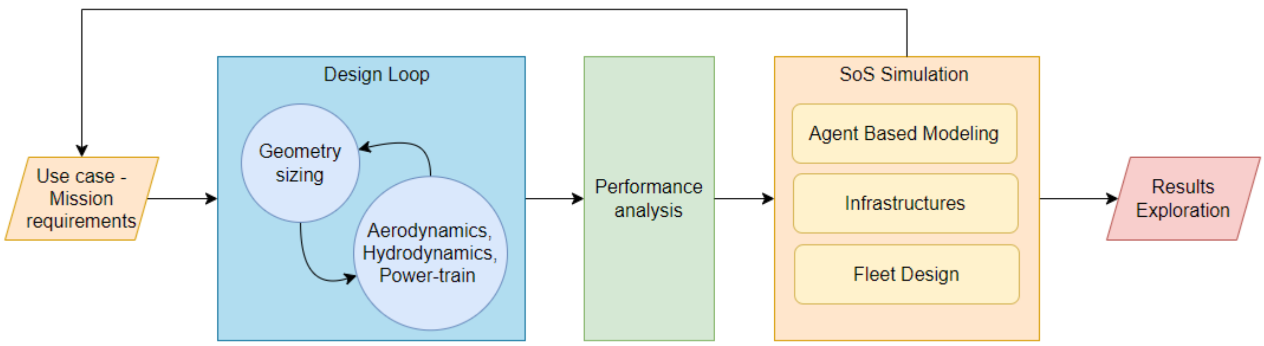


Figure 8.1: SoS driven design framework.

An exploration of the results will follow. A seaplane will be designed with the newly created SoS-driven seaplane design framework. By comparing the output seaplane to currently operated seaplanes, it will be possible to capture which differences the method, and in particular the ABM, caused on the main design parameters. Moreover, the SoS analysis will clear what the minimum requirements are for seaplanes to offer a competitive alternative to the current modes of transportation in terms of design parameters as well as SoS driving characteristics. With the latter meaning fleet operation evaluations, seaports location, environmental impact, and traveling time and cost.

The MSc thesis will be carried out at DLR Institute for System Architectures in Aeronautics (DLR-SL).

Here, technical support as well as all necessary hardware for the project is provided. Moreover, DLR offers the possibility of using their software for the development of the SoS-driven design methodology. The project will be also part of the EU project COLOSSUS [1], and for this reason more tools will be available from the project partners. These will be evaluated in comparison with tools already available at DLR and open source tools. The tool palette will be composed choosing software with the highest level of fidelity in the limits of the computational power available. The picture will be completed with custom made tools where needed.

The main data that will be treated in this project are aircraft geometry and mass specifics and performance parameters. To handle efficiently this type of data, the data format CPACS [45] will be used. Regarding the storage of these data, two digital storage will be used: my work laptop and DLR cloud, along with one physical storage: a USB flash-drive.

Verification will be carried out during and after the implementation phase. As per standard programming protocols, code is not compiled during the verification. Instead, traditional human review of code and processes of the design workflow will be performed throughout the project, for the different work packages. These are useful to check the correct operation of the single blocks present in the design method: design loop, performance analysis and SoS analysis. At the end of the implementation phase, one last verification will be performed to check the complete framework, focusing on the interactions between the blocks.

Only after the final verification is completed, a validation exercise will be performed. As anticipated in Chapter 5, validating ABM is not a straightforward process and it poses great challenges. An attempt to validate the work will be performed by executing one iteration of the workflow, so that the SoS analysis will not feed-back the design block. Setting the input with the design parameters of an existent seaplane, it could be possible to validate the methodology by comparing the output design with the real aircraft performance, and by comparing the results of the SoS block with information from literature about the operation of the seaplane in a real case example.

The outcomes of the MSc Thesis project are on different levels. Firstly, the developed design methodology will be made publicly available. Moreover, the seaplanes designed with the tool will be used to assess the contribution of this aircraft configuration on reducing airport congestion, noise and CO2 emissions of the current aviation system. This MSc thesis will also open the way of SoS engineering into aircraft design. In fact, it will allow to evaluate the impact of the addition of ABM to traditional design methodologies on aircraft design. For this purpose, results obtained with the new design tool will be compared with existing seaplanes (designed with traditional methodologies).

[1] COLOSSUS `https://colossus-sos-project.eu/`

9

Project Planning

A Gantt chart with the main milestones and tasks can be found in Appendix A.1. Dependencies between tasks are indicated with grey lines connecting them together.

The MSc project can be considered already started with the "Project Planning" and "Literature Research" the 1st of May. These two tasks have been carried out simultaneously for the past months. The First milestone was achieved with the official kick-off of the MSc thesis project the 26th of May. In July, the first work package will start. This will entail sketching the design workflow, setting the tools singularly, better defining their role in the workflow. In parallel, the 17th of July, the second work package will start. Here, the SoSID Toolkit from DLR [42] will be adapted to allow simulations including seaplanes. After the summer holidays, the implementation phase (dependent on the two previously mentioned WPs) will follow. During the implementation, all tools will be connected to each other, and the framework finalised. By the end of the first week of October, following the implementation, the preliminary results will be collected in order to prepare for the MID-term evaluation, the 27th of October. An optimization of the design workflow will follow the feedback obtained during the review. To complete the core work of the thesis, a verification and validation phase will take place in the beginning of December, until the Green Light meeting the 18th of the same month. At the same time, the report will be written, and a first draft submitted the first week of December. The final version of the report will be handed in the 15th of January. In conclusion, after the Christmas holidays planned for the last week of December, the student will prepare for the defense of the thesis planned for the 29th of January.

10

Conclusions

This literature study aimed to answer questions regarding the state of the art of seaplanes, their operation and design methodologies, as well as the discipline of SoS engineering and its application in design. The exact list of questions is presented in Section 1.2.

In the first part of the review (Chapter 2), seaplanes were investigated in a broad sense, starting from their history, to their technical characteristics. It was fund that they played an important role in the aviation industry during the first half of the past century. Their popularity grew thanks to their ability of taking-off and landing on water bodies. However, during and after World War II, numerous run-ways were built worldwide, and seaplanes' primary strength lost relevance. The flaws of seaplane designs became more apparent, outweighing their advantages and rendering them obsolete compared to conventional aircraft.

Following, the concept of System of Systems was explored, and applied to seaplanes in Chapter 3. This exercise was useful not only to review the current state of SoS engineering, it was beneficial as it served the purpose of identifying all systems which include seaplanes, and defining their role in the seaplane SoS.

In Chapter 4, seaplane design was specifically investigated. Methods for aerodynamics and hydrodynamics estimations were compared. In addition, a review of the cutting edge technologies for propulsion systems was carried out. The contributions of the highest exponents of SoS engineering to SoS simulation techniques were analysed in Chapter 5.

During this literature study, a renewed interest in seaplanes was encountered, with new research published recently, after a long period of "silence" following WWII. In particular, it emerged that the role of seaplanes in the transportation system is very limited. The existent design methodologies are outdated and lack of an holistic view of the system of interest.

This MSc Thesis project is intended to contribute to this new stream, and to demonstrate the potential of seaplanes as a future sustainable means of transportation. For this purpose, a novel design framework for seaplane conceptual design is proposed. To offer a new perspective on seaplane design, the framework will include a System-of-Systems analysis which will drive the design loop. Agent Based Modeling was found to be a perfect match for the transportation system and it could bring a positive impact on seaplane design.

The framework to be developed will be validated by designing a seaplane, which will be used to assess the contribution of this aircraft configuration on reducing airport congestion, and noise and CO2 emissions of the current aviation system. Moreover, this MSc thesis will open the way of SoS engineering into aircraft design. In fact, it will allow to evaluate the impact of adding a SoS simulation tool to traditional design methodologies on aircraft design.

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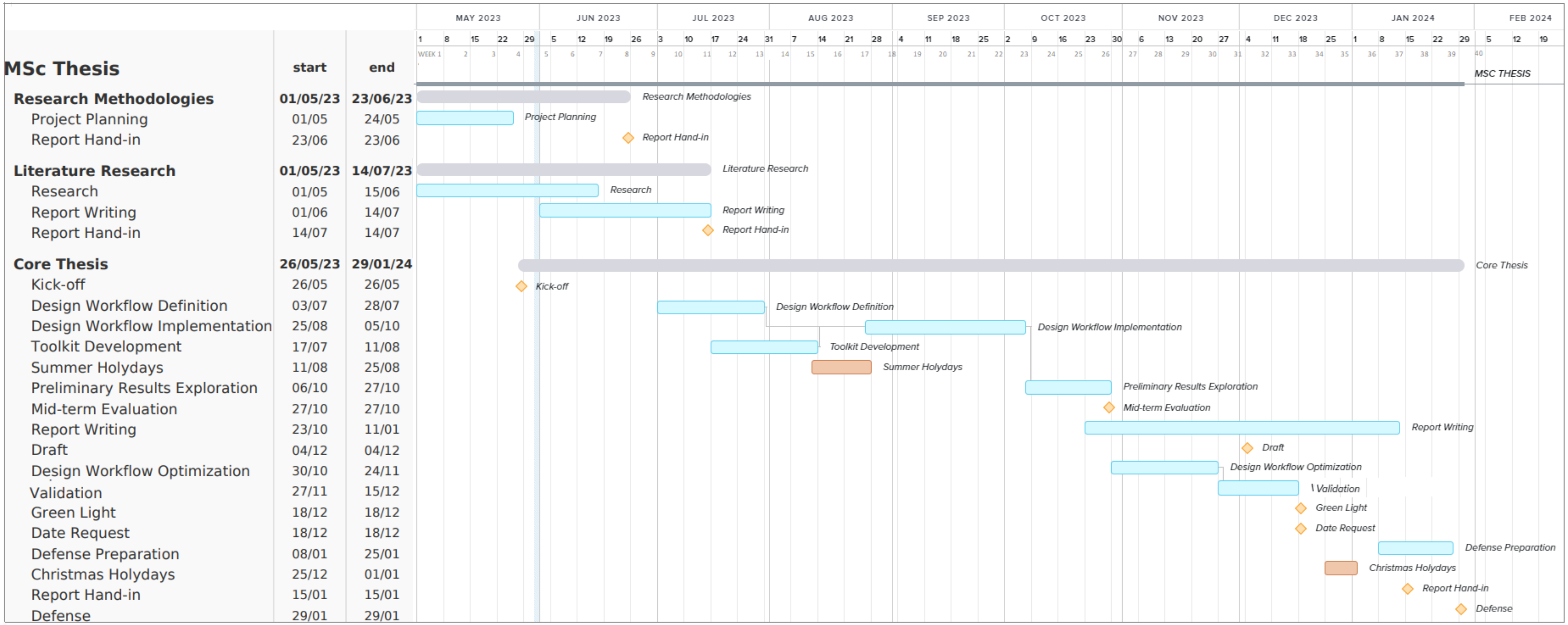
A

Gantt Chart

A.1 Gantt Chart



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A
Software

A.1. SoSID Toolkit

The SoSID Toolkit model is introduced by Kilkis et al. [12] and showcased by Prakasha et al. [2]. Following, the main features of the model are summarized.

The Toolkit is organized into three primary branches: the demand model, the agent model, and the alternative transportation model. The travel demand can be expressed in the Toolkit in terms of hourly distribution over one day. In particular, two curves should be defined at every port, one for incoming and one for outgoing passengers. Part of the scenario definition is also the allocation of the ports. This information can be provided in the form of GPS coordinates.

Three types of agents are defined in the Toolkit: aircraft, port-manager, and dispatcher agents. The aircraft agents' main tasks are to communicate to the dispatcher agent their availability to perform a mission and to fly it. The port manager agents provide take-off and landing clearance. The dispatcher agent reads the flight requests, finds the best route for each mission, and finally assigns and dispatches the flights to the aircraft agents.

One of the main advantages of ABMS is the possibility of modeling uncertainties [7]. In the Toolkit, three main types of uncertainties in fleet operation can be represented:

- Resources uncertainties such as refueling/recharging rates at each port, aircraft batteries technological level, fleet size, etc.
- Timing uncertainties namely, aircraft turnaround time, aircraft taxing time, and grouping time window.
- Demand uncertainties which are the demand volume, and its temporal and geographical distribution.

For the scope of this thesis, one parameter representative of each category was used to study the effects of the different kind of uncertainties: fleet size, grouping time window, and overall demand volume.

A.1.1. Aircraft agent performance modeling

The aircraft agents' behavior was adapted for the simulation of seaplanes by implementing a mission profile including taxi, take-off, climb, cruise, descent, loiter, and landing phases. Moreover, in the ABMS, the input aircraft is required to fly a variety of missions of different length, and where payload and fuel mass could assume different values at every departure. For this reason, it was not possible to input the aircraft mission performance at simulation start, but we needed to model them in the simulation. The agent performance model used to monitor the aircraft fuel consumption has been updated in the following way.

Taxi, take-off, and landing fuel consumption are considered constant. These values are estimated once for every seaplane in the aircraft design block of the framework. Fuel consumption during climb, cruise, and descent are calculated at every time step starting from the values of fuel mass flow with respect to mass for the design mission. The aircraft mass is updated at every time step by subtracting the instantaneous fuel consumption.

In Fig. A.2, fuel mass flow against mass is plotted for the design mission and a representative simulated mission of a placeholder seaplane design. (Note that OpenArchBuilder assumes linear dependency of fuel mass flow w.r.t. mass during each flight phase). The fuel mass flow during climb for the simulated mission is obtained by translating the line representing the design mission climb phase. This is achieved by employing Eq. A.1 which describes a grid of parallel lines.

$$y = ax + qk \tag{A.1}$$

Where a is the slope and q is the y-intercept of the design mission climb line. k is a constant that determines the spacing between the two lines and it is defined for each simulated mission as a function of the TOM (Eq. A.2).

$$k = \frac{\dot{m}_F^0 - a \cdot TOM}{q} \tag{A.2}$$

Where $\dot{m}_F^0$ is the design mission initial fuel mass flow value.

The fuel mass flow during cruise is assumed to vary linearly across different missions. Therefore, the fuel mass flow for the simulated cruise is obtained directly from the line equation describing the cruise phase of the design mission. The loiter phase is considered a continuation of cruise and is thus modelled in the same way. Finally, the fuel mass flow during descent for the simulated mission is obtained in an analogous way as for the climb phase.

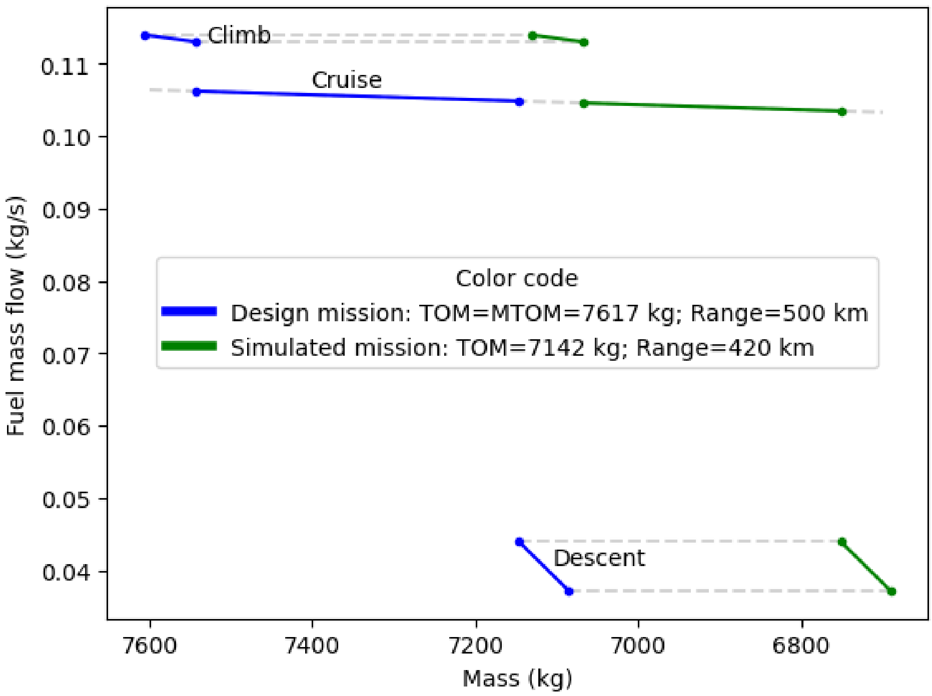

Figure A.1: Aircraft agents performance modeling

The use of these equations and approximations is justified by a preliminary investigation carried out for a placeholder seaplane. In particular, a set of missions of different ranges and TOM were simulated.

Three representative missions are reported in Fig. **??**, where the fuel mass flow against mass is plotted for each one.

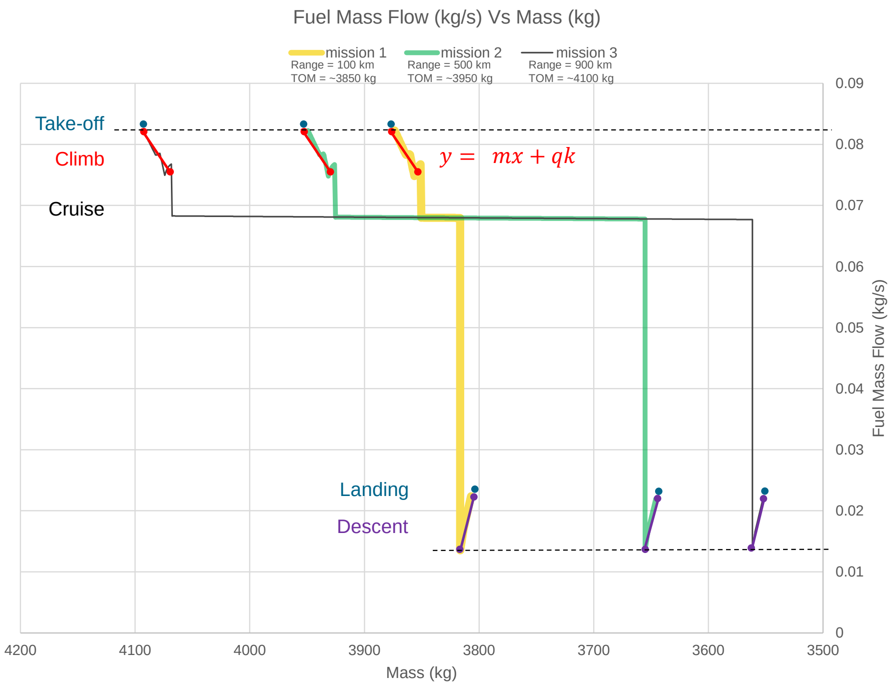

Figure A.2: Mission performance studies for fixed aircraft and three missions

It resulted that the fuel mass flow at take-off and landing stayed almost unchanged (blue dots) and thus was considered to be constant. Considering that the take-off and landing maneuvers would start at sea level and end at 457 m, and vice versa, and that vertical and horizontal speeds are constant, the times could also be fixed to a constant value which is calculated for every seaplane in the aircraft design block of the framework.

Moreover, it appears that the climb phase lines start at a fixed value for each mission (black dashed line) and maintain the same slope. For this reason, we can consider them as part of a grid of parallel lines. The grid equation is used to calculate the fuel mass flow of the aircraft as explained above. An analogous reasoning was applyed for the descent phase lines.

In addition, the investigation revealed that lines representing cruise phases in the different missions were overlapped. They maintain a linear trend across all missions, meaning that one single line approximates fuel mass flow for missions of different lengths and with cruise starting at different mass.

A.2. OpenArchBuilder

OpenArchBuilder [13] is a tool for electric propulsion systems conceptual design. It makes use of the open source tool openconcept [14], and OpenAD [15], to size the propulsion system components and perform mission analysis. This is done through an optimization loop which aims to minimize fuel consumption and MTOM of the vehicle.

The optimization problem set up in this thesis is represented in form of XDSM diagram in Fig. **??**. The design vector, objective function, and main constraints of the problem follow:

- Design vector:

$$\vec{x} = [d_{prop}, m_{battery}, P_{motor}(rated), P_{turboshaft}(rated), DoH_{CR}, DoH_{climb}, V_{climb}, V_{descent}, V_{r-climb}, V_{r-CR}, V_{r-descent}, V_{loiter}, ROC, ROD, r-ROC, r-ROD] \quad \text{(A.3)}$$

- Objective function:

$$f = m_F + \frac{MTOM}{15} \tag{A.4}$$

- Constraints:

$$\begin{aligned}
SOC &\geq 0 \\
0 &\leq throttle \leq 1 \\
1.8 &\leq d_{prop} \leq 3.0m \\
0 &\leq m_{battery} \leq 1000kg \\
0.1 &\leq DoH_{CR} \leq 1.0 \\
0.1 &\leq DoH_{climb} \leq 1.0 \\
0.01 &\leq P_{motor} \leq 0.1 \\
0.01 &\leq P_{turboshaft} \leq 0.1 \\
55.0 &\leq V_{climb} \leq 70.0m/s \\
55.0 &\leq V_{descent} \leq 70.0m/s \\
55.0 &\leq V_{r-climb} \leq 70.0m/s \\
55.0 &\leq V_{r-CR} \leq 70.0m/s \\
55.0 &\leq V_{r-descent} \leq 70.0m/s \\
55.0 &\leq V_{loiter} \leq 70.0m/s \\
5.0 &\leq ROC \leq 6.4m/s \\
5.0 &\leq ROD \leq 6.4m/s \\
5.0 &\leq r - ROC \leq 6.4m/s \\
-3.0 &\leq r - ROD \leq -2.0m/s
\end{aligned} \tag{A.5}$$

Where SOC is the State Of Charge of the battery at the end of the mission.

The cruise horizontal speed is fixed at the value dictated by the design variable M_{CR} passed by the SoS-driven optimization loop. The vertical speed at cruise is set to zero to ensure cruise at constant altitude. The Degree of Hybridization (DoH) with respect to power is considered to be zero during descent and the entire reserve segment [16], while optimized for climb and cruise.

The technology assumptions formulated by [13] were adopted for this implementation. However, the battery pack specifications were considered to be too optimistic for a 2030+ time frame. Thus, Li-ion batteries with a specific power of 1 kW/kg and a specific energy of 350 Wh/kg were considered instead [16]–[19]. The most relevant assumptions are listed in Table A.1. A more detailed explanation of assumptions and design choices can be found in [13].

Table A.1: Technological assumptions for powertrain sizing

Component	Specific Power (kW/kg)	Efficiency	PSFC (lb/hp/hr)
Battery	1	97 %	-
Motor	5	97 %	-
Generator	5	97 %	-
Converter	10	97 %	-
Turboshaft	7.15	-	0.6
Bus	-	95 %	-

While OpenArchBuilder was used by [20] for an architecture optimization problem, in this application, the input architecture is fixed to a parallel hybrid-electric configuration. The choice is based on the analysis carried out in [20], where it is stated that this configuration performs better in terms of weight and fuel consumption over a wide range of degrees of hybridization. This statement is also confirmed by the results of [13].

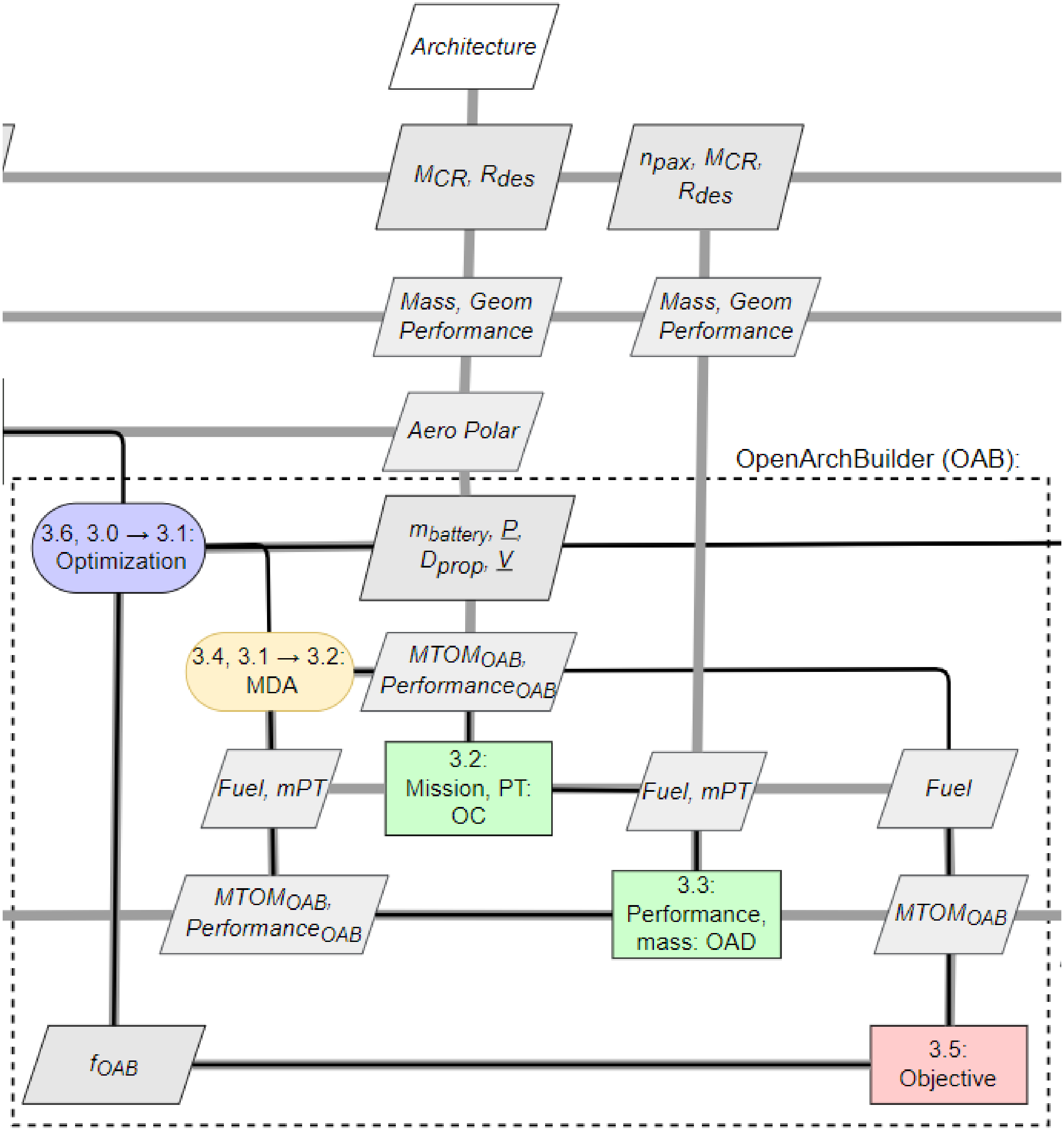

Figure A.3: Zoom in the XDSM diagram for the nested optimization loop in OpenArchBuilder

B

Ferry schedule

Origin	Destination	Departure time	Arrival time
Piraeus	Heraklio	01/08/2023 18:00:00	02/08/2023 04:10:00
Piraeus	Heraklio	01/08/2023 21:00:00	02/08/2023 06:15:00
Piraeus	Milos	01/08/2023 07:40:00	01/08/2023 11:05:00
Piraeus	Milos	01/08/2023 09:00:00	01/08/2023 11:40:00
Piraeus	Milos	01/08/2023 12:00:00	01/08/2023 15:20:00
Piraeus	Milos	01/08/2023 14:55:00	01/08/2023 22:05:00
Piraeus	Milos	01/08/2023 15:50:00	01/08/2023 19:15:00
Piraeus	Thira	01/08/2023 07:00:00	01/08/2023 11:45:00
Piraeus	Thira	01/08/2023 07:25:00	01/08/2023 15:10:00
Piraeus	Thira	01/08/2023 09:00:00	01/08/2023 13:55:00
Piraeus	Thira	01/08/2023 14:55:00	02/08/2023 03:45:00
Piraeus	Thira	01/08/2023 16:00:00	01/08/2023 22:05:00
Piraeus	Thira	01/08/2023 18:01:00	02/08/2023 00:05:00
Piraeus	Mykonos	01/08/2023 07:00:00	01/08/2023 09:35:00
Piraeus	Mykonos	01/08/2023 07:30:00	01/08/2023 13:20:00
Piraeus	Mykonos	01/08/2023 08:45:00	01/08/2023 11:30:00
Piraeus	Mykonos	01/08/2023 16:00:00	01/08/2023 18:55:00
Piraeus	Mykonos	01/08/2023 16:00:00	01/08/2023 21:00:00
Piraeus	Chios	01/08/2023 16:00:00	02/08/2023 06:10:00
Piraeus	Chios	01/08/2023 20:00:00	02/08/2023 04:10:00
Piraeus	Samos	01/08/2023 15:00:00	02/08/2023 00:30:00
Piraeus	Samos	01/08/2023 16:00:00	02/08/2023 01:10:00
Piraeus	Astypalea	01/08/2023 12:00:00	01/08/2023 20:10:00
Piraeus	Astypalea	01/08/2023 17:30:00	02/08/2023 04:25:00
Piraeus	Karpathos	01/08/2023 15:00:00	02/08/2023 11:10:00
Piraeus	Karpathos	01/08/2023 18:01:00	02/08/2023 07:45:00
Piraeus	Rhodes	01/08/2023 12:00:00	02/08/2023 06:10:00
Piraeus	Rhodes	01/08/2023 15:00:00	02/08/2023 06:40:00
Piraeus	Rhodes	01/08/2023 18:00:00	02/08/2023 09:10:00
Piraeus	Rhodes	01/08/2023 18:01:00	02/08/2023 13:10:00
Piraeus	Kos	01/08/2023 12:00:00	01/08/2023 23:55:00
Piraeus	Kos	01/08/2023 15:00:00	02/08/2023 02:30:00
Piraeus	Kos	01/08/2023 18:00:00	02/08/2023 05:50:00
Piraeus	Mytilene	01/08/2023 15:00:00	02/08/2023 07:30:00
Piraeus	Mytilene	01/08/2023 16:00:00	02/08/2023 09:00:00
Piraeus	Mytilene	01/08/2023 20:00:00	02/08/2023 08:15:00
Piraeus	Lemnos	01/08/2023 15:00:00	02/08/2023 12:50:00

Piraeus	Lemnos	01/08/2023 16:00:00	02/08/2023 14:25:00
Heraklio	Thira	01/08/2023 08:00:00	01/08/2023 09:50:00
Heraklio	Thira	01/08/2023 08:45:00	01/08/2023 10:35:00
Heraklio	Thira	01/08/2023 09:40:00	01/08/2023 11:35:00
Heraklio	Thira	01/08/2023 22:45:00	02/08/2023 01:55:00
Heraklio	Mykonos	01/08/2023 08:00:00	01/08/2023 12:35:00
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Heraklio	Piraeus	01/08/2023 22:45:00	02/08/2023 08:25:00
Milos	Thira	01/08/2023 11:50:00	01/08/2023 13:50:00
Milos	Thira	01/08/2023 22:25:00	02/08/2023 03:45:00
Milos	Mykonos	01/08/2023 08:00:00	01/08/2023 10:40:00
Milos	Andros	01/08/2023 13:00:00	01/08/2023 22:00:00
Milos	Chios	01/08/2023 13:10:00	02/08/2023 04:15:00
Milos	Chios	01/08/2023 15:45:00	02/08/2023 05:00:00
Milos	Samos	01/08/2023 12:25:00	02/08/2023 01:10:00
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Milos	Piraeus	01/08/2023 13:10:00	01/08/2023 20:20:00
Milos	Piraeus	01/08/2023 16:35:00	01/08/2023 19:15:00
Milos	Piraeus	01/08/2023 19:30:00	01/08/2023 22:50:00
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Thira	Heraklio	01/08/2023 16:00:00	01/08/2023 17:45:00
Thira	Heraklio	01/08/2023 17:20:00	01/08/2023 19:15:00
Thira	Milos	01/08/2023 07:30:00	01/08/2023 12:50:00
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Thira	Milos	01/08/2023 15:00:00	01/08/2023 17:10:00
Thira	Mykonos	01/08/2023 09:20:00	01/08/2023 11:35:00
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Thira	Kos	01/08/2023 00:05:00	01/08/2023 07:20:00
Thira	Lemnos	01/08/2023 08:05:00	02/08/2023 07:00:00
Thira	Piraeus	01/08/2023 02:30:00	01/08/2023 08:25:00
Thira	Piraeus	01/08/2023 04:00:00	01/08/2023 09:40:00
Thira	Piraeus	01/08/2023 07:30:00	01/08/2023 20:20:00
Thira	Piraeus	01/08/2023 07:35:00	01/08/2023 13:30:00
Thira	Piraeus	01/08/2023 09:20:00	01/08/2023 14:45:00
Thira	Piraeus	01/08/2023 12:20:00	01/08/2023 17:05:00
Thira	Piraeus	01/08/2023 14:20:00	01/08/2023 19:15:00
Thira	Piraeus	01/08/2023 15:30:00	01/08/2023 23:20:00
Thira	Piraeus	01/08/2023 15:45:00	01/08/2023 23:20:00
Mykonos	Heraklio	01/08/2023 12:45:00	01/08/2023 17:45:00
Mykonos	Heraklio	01/08/2023 14:35:00	01/08/2023 19:15:00
Mykonos	Milos	01/08/2023 17:10:00	01/08/2023 19:55:00

Mykonos	Thira	01/08/2023 09:50:00	01/08/2023 11:45:00
Mykonos	Thira	01/08/2023 10:00:00	01/08/2023 11:55:00
Mykonos	Thira	01/08/2023 11:10:00	01/08/2023 14:40:00
Mykonos	Thira	01/08/2023 12:00:00	01/08/2023 14:30:00
Mykonos	Thira	01/08/2023 12:45:00	01/08/2023 15:35:00
Mykonos	Thira	01/08/2023 14:05:00	01/08/2023 16:40:00
Mykonos	Thira	01/08/2023 19:10:00	01/08/2023 22:05:00
Mykonos	Andros	01/08/2023 07:35:00	01/08/2023 10:00:00
Mykonos	Andros	01/08/2023 10:55:00	01/08/2023 12:20:00
Mykonos	Andros	01/08/2023 13:45:00	01/08/2023 16:10:00
Mykonos	Chios	01/08/2023 20:00:00	02/08/2023 04:55:00
Mykonos	Chios	01/08/2023 21:20:00	02/08/2023 06:15:00
Mykonos	Samos	01/08/2023 12:15:00	01/08/2023 15:55:00
Mykonos	Samos	01/08/2023 20:00:00	02/08/2023 00:30:00
Mykonos	Samos	01/08/2023 21:20:00	02/08/2023 01:10:00
Mykonos	Mytilene	01/08/2023 20:00:00	02/08/2023 07:30:00
Mykonos	Mytilene	01/08/2023 21:20:00	02/08/2023 09:00:00
Mykonos	Lemnos	01/08/2023 20:00:00	02/08/2023 12:50:00
Mykonos	Lemnos	01/08/2023 21:20:00	02/08/2023 14:25:00
Mykonos	Piraeus	01/08/2023 11:45:00	01/08/2023 14:45:00
Mykonos	Piraeus	01/08/2023 12:00:00	01/08/2023 14:55:00
Mykonos	Piraeus	01/08/2023 14:15:00	01/08/2023 20:00:00
Mykonos	Piraeus	01/08/2023 14:35:00	01/08/2023 17:05:00
Mykonos	Piraeus	01/08/2023 17:20:00	01/08/2023 21:50:00
Mykonos	Piraeus	01/08/2023 17:35:00	01/08/2023 20:35:00
Mykonos	Piraeus	01/08/2023 18:25:00	01/08/2023 23:15:00
Mykonos	Piraeus	01/08/2023 20:10:00	02/08/2023 00:50:00
Andros	Milos	01/08/2023 15:45:00	01/08/2023 22:05:00
Andros	Thira	01/08/2023 15:45:00	01/08/2023 22:05:00
Andros	Mykonos	01/08/2023 10:00:00	01/08/2023 12:20:00
Andros	Mykonos	01/08/2023 15:45:00	01/08/2023 17:10:00
Andros	Mykonos	01/08/2023 19:45:00	01/08/2023 22:10:00
Andros	Mykonos	01/08/2023 20:10:00	01/08/2023 22:30:00
Chios	Milos	01/08/2023 08:50:00	02/08/2023 22:05:00
Chios	Milos	01/08/2023 22:00:00	02/08/2023 22:05:00
Chios	Mykonos	01/08/2023 08:50:00	01/08/2023 18:05:00
Chios	Samos	01/08/2023 08:50:00	01/08/2023 11:35:00
Chios	Samos	01/08/2023 11:05:00	01/08/2023 13:40:00
Chios	Mytilene	01/08/2023 05:45:00	01/08/2023 08:45:00
Chios	Lemnos	01/08/2023 06:35:00	01/08/2023 14:25:00
Chios	Piraeus	01/08/2023 08:50:00	01/08/2023 23:15:00
Chios	Piraeus	01/08/2023 11:05:00	02/08/2023 00:50:00
Chios	Piraeus	01/08/2023 21:45:00	02/08/2023 06:35:00
Chios	Piraeus	01/08/2023 22:00:00	02/08/2023 06:00:00
Samos	Milos	01/08/2023 12:15:00	02/08/2023 22:05:00
Samos	Milos	01/08/2023 13:40:00	02/08/2023 22:05:00
Samos	Mykonos	01/08/2023 16:45:00	01/08/2023 20:25:00
Samos	Mykonos	01/08/2023 03:00:00	01/08/2023 07:40:00
Samos	Mykonos	01/08/2023 13:40:00	01/08/2023 18:05:00
Samos	Chios	01/08/2023 02:10:00	01/08/2023 06:15:00
Samos	Chios	01/08/2023 03:30:00	01/08/2023 06:15:00
Samos	Mytilene	01/08/2023 01:00:00	01/08/2023 07:30:00
Samos	Mytilene	01/08/2023 02:20:00	01/08/2023 07:30:00
Samos	Mytilene	01/08/2023 03:30:00	01/08/2023 09:00:00
Samos	Lemnos	01/08/2023 01:00:00	01/08/2023 12:50:00
Samos	Lemnos	01/08/2023 02:20:00	01/08/2023 12:50:00

Samos	Lemnos	01/08/2023 03:30:00	01/08/2023 14:25:00
Samos	Piraeus	01/08/2023 12:15:00	01/08/2023 23:15:00
Samos	Piraeus	01/08/2023 13:40:00	01/08/2023 23:15:00
Samos	Piraeus	01/08/2023 14:10:00	02/08/2023 00:50:00
Samos	Piraeus	01/08/2023 15:20:00	02/08/2023 00:50:00
Astypalea	Milos	01/08/2023 04:45:00	03/08/2023 22:05:00
Astypalea	Milos	01/08/2023 06:00:00	01/08/2023 22:50:00
Astypalea	Rhodes	01/08/2023 04:30:00	01/08/2023 16:25:00
Astypalea	Rhodes	01/08/2023 16:00:00	02/08/2023 02:00:00
Astypalea	Rhodes	01/08/2023 20:30:00	02/08/2023 06:10:00
Astypalea	Kos	01/08/2023 04:30:00	01/08/2023 08:45:00
Astypalea	Kos	01/08/2023 20:30:00	01/08/2023 23:55:00
Astypalea	Piraeus	01/08/2023 02:15:00	01/08/2023 10:40:00
Astypalea	Piraeus	01/08/2023 04:45:00	01/08/2023 15:35:00
Astypalea	Piraeus	01/08/2023 06:00:00	01/08/2023 16:40:00
Karpathos	Heraklio	01/08/2023 15:10:00	01/08/2023 21:50:00
Karpathos	Thira	01/08/2023 20:55:00	02/08/2023 07:05:00
Karpathos	Thira	01/08/2023 22:15:00	02/08/2023 07:05:00
Karpathos	Rhodes	01/08/2023 08:30:00	01/08/2023 13:10:00
Karpathos	Rhodes	01/08/2023 09:40:00	01/08/2023 13:10:00
Karpathos	Rhodes	01/08/2023 10:45:00	01/08/2023 15:25:00
Karpathos	Rhodes	01/08/2023 11:40:00	01/08/2023 17:35:00
Karpathos	Rhodes	01/08/2023 11:55:00	01/08/2023 15:25:00
Karpathos	Rhodes	01/08/2023 12:45:00	01/08/2023 16:25:00
Karpathos	Kos	01/08/2023 11:40:00	01/08/2023 22:40:00
Karpathos	Piraeus	01/08/2023 15:10:00	02/08/2023 08:25:00
Karpathos	Piraeus	01/08/2023 18:55:00	02/08/2023 09:55:00
Karpathos	Piraeus	01/08/2023 20:15:00	02/08/2023 09:55:00
Karpathos	Piraeus	01/08/2023 20:55:00	02/08/2023 13:10:00
Karpathos	Piraeus	01/08/2023 22:15:00	02/08/2023 13:30:00
Rhodes	Heraklio	11/01/2023 00:00:00	01/08/2023 21:50:00
Rhodes	Thira	01/08/2023 11:00:00	02/08/2023 01:55:00
Rhodes	Thira	01/08/2023 17:00:00	02/08/2023 03:30:00
Rhodes	Astypalea	01/08/2023 10:30:00	01/08/2023 21:50:00
Rhodes	Astypalea	01/08/2023 16:00:00	02/08/2023 02:00:00
Rhodes	Astypalea	01/08/2023 20:30:00	02/08/2023 06:00:00
Rhodes	Karpathos	01/08/2023 07:30:00	01/08/2023 11:00:00
Rhodes	Karpathos	01/08/2023 11:00:00	01/08/2023 14:40:00
Rhodes	Karpathos	01/08/2023 15:00:00	01/08/2023 18:35:00
Rhodes	Karpathos	01/08/2023 17:01:00	01/08/2023 20:35:00
Rhodes	Kos	01/08/2023 08:00:00	01/08/2023 10:20:00
Rhodes	Kos	01/08/2023 10:30:00	01/08/2023 17:40:00
Rhodes	Kos	01/08/2023 13:00:00	01/08/2023 20:15:00
Rhodes	Kos	01/08/2023 16:00:00	01/08/2023 21:50:00
Rhodes	Kos	01/08/2023 17:00:00	01/08/2023 19:45:00
Rhodes	Kos	01/08/2023 18:45:00	01/08/2023 22:40:00
Rhodes	Piraeus	01/08/2023 11:00:00	02/08/2023 08:25:00
Rhodes	Piraeus	01/08/2023 17:00:00	02/08/2023 08:20:00
Rhodes	Piraeus	01/08/2023 17:01:00	02/08/2023 13:30:00
Rhodes	Piraeus	01/08/2023 18:15:00	02/08/2023 12:00:00
Kos	Heraklio	01/08/2023 06:40:00	02/08/2023 01:50:00
Kos	Heraklio	01/08/2023 12:55:00	02/08/2023 01:50:00
Kos	Heraklio	01/08/2023 20:30:00	02/08/2023 04:10:00
Kos	Thira	01/08/2023 20:15:00	02/08/2023 03:30:00
Kos	Astypalea	01/08/2023 17:50:00	01/08/2023 21:50:00
Kos	Astypalea	01/08/2023 22:20:00	02/08/2023 02:00:00

Kos	Karpathos	01/08/2023 03:10:00	01/08/2023 11:10:00
Kos	Rhodes	01/08/2023 03:00:00	01/08/2023 08:55:00
Kos	Rhodes	01/08/2023 06:40:00	01/08/2023 09:40:00
Kos	Rhodes	01/08/2023 12:55:00	01/08/2023 16:30:00
Kos	Rhodes	01/08/2023 15:00:00	01/08/2023 17:15:00
Kos	Rhodes	01/08/2023 15:05:00	01/08/2023 17:20:00
Kos	Rhodes	01/08/2023 16:10:00	01/08/2023 18:25:00
Kos	Rhodes	01/08/2023 00:20:00	01/08/2023 06:10:00
Kos	Piraeus	01/08/2023 00:20:00	01/08/2023 12:00:00
Kos	Piraeus	01/08/2023 20:30:00	02/08/2023 08:25:00
Kos	Piraeus	01/08/2023 22:20:00	02/08/2023 10:40:00
Kos	Piraeus	01/08/2023 23:00:00	02/08/2023 11:25:00
Mytilene	Heraklio	01/08/2023 06:10:00	03/08/2023 06:00:00
Mytilene	Heraklio	01/08/2023 18:00:00	03/08/2023 04:10:00
Mytilene	Mykonos	01/08/2023 06:10:00	01/08/2023 18:05:00
Mytilene	Chios	01/08/2023 18:00:00	01/08/2023 21:00:00
Mytilene	Samos	01/08/2023 06:10:00	01/08/2023 11:35:00
Mytilene	Samos	01/08/2023 08:30:00	01/08/2023 14:50:00
Mytilene	Lemnos	01/08/2023 08:45:00	01/08/2023 12:50:00
Mytilene	Lemnos	01/08/2023 10:00:00	01/08/2023 14:25:00
Mytilene	Piraeus	01/08/2023 06:10:00	01/08/2023 23:15:00
Mytilene	Piraeus	01/08/2023 08:30:00	02/08/2023 00:50:00
Mytilene	Piraeus	01/08/2023 18:00:00	02/08/2023 06:00:00
Lemnos	Heraklio	01/08/2023 01:05:00	03/08/2023 04:10:00
Lemnos	Mykonos	01/08/2023 01:05:00	01/08/2023 18:05:00
Lemnos	Chios	01/08/2023 01:05:00	01/08/2023 08:30:00
Lemnos	Samos	01/08/2023 01:05:00	01/08/2023 11:35:00
Lemnos	Samos	01/08/2023 03:30:00	01/08/2023 13:40:00
Lemnos	Mytilene	01/08/2023 01:05:00	01/08/2023 05:25:00
Lemnos	Mytilene	01/08/2023 03:30:00	01/08/2023 07:35:00
Lemnos	Piraeus	01/08/2023 01:05:00	01/08/2023 23:15:00
Lemnos	Piraeus	01/08/2023 03:30:00	02/08/2023 00:50:00