

Proceeding Paper

# Aircraft Design Capabilities for a System-of-Systems Approach (eVTOL and Seaplane Design) <sup>†</sup>

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**Abstract:** A System-of-Systems (SoS) approach is characterized by a strong cooperation between multiple constituent systems to achieve the desired objectives; the performance of an SoS will therefore be dependent on the performance of its constituent systems. However, due to the large number of stakeholders involved in a general SoS scenario, it is not the case that designing and optimizing the constituent systems’ performance with respect to their local design variables will lead to the optimal performance of the given SoS. The aim of the present work is to describe how the design and optimization of two aerial platforms, an all-electric Vertical Take-Off and Landing vehicle and a multi-role hybrid-electric seaplane, will be carried out for a multimodal mobility scenario, accounting not only for the performance-based design requirements but also for needs of all the relevant actors identified in the scope of the proposed use case, illustrating their effects on the architecting of the multidisciplinary design process. This research demonstrates how a structured methodology for the integration of needs and requirements from multiple perspectives can improve the efficiency of the design process, strengthening the connection between the vehicle level and the System-of-Systems level.

**Keywords:** aircraft conceptual design; SoS-oriented design; aircraft MDA



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## 1. Introduction

A key concept in the System-of-Systems (SoS) approach is the cooperation between multiple systems to achieve a desired objective that commonly could not be achieved by each constituent system when operating on their own [1]. From a theoretical perspective, the choice of constituent systems (CSs) composing an SoS depends on the problem to be solved; the performance and flexibility of such an SoS will therefore be dependent on the performance of its constituent systems and on their capability to adapt to the operating environment [2]. However, due to the complexity of an SoS, it is not said that designing and optimizing the CSs’ performance, with respect to their local role in the SoS network, will lead to the optimal performance of a given SoS.

The research presented in this paper is carried out in the frame of the COLOSSUS “Collaborative System of Systems Exploration of Aviation Products, Services & Business Models” project, an international research project funded by the European Commission within the Horizon Europe program [3].

### *Proposed Approach: An Overview*

The aircraft design process has always been strongly multidisciplinary [4]. In recent years, the increasing sensitivity towards reduced environmental impacts has led to deep investigations of disruptive vehicle architectures, leveraging new modes of transportation like Advanced Air Mobility vehicles [5,6], retrofitting existing solutions with innovative powertrains [7,8], and developing new design methodologies for hybrid-electric aircraft operating in the commuter and regional segments [9–12].

The larger flexibility of the SoS perspective and the need to identify an optimum SoS architecture that is capable of maximizing the value of the SoS itself, in terms of the quantifiable expectations of all the involved actors [13], fosters a deeper integration across all the levels of the SoS hierarchy, including the SoS level, the constituent system level and the sub-systems level. In classical Multidisciplinary Design and Optimization (MDO) processes, the coupling between the CSs and the sub-systems levels is usually resolved by means of performance-based constraints and Multidisciplinary Design and Analysis (MDA) loops, ensuring consistency; however, due to the generally higher abstraction of an SoS, connections between the latter and the CSs are often reduced to the straightforward evaluation of figures of merit at the SoS level for one or more collections of constituent systems. The process is eventually iterated until a satisfactory collection of CSs is obtained, often leveraging extensive design space explorations [14]. In the COLOSSUS project, stakeholders' needs will be integrated in the MDO framework to capture SoS dependencies, allowing higher-level constraints to shape the vehicle MDO process.

## **2. Use Case Definition and Stakeholder Identification**

Within the COLOSSUS project, two use cases have been defined: ADAM and EVE. Both use cases share the same novel air vehicles: an eVTOL vehicle for passengers and freight and a multi-role seaplane with hybrid propulsion. The ADAM (Advanced Air Mobility) use case focuses on creating a business model for sustainable intermodal mobility and evaluating the concept for performance, competitiveness, environmental impact, and life cycle footprint. In contrast, the EVE use case is geared towards developing an integrated fast-response approach to mitigating the risks and damages caused by wildfires. The research presented here focuses on the ADAM use case [3]. The stakeholder management approach in the COLOSSUS project requires the identification of all possible actors from a broad perspective. A “map of stakeholders” has been created, reflecting both primary and secondary stakeholders, from aircraft manufacturers to local authorities [15]. Stakeholders are individuals or organizations that can affect or will be affected by the project's outcomes. To enable the integration of their needs and requirements, from the vehicle operating environment and from the SoS context, into the aircraft design process, an initial filtering has been performed to identify the subset of stakeholders with the greatest impact on the architectural and operational aspects of the vehicles.

Table 1 shows the different classes of stakeholders, randomized to avoid biases, ranging from regulators and policy makers, like Air Traffic Management (ATM) operators and Original Equipment Manufacturers (OEMs), to the end users of the aerial platforms, like passengers and airlines.

**Table 1.** Stakeholders considered to have an impact on the aircraft design process. Adapted from [15].

<b>ADAM Stakeholders</b>		
(1) Air Travelers (Passengers)	(2) Pilots	(3) Policy Makers
(4) Airlines (Operators)	(5) Vertiports (Infrastructures)	(6) OEMs
	(7) ATM Operators	

### 3. Methodology

The necessity of strengthening the coupling between constituent systems' performance and their operational environment calls for a deeper understanding of how the needs and requirements coming from the upper levels affect existing Top-Level Aircraft Requirements (TLARs), and how both affect the overall MDO problem formulation, from the choice of design variables and constraints to the definition of objectives. Therefore, to support tactical exploration at the SoS level, a three-design-loop campaign was formulated, leveraging conceptual design methodologies for the initial stages of the design campaign and high-fidelity analysis for the final assessment process. The three-design-loop decomposition permits the investigation of how stakeholders' needs have different impacts on the architecture of the vehicle design process, specifically in the early conceptual stage.

In classical conceptual design processes, four distinct phases can be identified, leading to the identification of the TLARs: (1) a market analysis for the identification of the most promising segment most suitable to host the development of a new product, (2) the identification of gaps within the identified segment to be filled by new products, (3) comparative studies among potential competitors to identify enabling technologies and potential weaknesses, and (4) the collection of dominant drivers for the vehicle design process [16].

Design requirements can be classified as performance-based, focusing on desired environmental, economic, and operational metrics (e.g., cruise Mach number, emissions reduction), and architecture-based, which narrow down potential architectures based on promising configurations, including wing-body position and powerplant arrangement.

In aircraft MDA and MDO problems from an SoS perspective, a key challenge is aligning the vehicle requirements with SoS-level needs. Traditionally, this is done through extensive DOE campaigns to explore the design space, with vehicle effectiveness measured by SoS merit functions combining KPIs [17].

To improve the connections between the SoS and CS levels, scenarios' requirements could be integrated in the conceptual design problem, leveraging the three-design-loop campaign, to narrow the size of the vehicle design variables space to those most affecting the KPIs at the SoS level and to improve the definition of the objectives at the CS level, therefore increasing the sensitivity of the vehicle design variables towards a larger requirement space. The research presented here will use an "SoS-oriented" aircraft design process for the ADAM use case. In the latter, the multi-role seaplane and the eVTOL vehicle serve as new passenger transport platforms intended to operate within a multimodal transportation environment. The different steps of the three-design-loop approach are schematically summarized as follows:

- *First Design Loop:* An exploration of the CSs' design space to provide a collection of concepts and solutions to be analyzed at the SoS level.
- *Second Design Loop:* The tapering of the design space, optimizing the best concepts identified in the first design loop.
- *Third Design Loop:* A performance assessment of the final vehicle configuration, leveraging high-fidelity numerical and experimental methodologies.

In this paper, the focus is on the first and second design loop. In the first design loop, the necessity of exploring the vehicle design space called for the identification of a collection of initial TLARs. Given the complexity of the conceptual design problem, the large sample size and numerous variables may have made a DOE impractical, with no assurance of meeting the SoS objectives. A solution was to narrow the design space by focusing on the variables most impacting the vehicle performance within the SoS framework.

In the design space exploration, the stakeholders having the most relevant impact were those whose metric functions were capable of influencing vehicles' performance by means of significant modifications to the overall platforms' layout and to their operational

parameters. Once a few promising solutions had been identified, the aim of the second design loop was to taper the vehicle design space, optimizing these best concepts. Given the relatively simple nature of the merit functions characterizing the early design phases, the MDO problem architect usually aggregates them, leveraging the weighted-sum method in order to reduce a multi-objective optimization problem to a single-objective problem. In this approach, weights are selected according to use-case-specific needs, or a sweep is performed to investigate the Pareto optimality. To enable an SoS-oriented aircraft MDO process and then potentially improve the synergy between the different levels of the SoS pyramid, two strategies were explored: (1) integrating the vehicle MoE at the SoS level into the CS MDO problem, implementing design variables as independent variables for the optimizer,  $x^t$ , while value metrics at the SoS level and design constrains at the CS level are treated as objective functions,  $f$ , and constraints,  $c$ , respectively; or by (2) tracing the merit functions at the SoS level to the KPIs at the lower CS level, using their quantifiable value to combine them into a single-objective function.

#### 4. Results and Discussion

To improve the conceptual design process, it is necessary to adopt an SoS-oriented design methodology, enabling the narrowing of the vehicle design variables space. The first step in this approach consists of identifying stakeholders whose merit functions most affect the design choices. Table 2 summarizes the list of design variables that will drive the DOE campaign, while stakeholders' metrics will be used to derive KPIs at the vehicle level to select the most promising configurations, focusing on sustainability and connectivity criteria.

**Table 2.** Stakeholders' metrics and the associated design variable space for the first design loop—ADAM.

Stakeholder	Metrics	Design Variables
European Union	Connectivity Sustainability	Payload, Design Range Powertrain Architecture, Hybridization Strategies
Passengers	Travel Time Sustainability	Design Speed, Design Range Powertrain Architecture.
Pilots	User-Friendly Aircraft	OBS Architecture
ATM Operators	Airport Operability	Wing Span, Wing Area

In the ADAM use case, two multimodal scenarios have been investigated in [17]; in both, the seaplane can serve as a means to connect coastal cities, having a range of 550 km, or to provide support in connecting the main islands in the Mediterranean Sea, therefore covering typical ranges from 200 km to 300 km. The eVTOL can work on typical routes up to 100 km to connect inter-city hubs. Travel time should consider stakeholders that want short and fast connections, therefore constraining the vehicles' operating speeds. Table 3 summarizes the TLARs.

Small air transport vehicles, in the commuter class category, as well as in the Vertical Take-Off and Landing class, have been considered promising platforms to host the integration of innovative powertrain solutions, ranging from hybrid-electric architectures [9,10] to all-electric ones [6], making the choice of powertrain configuration an additional design variable. Parameters such as design range, operating speeds, mission profiles, and architectural layouts then serve as links between vehicle-level requirements and stakeholder needs, narrowing the design space to align with higher, SoS-level, objectives.

To manage the effects of known sources of variability in performing comparisons, “blocking” strategies were implemented. In the conceptual design stage, typical parameters introducing variability in vehicle performance include mission profile parameters and powertrain architectures. The blocking sample for the powertrain architectures is presented in Table 4, referring to an entry into service year in 2050 and showing two hybrid-electric configurations for the seaplane: one integrating Solid-State Batteries (SSBs) paired with Permanent Magnet Synchronous Machines (PMSMs), while the other employs Proton-Exchange Membrane (PEM) fuel cells. Given the fully electric nature of the eVTOL vehicle, a battery-based propulsion system was selected. To enable fair comparisons between configurations, influenced by differences in mission profile parameters, an additional blocking sample was created for the seaplane, consolidating mission parameters as summarized in Table 5.

**Table 3.** The top-level requirements for the seaplane’s and the eVTOL’s conceptual design and design space exploration—ADAM.

Vehicle	TLAR	Value	Unit
Seaplane	Take-Off Distance	≤1000.0	m
	Cruise Range	200.0 to 550.0	km
	Cruise Speed	250.0 to 400.0	km/h
	Cruise Altitude	3048.0 to 4724.0	m
	# Passengers	13 to 18	-
	MTOM	≤8618.0	kg
eVTOL	Cruise Range	50.0 to 200.0	km
	Cruise Speed	100.0 to 200.0	km/h
	Cruise Altitude	300.0	m
	# Passengers	4	-
	Wing AR	6.0 to 10.0	-
	# Propellers	4 to 10	-

**Table 4.** Powertrain architecture blocking sample. Entry into service year 2050.

Vehicle	Thermal Engine	Battery	Fuel Cell	Electric Machines	ID
Seaplane	Piston <sup>1</sup>	SSB	-	PMSMs	BAT-TH
	Piston <sup>1</sup>	-	PEM	PMSMs	FC-TH
eVTOL	-	SSB	-	PMSMs	AE

<sup>1</sup> Diesel plus 20% biodiesel blend.

Table 6 provides a summary of the design variables guiding the design space explorations. For the eVTOL, a factorial design was generated, while Latin hypercube sampling on hybridization ratios guided the DOE activities for the seaplane. These ratios, termed “supplied power ratios”, denoted as  $\Phi$ , represent the proportion of power drawn from the electrical portion of the powertrain relative to the total available power.

**Table 5.** Mission profile blocking sample—seaplane.

Cruise Range [km]	Cruise Speed [km/h]	Cruise Altitude [m]	Passengers	ID
450.0	335.0	3810.0	13	A
350.0	325.0	3657.5	15	B
500.0	365.0	4724.0	17	C
550.0	400.0	4115.0	18	D

To facilitate the assessment of vehicle performance at the SoS level, only vehicle configurations achieving the highest values for the KPIs at the vehicle level were selected, focusing on the sustainability metrics outlined in Table 2. For the seaplane, the primary environmental KPIs include Payload–Range Energy Efficiency (PREE), block fuel consumption, and block CO<sub>2</sub> emissions per Available Seat Kilometer (ASK). For the eVTOL, the focus was on energy consumption (EC) per ASK. Table 7 summarizes the selected KPIs and their mathematical formulations, units of measurement, and direction of improvement.

**Table 6.** DOE design variables.

Vehicle	DOE Variable	Min. Value	Max. Value	Unit
Seaplane	$\Phi_{TO}$	0.0	0.25	-
	$\Phi_{CL}$	0.0	0.20	-
	$\Phi_{CR}$	0.0	0.20	-
eVTOL	Cruise Range	50.0	200.0	km
	Cruise Speed	100.0	200.0	km/h
	Propellers	4	10	-
	Wing AR	6.0	10.0	-

**Table 7.** Vehicles’ environmental KPIs.

Vehicle	KPI	Formulation	Unit	Direction
Seaplane	PREE	$N_{pax}Range/E$	(seat km)/kWh	↑
	Fuel per ASK	$m_{BF}/(N_{pax}Range)$	g/(seat km)	↓
	CO <sub>2</sub> per ASK	$m_{CO_2}/(N_{pax}Range)$	g/(seat km)	↓
eVTOL	EC	$1/PREE$	kWh/(seat km)	↓

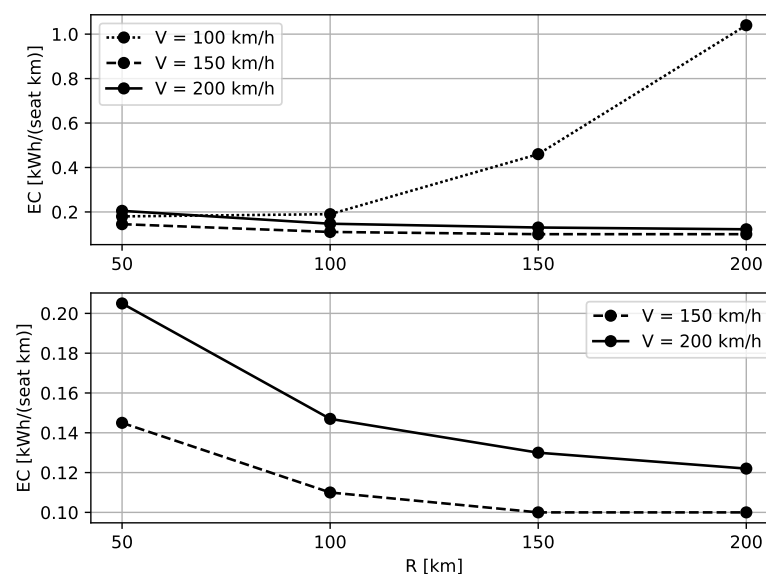
The design space exploration conducted on the seaplane led to more than 500 configurations, divided into eight groups, one for each combination of powertrain architecture and mission profile parameters, while for the eVTOL, more than 140 configurations were investigated out of a full-factorial design. Table 8 collects the environmental performance of the optimal, in a DOE sense, seaplanes in each group. On the other hand, Figure 1 illustrates the optimal, again in a DOE sense, eVTOL configurations.

**Table 8.** Environmental performance of seaplane. Entry into service year 2050.

Powertrain ID	Mission Profile ID	PREE	Fuel per ASK	CO <sub>2</sub> per ASK
BAT-TH	A	3.65	20.06	63.39
	B	3.80	19.42	61.37
	C	3.62	20.30	64.15
	D	3.27	22.43	70.88
FC-TH	A	3.63	19.65	62.09
	B	3.76	19.09	60.32
	C	3.62	19.72	62.31
	D	3.27	21.75	68.73

A first analysis of the results presented in Table 8 shows that both powertrain architectures present comparable performances, with fuel-cell-based configurations barely outperforming battery-based ones. Given the dependency between environmental KPIs at the vehicle level and sustainability metrics at the SoS level, pushing such set of seaplanes in the SoS context will lead to comparable values towards such sustainability metrics. In

parallel, Figure 1 illustrates the connection between range performance and fuel consumption of the eVTOL vehicle. Improving the former leads to a lower energy consumption, showing that increasing the importance of connectivity criteria at the SoS level could also improve the values of the sustainability metrics. In particular, the solutions at a speed equal to 100 km/h, in which a higher range leads to an increase in the required energy, make the eVTOL behaviour similar to multicopter vehicles. The identification of the objectives and requirements driving the value metrics at the SoS level enables a focused narrowing of the aircraft design space. This process reduces the hundreds of design variables typically encountered in a comprehensive MDO process to a few selected ones. These parameters not only guide the selection of the vehicle architecture, in alignment with CS-level KPIs, but also show a significant influence on outcomes within the SoS environment. Consequently, this approach eliminates the need for extensive DoE on CS-level variables with minimal influence.



**Figure 1.** Environmental performance of eVTOL. Entry into service year 2050.

## 5. Conclusions

This study demonstrated the potential of adopting an SoS-oriented approach in designing aerial platforms like eVTOLs and hybrid-electric seaplanes. The development of a multi-loop design process and the integration of stakeholder requirements allow for a structured yet flexible framework, where initial conceptual designs are refined through targeted optimization based on stakeholder metrics. This method not only achieves specific performance goals but also aligns with broader sustainability and operational requirements at the SoS level. Future research should aim to strengthen the linkage between SoS-level needs and vehicle-level requirements. This can be achieved by employing higher-fidelity disciplinary models, advanced surrogate modeling techniques, and incorporating additional SoS metrics and stakeholders into the vehicle MDO process. For instance, the inclusion of perspectives from OEMs and airlines could enable the integration of profitability metrics directly tied to economic performance, development, production, and total operating costs. Assessing the relative importance of SoS-level metrics could further facilitate trade-off studies at the CS level, showcasing the ability of an SoS-oriented aircraft design process to adapt to evolving SoS environments.

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ing—review and editing, M.T. and M.R. All authors have read and agreed to the published version of the manuscript.

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## Abbreviations

The following abbreviations are used in this manuscript:

ASK	Available Seat Kilometre
ATM	Air Traffic Management
CS	constituent system
DOE	Design of Experiments
EC	energy consumption
eVTOL	electric Vertical Take-Off and Landing
KPI	Key Performance Indicator
MDA	Multidisciplinary Design and Analysis
MDO	Multidisciplinary Design and Optimization
MoE	Measure of Effectiveness
OBS	On-Board System
PREE	Payload–Range Energy Efficiency
SoS	System-of-Systems
TLAR	Top-Level Aircraft Requirement

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