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INTEGRATING MANUFACTURING CRITERIA INTO VALUE-DRIVEN DESIGN WORKFLOWS: A MODEL-BASED APPROACH

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‘’E sognare non vuol dire che stai lì a dormire’’
(Rancore)

*‘’Io cerco semplicemente di combattere come fanno tutti gli altri
e di rimanere vivo in un mondo che non ti vuole vivo’’*

(Marilyn Manson)

INDEX

CONTENTS

ABSTRACT

The increasing complexity of modern aircraft design calls for integrated, multidisciplinary approaches that account for manufacturing, cost, and operational constraints from the earliest development stages. This thesis, developed within the COLOSSUS European Project, focuses on embedding manufacturing evaluation into trade space exploration tasks using a Model-Based Systems Engineering (MBSE) framework, with particular emphasis on the EVE (Eco-friendly air Vehicles for multiple operating Environments) use case for wildfire suppression.

Building upon AGILE and AGILE 4.0 methodologies, which demonstrated the potential of integrating manufacturing considerations into digital engineering workflows, this research systematically models manufacturing costs, production times, quality, and automation metrics and couples them with aircraft performance indicators to guide optimal design choices. Two operational scenarios—an inland wildfire and an island wildfire—are used to simulate real-world firefighting missions and identify environmental and logistical constraints affecting aircraft design.

A key contribution of this work is the development of a Python-based tool for estimating manufacturing costs and times for key fuselage components (frames, stringers, and skin panels), leveraging real-world datasets provided by TECNAM. The results are further analyzed through the VALORISE platform, which supports value-driven tradespace exploration based on cost, time, quality, and automation scores.

Additionally, the ARMADE tool, developed by DLR, is employed to formalize stakeholder needs and requirements across multiple system layers—from the System of Systems (SoS) level down to aircraft subsystems. This structured approach ensures traceability and alignment of design choices with operational, technical, and regulatory constraints.

Ultimately, this thesis demonstrates the effectiveness of manufacturing-aware, stakeholder-driven design methodologies in developing scalable, cost-effective, and sustainable aerospace solutions. The outcomes support the COLOSSUS project's vision of digital, collaborative engineering, providing a holistic and data-driven decision-making framework for future aircraft development.

CHAPTER 1: INTRODUCTION

1.1 CONTEXT: COLOSSUS EUROPEAN PROJECT

COLOSSUS, which is the acronym of **‘’Collaborative System of Systems Exploration of Aviation Products, Services and Business Models’’**, paves the way for future European aviation products and services. The objective is to boost the digital transformation of aviation and air transportation in order to enable European competitiveness in a key industrial sector. The expected outcome of **COLOSSUS** is to provide Europe’s aviation sector with a platform to develop new and breakthrough products and technology in supporting the design of System of Systems approach.

The latter can be defined formally as elements that interact to providing a unique capability that none of the Constituent systems (system or aircraft) can accomplish on its own. [1]

To be clearer, ‘’System of Systems’’ can be expressed as an aircrafts’ fleet, where in the specific there are both seaplanes and eVTOL aircraft.

In the following figure is depicted the COLOSSUS logo:

Figure 1: Colossus logo [2]

Main technical objectives of **COLOSSUS** are:

1. To create a Transformative Digital Collaborative Framework (TDCF) that allows European aviation to perform research, technology development and innovation in a holistic system-of-systems approach. The TDC Framework shall support modelling, analysis, optimization and evaluation of complex products and services under consideration of real-world conditions.

2. To expand and test the capabilities and performance of the TDC Framework with two Use Cases, both reflecting real cases and thus possess a value of their own. These Use Cases are:

- **Use Case 1**: Developing an integrated fast-response approach for preventing, detecting and fighting wildfires by combining latest developments in the fields of aircraft design and technology, automation, AI and digitalization. For clear distinction, this use case was named EVE (eco-friendly air vehicles for multiple operating environments).

- **Use Case 2**: Creating a business model for sustainable 4D-intermodal mobility and evaluating the concept for performance, competitiveness, environmental impact and life cycle footprint. This use case was named ADAM (advanced air mobility).

3. To perform conceptual studies for two products which could be transverse technology enablers for multi-modal mobility and affordable decarbonization of aviation: a Multi-Role **seaplane** with hybrid propulsion and a Multi-Role **eVTOL** based advanced air mobility of passengers and goods.

   Both aircraft's concept are shown in the following picture:

Figure 2: Visualisation of the aircraft concepts – Multi-Role seaplane and eVTOL air mobility vehicle [3]

- **Multi-Role Seaplane** is the first seaplane in this 9-12 pax CS 23 class to be designed for both mobility (cargo/pax), wildfire fighting, and additional special operations requirement. Entry into services is assumed to be 2035. Seaplane will have hybrid propulsion architectures to reduce fuel burn and emissions by 30%, compared to a baseline aircraft in operation before 2020. The all-composite aircraft with modern compound hydrofoil – hull system will enable easy take-off and landing in adverse conditions. The aircraft is designed to have minimal maintenance and operating cost/downtime. Distributed propulsion systems will be studied for improving the landing and take-off capability and performance. The noise emission constraint for design would be on par or beyond flightpath 2050 goals.

- **Multi-Role eVTOL** Advanced Air Mobility vehicle is a 2-6 pax all-electric vertical take-off and landing aircraft. The entry into service is assumed to be 2030. The ever-increasing interest in Urban Air Mobility

(UAM) is advancing the eVTOL designs. The vehicle designed in this research project will reap the benefit of performed and ongoing research at **COLOSSUS** partners and global trends. The activity will evolve a multi- role eVTOL AAM product which can perform autonomous missions for wildfire fighting by 2025 and autonomous flight for passenger transport by 2030. Since the AAM vehicles will be operated in densely populated urban areas, noise footprint will be one of the main design requirements.

Many national and international research centers, industries and universities are involved in the European Project **COLOSSUS**. Among others, there are:

- **Deutsches Zentrum für Luft- und Raumfahrt Ev [DLR] – Institute of System Architectures in Aeronautics (De, Coordinator)**;
- **Universitá degli Studi di Napoli Federico II (It, Partner)**.

The synergy between two entities provides the frame in which this master thesis activity takes place (see Figure 3).

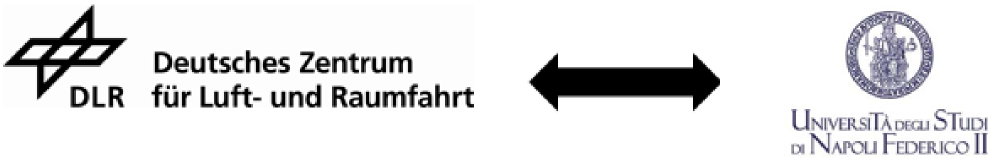


Figure 3: Sinergy between entities involved in the Master Thesis Activities

1.2 THESIS SCOPE & OBJECTIVES

The scope and the objectives of the master thesis are explained in this section. As mentioned in the previous section, one of the main objectives is to create a TDCF. Some of the processes characterizing the TDCF are Problem Definition, the System Specification and the evaluation, particularly the analysis considering the concurrent integration of manufacturing and design.

The **AGILE** and **AGILE 4.0** initiatives have introduced a paradigm shift by embedding manufacturing considerations directly within the MDO process through **MBSE**-driven methodologies. This integration allows for dynamic evaluation of trade-offs and enhances collaboration across various stakeholders in the aerospace supply chain. These are the two main objectives and briefly introduced here-after, respectively in sections 1.2.1 and 1.2.2.

1.2.1 PROBLEM DEFINITION & SYSTEM SPECIFICATION

Problem Definition Process involves the issues the project aims to resolve. It includes all the preliminary design analyses that are carried out upstream. The objective is to avoid errors at a later stage and recognize from the early design phase if some variables should be considered or not to describe the real essence of problem under discussion. Particularly, the main stakeholders involved in the problem are analyzed and their needs identified. These needs are translated into requirements that the system under design should fulfill to solve the problem. The analysis of the requirements is part of the System Specification Process. The link between Stakeholders, Needs and Requirements is shown in Figure 4.

Figure 4: Stakeholders, Needs and System Requirements relationship

In this thesis, the focus is the System of Systems (SoS), Constituent System (CS) and Subsystem (subCS). These represent three system levels since the System of Systems consists by Constituent Systems which include Subsystem. For example:

- System of Systems is the fleet.
- Constituent System is the Seaplane or the eVTOL.
- The Subsystem is the engine.

For System of Systems and Constituent System, Stakeholders, Needs and Requirements are derived.

In this master thesis activity, the main problem to face is firefighting. As already mentioned before, EVE is the use case related to firefighting, which develops an integrated fast-response approach for preventing, detecting and fighting wildfires. Many stakeholders are involved inside the EVE application case. One of them is for instance the fire department. The fire department has an interest in the SoS but also in the CS. In fact, from one side the department would like to minimize the time to extinguish the fire. This need can be translated into a requirement related to the SoS as shown in Figure 5. In addition, the fire department would like to have well equipped aircraft. This can be translated as a requirement for the CS.

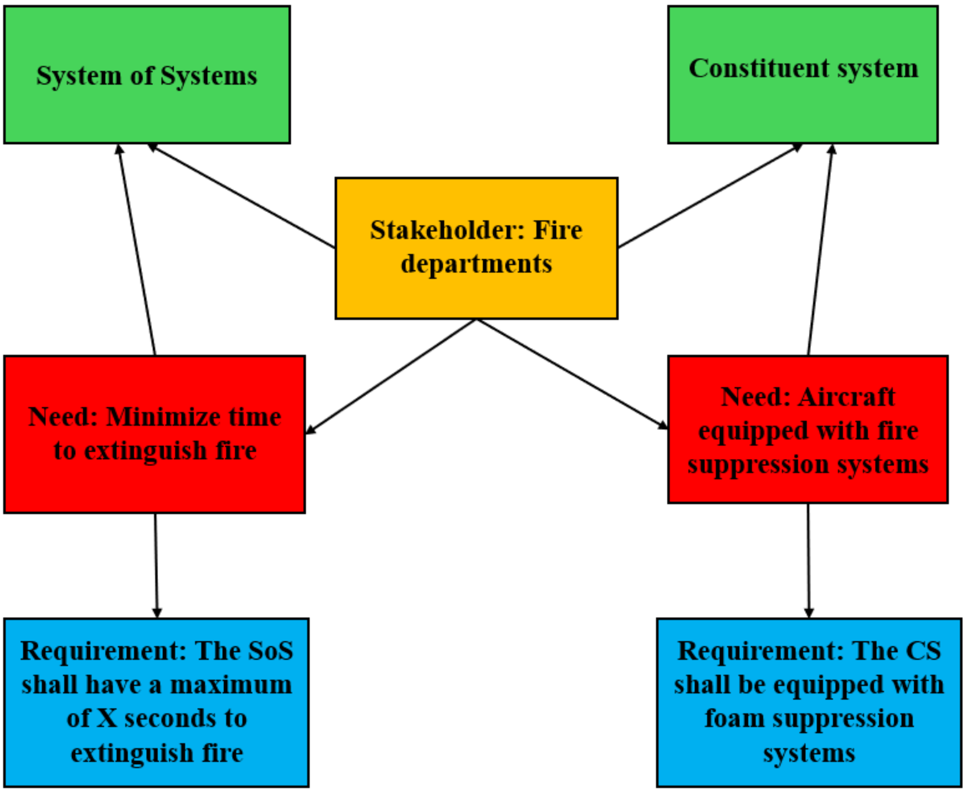


Figure 5: Example of System of Systems (SoS) and Constituent System (CS), Stakeholders (yellow box), Needs (red boxes) and Requirements (blue boxes)

The objective of this master thesis activity is to identify all the Stakeholders, Needs and Requirements related to the SoS and CS, identify the links between them and use a model-based approach to increase traceability.

1.2.2 MANUFACTURING & DESIGN EVALUATION

The integration of manufacturing considerations into the early stages of aircraft design has become an essential aspect of modern aerospace engineering. Traditionally, **Multidisciplinary Design Optimization** frameworks have primarily focused on enhancing vehicle performance metrics such as aerodynamics, structural integrity, and fuel efficiency, while manufacturing aspects have often been treated as secondary constraints or post-design evaluations. However, recent advancements in **Model-Based Systems Engineering** and digital engineering methodologies have highlighted the benefits of incorporating manufacturing-related parameters from the conceptual design phase. Projects such as **AGILE and AGILE 4.0** have demonstrated how an integrated approach can lead to significant cost and time savings while improving the overall manufacturability and feasibility of new aircraft designs.

This thesis aims to extend and refine this approach by analyzing how manufacturing costs and production times can be systematically estimated, modeled, and incorporated into the design optimization process. A key objective is to establish a structured methodology that enables real-time assessment of manufacturing trade-offs alongside traditional performance evaluations. This integration is particularly relevant for the **COLOSSUS** project, which emphasizes the development of a digital collaborative framework for the design of complex aviation systems.

The primary goal of this research is to develop a framework that systematically integrates manufacturing considerations within the MDO process. This involves different key aspects, which were described as following.

Leveraging empirical data and computational tools to quantify manufacturing costs and production times for different structural configurations. The analysis will focus on key fuselage components, including:

- **Frames**, which are analyzed with composite-carbon, alloy, and titanium.
- **Stringers**, which are evaluated in composite-carbon and alloy.
- **Skin panels**, which are assessed using composite-carbon, composite-glass, composite-Kevlar, and alloy.

The dataset for this evaluation has been provided by **TECNAM**, a recognized aircraft manufacturer, and will serve as the foundation for further computational modeling. A custom **Python-based computational tool** will be used to automate the generation of manufacturing cost and time estimates, exploring different material-process combinations.

One of the critical trade-offs in aerospace design is the balance between weight reduction and manufacturing feasibility. In this thesis, the following parameters will be analyzed and correlated:

- **Manufacturing cost and time**, which determine economic feasibility.
- **Manufacturing quality score**, assessing structural robustness and precision.
- **Manufacturing automation score**, evaluating the potential for process automation and scalability.

By integrating these metrics into the optimization framework, it will be possible to conduct a **multi-objective optimization**, identifying design solutions that meet both performance and manufacturing efficiency targets.

The thesis will present an advanced **Multidisciplinary Design Optimization** strategy that considers both aircraft performance and manufacturing constraints. This includes:

- Single-objective and multi-objective optimization approaches.
- Trade-off analysis to balance performance, cost, and manufacturability.
- Value-driven design assessments, quantifying the added value of alternative manufacturing technologies such as additive manufacturing and automated assembly lines.

The optimization process will leverage computational tools such as **VALORISE**, a specialized platform for evaluating trade-offs in aerospace manufacturing. The use of **digital twins** and virtual prototyping will further enhance predictive accuracy, enabling proactive adjustments before finalizing design configurations.

1.3 THESIS STRUCTURE

The activities performed to achieve the objectives introduced in the previous section are organized in five main chapters, each one addressing a specific aspect of research study. A brief overview of the chapters is provided here after:

- **Chapter 1: Introduction**

  Presents the context of the COLOSSUS European project, the motivation and objectives of the thesis, and introduces the methodology based on integrating manufacturing considerations into a model-based design process.

- **Chapter 2: Literature review**

  Reviews relevant literature on Multidisciplinary Design Optimization (MDO), Model-Based Systems Engineering (MBSE), and their integration with manufacturing constraints. Particular focus is given to the advancements proposed by the AGILE and AGILE 4.0 projects, identifying limitations of classical approaches and opportunities enabled by digital tools and collaborative frameworks.

- **Chapter 3: Methodology**

  Details the approach developed in this work, structured around four pillars: the EVE use case for wildfire suppression, stakeholder and requirement analysis through ARMADE, manufacturing cost/time modeling using a Python tool, and value-driven tradespace exploration via the VALORISE platform.

- **Chapter 4: Application case**

  Applies the methodology to a practical aircraft design problem, comparing landplane and seaplane configurations. Includes the computational results of manufacturing cost and time estimations and performs trade-off analyses using the VALORISE platform to support decision-making.

- **Chapter 5: Conclusions**

  Summarizes the key findings and contributions of the thesis, highlights limitations, and suggests directions for future research. It reflects on the value of manufacturing-aware and stakeholder-driven methodologies in supporting sustainable aircraft design.

CHAPTER 2: LITERATURE REVIEW

2.1 PROBLEM DEFINITION & SYSTEM SPECIFICATION

The **COLOSSUS** project targets the development of new Transformative Digital Collaborative Technologies that aim at accelerating, improving and streamlining the development of complex System of Systems. These technologies include new development methodologies and their implementation into original tools that leverage promising approaches such as MBSE.

These technologies expand the development frameworks developed in **AGILE** and **AGILE 4.0** projects, where the scope is about the design and optimization of aeronautical systems, for instance aircraft and subsystems. The process defined in AGILE 4.0 extends the scope addressed in the previous AGILE project, where the focus is on the last part of the development process, where aircraft systems and subsystems are designed and optimized according to a typical MDO approach. Technologies for the formulation (for example MDAx tool) and execution (for instance RCE) of MDO processes are exploited and expanded in the COLOSSUS project to cover subsystem, system and System of Systems levels. So, An MBSE approach is adopted, therefore leveraging models instead of documents for the collection, representation and sharing of information produced during the whole development process. Thus, the COLOSSUS project aims at extending the scope of the AGILE and AGILE 4.0 technologies to address the System of Systems level. The multi-level approach, in which the System of Systems approach is included as well, is depicted in the following figure:

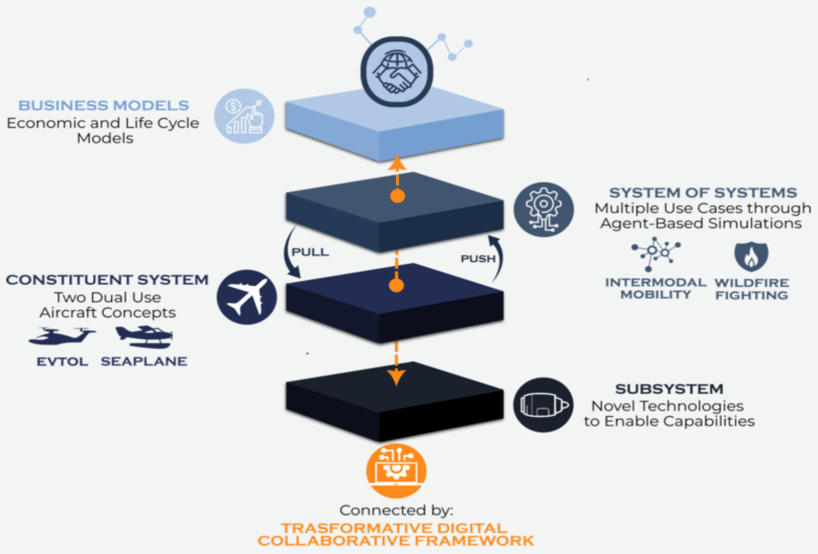


Figure 6: Multi-level approach for the holistic design of aviation systems [3]

Therefore, moving now towards the concrete framework, DLR developed this one, based on ‘’Model based system engineering’’, about the entire design process of any A/C.

The described framework is depicted below:

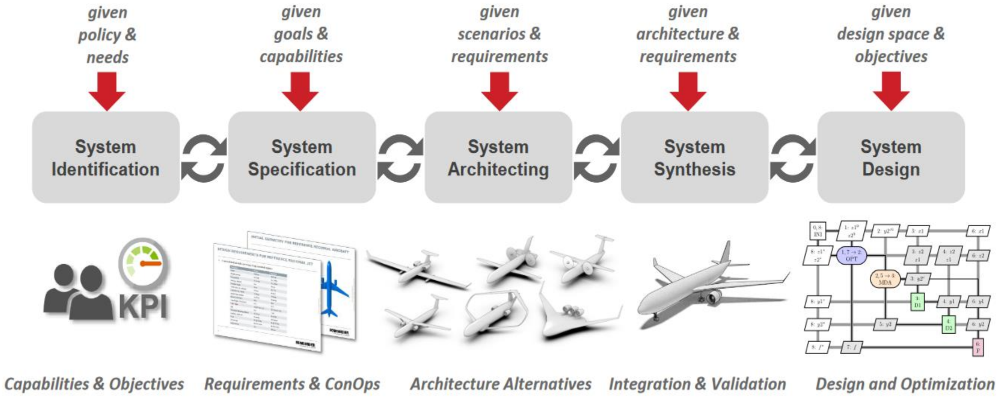


Figure 7: Systems Engineering Product Development process set up in AGILE 4.0 for the collaborative development of complex aeronautical systems [4]

2.2 MANUFACTURING & DESIGN

The development of aerospace systems has traditionally been driven by performance metrics, with manufacturing considerations often treated as secondary constraints. However, the increasing complexity of modern aircraft and the demand for more cost-effective and sustainable solutions have necessitated a shift toward integrated design approaches. **Model-Based Systems Engineering** (MBSE) and **Multidisciplinary Design Optimization** (MDO) have emerged as key methodologies to address this challenge, enabling a more holistic evaluation of trade-offs between performance, cost, and manufacturability. [5]

According to the authors that described the **MBSE** and **MDO** processes, in classical MDO frameworks, manufacturing constraints were typically included as fixed parameters, limiting their impact on early design decisions. This often resulted in suboptimal manufacturability, leading to increased costs and prolonged development times.

The following sections explore the limitations of classical MDO approaches, the advancements brought by AGILE and AGILE 4.0, and the optimization strategies employed to balance manufacturing costs, production timelines, and vehicle performance. By leveraging digital engineering tools and real-time data exchange, AGILE 4.0 establishes a framework for a more agile, efficient, and sustainable aerospace design process.

2.2.1 CONTEXT: AGILE AND AGILE 4.0

AGILE and AGILE 4.0 mark a paradigm shift in aeronautical MDO by embedding manufacturing considerations within an MBSE-driven framework. This methodology allows for a more integrated, agile, and cost-effective approach, optimizing aircraft performance and manufacturability as well. The findings from AGILE 4.0 highlight the significant advantages of digital engineering, offering a scalable solution for future aerospace design challenges. Additionally, the integration of MBSE formalization in AGILE 4.0 ensures improved standardization, traceability, and reusability of MDO frameworks across different projects and organizations.

Furthermore, the advanced cross-disciplinary integration facilitated by MBSE allows for continuous refinement of manufacturing processes alongside performance optimization, ensuring a seamless transition from conceptual design to production. By integrating digital technologies, AGILE 4.0 enhances collaboration across the aeronautical supply chain, fostering a more synchronized and resilient aerospace development ecosystem.

2.2.2 MANUFACTURING IN CLASSICAL MDO APPROACHES

Traditionally, MDO has focused primarily on optimizing vehicle performance metrics such as aerodynamics, structural integrity, and fuel efficiency. Manufacturing considerations, including cost estimation and production constraints, were often treated as secondary factors or post-design evaluations rather than being integrated into the early design process. Classical MDO frameworks typically employed cost functions or penalty terms to account for manufacturability, but these were often simplistic, lacking dynamic interactions with other design parameters.

Figures of merit, typically integrated as objective functions in classical MDO problems generally prioritized:

- **Weight minimization**, directly influencing fuel consumption and performance.
- **Aerodynamic efficiency**, maximizing lift-to-drag ratio.
- **Structural robustness**, ensuring compliance with safety regulations.
- **Production feasibility**, but often as a secondary concern, resulting in suboptimal manufacturability in real-world applications.

Manufacturing-related constraints were often imposed in a static manner, without adaptive decision-making during the optimization process. This limited the ability to perform real-time trade-offs between manufacturing complexity, cost, and performance. The absence of digital design integration also meant that changes in manufacturing processes often required costly redesign efforts late in the development cycle.

Design optimization is a structured and systematic process used to enhance engineering systems by methodically adjusting design variables while adhering to predefined constraints. Traditional engineering design methods rely on iterative trial-and-error approaches, heavily dependent on human intuition and experience. However, modern design optimization replaces these manual iterations with automated, algorithm-driven methods that efficiently explore the design space to identify the best possible solutions. [6]

According to the authors, in MDO, multiple engineering disciplines are considered simultaneously, ensuring that interactions between subsystems are accurately captured. Traditional sequential optimization methods optimize each subsystem independently, often leading to suboptimal solutions at the system level. MDO overcomes this limitation by coordinating various disciplinary analyses, enabling engineers to achieve improved performance, reduced development time, and lower costs while maintaining design feasibility.

The foundation of any optimization problem includes:

1. **Design Variables $\bar{X}$:** Independent parameters that define the system configuration and influence performance.
2. **Objective Function $f(\bar{X})$:** A scalar/vector function representing the goal of optimization, such as weight, efficiency or cost. After that it is possible to decide whether minimize or maximize the latter dataset.
3. **Constraints $g(\bar{X}), h(\bar{X})$:** Limitations imposed on the design variables to ensure feasibility, including inequality constraints $g(\bar{X}) \leq 0$ and equality constraints $h(\bar{X}) = 0$.
4. **Bounds on Variables:** Upper and lower limits defining the range within which design parameters can vary.

A typical MDO formulation can be mathematically expressed as:

$$\begin{aligned} \text{minimize:} \quad & f(\bar{X}) \\ \text{w.r.t.} \quad & \bar{X} \\ \text{subject to:} \quad & g(\bar{X}) \leq 0 \\ & h(\bar{X}) = 0 \end{aligned}$$

This formulation ensures that the optimization algorithm operates within a feasible design space while seeking to improve the objective function.

MDO plays a crucial role in modern engineering, particularly in industries where multiple subsystems interact and influence overall system behavior. Some key advantages of MDO include:

- **Accounting for Interdependencies:** Many engineering systems consist of interconnected components that affect one another. MDO systematically considers these interdependencies to produce more accurate and realistic design solutions.
- **Handling Conflicting Objectives and Constraints:** Engineering designs often involve trade-offs, such as balancing structural weight against aerodynamic performance in aerospace applications. MDO helps identify optimal trade-offs that satisfy multiple competing requirements.
- **Enhancing Design Efficiency and Performance:** By optimizing all subsystems simultaneously rather than sequentially, MDO enables engineers to achieve superior overall performance and efficiency while minimizing redesign efforts.

A classic example of an MDO problem in aerospace engineering is the minimization of fuel consumption while maintaining aerodynamic efficiency and structural integrity.

This problem can be formulated as:

$$\begin{aligned} \text{minimize:} \quad & m_{fuel}(X) \\ \text{w.r.t.} \quad & X \\ \text{subject to:} \quad & C_L \geq C_{Lmin} \\ & C_D \leq C_{Dmax} \\ & W \leq W_{max} \end{aligned}$$

Where:

- m_{fuel} represents the total fuel mass.
- C_L is the lift coefficient, ensuring sufficient aerodynamic lift.
- C_D is the drag coefficient, which must remain within acceptable limits.
- W is the structural weight, constrained to meet safety and performance criteria.
- X includes design variables such as wing aspect ratio, taper ratio and engine thrust.

This problem integrates multiple disciplines such as aerodynamics, structural mechanics, and propulsion making it a suitable candidate for MDO methodologies.

MDO strategies vary based on how subsystems are coupled and how optimization problems are structured. Common architectures include:

- **Monolithic Approaches:** Solve all coupled equations simultaneously within a unified framework. This ensures global optimality but requires substantial computational resources.
- **Distributed Approaches:** Decompose the optimization problem into smaller, more manageable subproblems. These subproblems are solved iteratively, enabling a more scalable and computationally efficient approach.
- **Hybrid Methods:** Combine elements of both monolithic and distributed approaches, balancing computational efficiency with solution accuracy.

Each approach has advantages and limitations, and the choice of MDO architecture depends on the complexity of the system, the computational budget, and the required accuracy of the solution.

Multidisciplinary Design Optimization is a powerful methodology for optimizing complex engineering systems by simultaneously considering multiple interacting disciplines. By carefully formulating the optimization problem, selecting appropriate constraints, and choosing efficient MDO architecture, engineers can achieve optimal designs that improve performance, reduce costs, and streamline the development process. As computational power and optimization algorithms continue to evolve, MDO is expected to play an increasingly critical role in engineering design across various industries.

2.2.3 OPTIMIZATION AND TRADE-OFFS IN AGILE AND AGILE 4.0

AGILE and AGILE 4.0 introduced an MBSE approach to bridge the gap between manufacturing and flight performance optimization. [5]

Key advancements in AGILE and AGILE 4.0 include:

- **Use of digital engineering tools** to model the entire product lifecycle, from conceptual design to production.
- **Implementation of a cyber-physical aeronautical supply chain**, enhancing collaboration among OEMs, Tier 1 suppliers and SMEs.
- **Reduction in design iteration cycles**, as MBSE enables automatic propagation of changes across disciplines, improving traceability and consistency.
- **Formalization of the AGILE Paradigm**, leveraging MBSE-driven methodologies to define a structured approach for the deployment and operation of collaborative MDO systems.
- **Advanced data exchange and interoperability frameworks**, ensuring that all stakeholders in the design and manufacturing chain can efficiently communicate and iterate on designs in real time.

This shift results in a more agile and cost-efficient design process, minimizing late-stage redesign efforts and enabling faster decision-making. The use of model-based digital twins allows engineers to simulate manufacturing processes alongside vehicle performance analyses, ensuring that trade-offs between production feasibility and system functionality are well understood before finalizing designs.

A major contribution of AGILE and AGILE 4.0 is the introduction of a holistic trade-space analysis, coupling manufacturing cost, production time, and vehicle performance. This approach enables real-time decision-making and significantly reduces design cycle inefficiencies.

AGILE 4.0 expanded the scope of MDO to include manufacturing and supply chain considerations. This evolution was driven by the need to reduce aircraft development costs and time-to-market while ensuring that production constraints were seamlessly incorporated into the design process. [7] [8]

AGILE 4.0 introduced a cyber-physical supply chain, integrating digital manufacturing models with the MDO framework. This integration allowed the evaluation of production costs, manufacturability, and supply chain efficiency within the optimization process.

Key advancements in AGILE 4.0 related to manufacturing include:

1. **Manufacturing-Aware Optimization:**

- Unlike traditional MDO approaches that focus solely on performance and weight reduction, AGILE 4.0 introduced design constraints that accounted for production feasibility, material availability, and assembly complexity.
- Manufacturing constraints were incorporated early in the optimization process, ensuring that the resulting designs could be efficiently produced without extensive redesign efforts.

2. **Digital Twin and Cyber-Physical Systems:**

- AGILE 4.0 leveraged digital twin technologies to simulate and evaluate manufacturing processes alongside design optimizations.
- This approach enabled real-time feedback between the design and manufacturing stages, allowing engineers to predict and mitigate production bottlenecks before physical prototyping.

3. **Supply Chain Integration:**

- The project introduced a digitalized supply chain network, enabling real-time assessment of the impact of design choices on production logistics and costs.
- By considering supplier constraints, lead times, and material sourcing within the MDO framework, AGILE 4.0 optimized designs that were not only technically superior but also aligned with existing manufacturing capabilities.

Several optimization studies within AGILE 4.0 demonstrated:

- **A 50% reduction in design-manufacturing iterations**, improving efficiency in transitioning from concept to production.
- **A 30% reduction in process development lead time**, through digital integration of design, manufacturing, and certification models.
- **Multi-objective optimization** balancing structural efficiency with manufacturability, leading to Pareto-optimal solutions that consider both aspects simultaneously.
- **Interoperability of MDAO and MBSE frameworks**, allowing integration of heterogeneous design tools and digital thread strategies.
- **Enhanced cost estimation accuracy**, as digital models help predict manufacturing expenses earlier in the design process, reducing budgetary overruns.
- **Scalability for complex aerospace projects**, ensuring that lessons learned from one design cycle can be transferred efficiently to future iterations.

By leveraging MBSE, AGILE 4.0 enables a real-time evaluation of trade-offs, ensuring that decisions made in the early design phases are aligned with production feasibility and cost-effectiveness. The integration of digital twins and virtual prototyping further enhances predictive accuracy, reducing the reliance on costly physical testing. Additionally, automated manufacturing process simulations allow designers to foresee potential bottlenecks and adjust accordingly before committing to large-scale production.

CHAPTER 3: METHODOLOGY

The ‘’Methodology’’ chapter outlines the structured approach adopted to achieve the objectives of this research. The study is developed within the COLOSSUS European Project, focusing on integrating manufacturing cost and time estimation within the Multidisciplinary Design Optimization (MDO) process. The primary application is the EVE (Eco-friendly air Vehicles for multiple operating Environments) use case, which investigates innovative aerial wildfire suppression solutions.

This chapter is divided into four key sections:

1. **EVE – Wildfire Suppression Use Case**: This section presents the development of wildfire-fighting scenarios, defining operational needs and environmental constraints. Two distinct scenarios—one in an inland mountainous region and another in a coastal island environment—are analyzed to assess different challenges and operational requirements for firefighting aircraft.
2. **Problem Definition & System Specification**: A systematic approach is applied to define stakeholders, their needs, and corresponding system requirements. The ARMADE tool, developed by DLR, is employed to ensure traceability between high-level objectives and technical specifications, particularly in the System-of-Systems (SoS) approach.
3. **Manufacturing & Design**: The research investigates how manufacturing cost and time estimation methodologies can be embedded into the early design stages. A Python-based computational framework is developed to evaluate manufacturing trade-offs for key structural components, including frames, stringers, and skin panels. The study incorporates real-world manufacturing datasets from TECNAM and explores various material-process combinations to enhance manufacturability.
4. **Value-Driven Tradespace Exploration**: This section introduces the application of the VALORISE platform, which enables multi-objective trade-off analysis by integrating cost, time, quality, and automation scores. By leveraging Multi-Attribute Utility Theory (MAUT), this approach facilitates data-driven decision-making, ensuring that manufacturing feasibility is considered alongside performance optimization.

Through these methodological steps, the study aims to bridge the gap between conceptual aircraft design and real-world manufacturing constraints, contributing to a more integrated, efficient, and sustainable aerospace development process.

3.1 EVE

The EVE use case focuses on developing an advanced and sustainable aerial firefighting system capable of addressing the increasing risks of wildfires in Europe. The approach is solution-agnostic, emphasizing stakeholder needs and the wildfire problem rather than predefining a specific technological solution. [11] According to the authors, to construct a realistic operational framework, two distinct wildfire-fighting scenarios have been developed: one in an alpine, landlocked region, and the other on a Mediterranean island. These scenarios consider different environmental and logistical challenges, ensuring a comprehensive assessment of operational needs. The development of these scenarios follows a top-down approach, ensuring traceability from high-level stakeholder needs to detail technical requirements. A structured methodology has been applied, including stakeholder workshops, expert consultations, and open-source research on wildfire dynamics. This approach enables the integration of AI, automation, and advanced aircraft technologies into a cohesive system capable of rapid response, effective fire suppression, and minimal ecological footprint.

Each scenario consists of three primary components:

- **Objectives:** The specific goals to be achieved in the wildfire-fighting operation.
- **Environmental Description:** The characteristics of the operational environment, including terrain, weather conditions, and available resources.
- **Events Timeline:** A sequence of events leading to the wildfire outbreak and subsequent firefighting operations.

Besides, for each scenario, there are three different environments, which are divided into blue, green and red. The latter is described subsequently. Hereafter a summary regarding the three different environments:

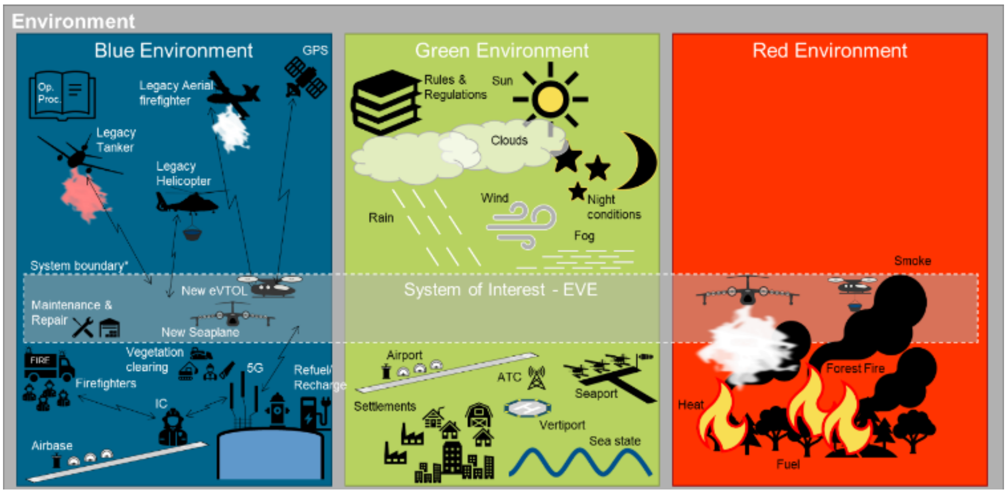


Figure 8: Environments representation

3.1.1 SCENARIO 1: INLAND WILDFIRE (LANDLOCKED REGION)

The first scenario takes place in the Pyrenees, near Luz-Saint-Sauveur, where wildfire is reported in a mountainous area. Due to dry vegetation and rough terrain, the local Incident Commander (IC) determines that aerial firefighting support is necessary. The firefighting operation is coordinated with local authorities and includes helicopters and a Canadair CL-415 aircraft.

The primary objectives are to:

- Reduce wildfire spread and damage to vegetation, infrastructure, and property.
- Minimize casualties and mitigate environmental impact, including carbon emissions.
- Ensure cost-effective and efficient aerial firefighting operations.

The operational environment is structured into three categories:

- **Blue Environment:** Involves direct response units, including ground firefighters, aerial assets, and command centers.
- **Green Environment:** Consists of meteorological and geographical factors, such as wind conditions, topography, and available resources.
- **Red Environment:** Represents the fire itself, its fuel sources, and its expansion dynamics.

A detailed timeline outlines key events, from the initial fire detection by tourists to the mobilization of firefighting teams. Coordination between air and ground units, along with resource management (e.g., fuel and water supply), plays a crucial role in the scenario's execution.

3.1.2 SCENARIO 2: ISLAND WILDFIRE (SEASIDE REGION)

The second scenario unfolds on Salamina Island, near Athens, where a wildfire is detected in a forested area close to residential zones. Given the proximity to urban settlements and the anticipated changes in wind direction, aerial firefighting assets are deployed to contain the fire. The local fire department coordinates operations with national authorities, supported by a helicopter dispatched from mainland Greece.

Key objectives mirror those of the inland scenario:

- Containing fire spread and minimizing ecological and infrastructural damage.
- Reducing environmental pollution and optimizing firefighting resources.
- Enhancing aerial firefighting effectiveness while ensuring operational safety.

The scenario's environmental framework follows the same categorization as the inland case, analyzing the interaction between response units (Blue), environmental factors (Green), and fire behavior (Red). Infrastructure, including Megara Airport, serves as a key operational hub for fuel and maintenance support.

A structured event timeline details the progression of the fire, from its ignition due to concentrated solar rays to the subsequent firefighting response. Strategic decision-making, driven by stakeholder needs and real-time meteorological updates, determines the efficiency of suppression efforts.

By addressing both the technical and operational aspects of wildfire response, EVE aims to develop a robust, adaptable, and efficient aerial firefighting strategy that aligns with the EU's climate neutrality objectives for 2050.

3.2 PROBLEM DEFINITION & SYSTEM SPECIFICATION

This section defines the problem addressed by the manufacturing-aware design methodology and formalizes the system specification process used to guide its implementation. Starting from the operational context and stakeholder needs, the approach structures the problem through a multi-layer system model using Model-Based Systems Engineering (MBSE) principles. The goal is to ensure that design choices align with both high-level mission objectives and production-related constraints, enabling a clear translation from requirements to technical system specifications.

As already mentioned, the problem definition and system specification deal with the identification of stakeholders, needs and requirements for different system layers that are the SoS, CS and sub-system

The definition of ‘’System of Systems’’ has been already provided in Chapter 1. Here-after, other terms are introduced for the sake of clarity:

- **Constituent System** or **System** or **Aircraft** or **System of Interest**: Constituent systems are integral components that can belong to one or more Systems of Systems (SoS). Each constituent system is independently functional, with its own development processes, management goals, and resource allocations. However, when integrated within an SoS, these systems interact to provide unique capabilities that enhance the overall performance of the SoS. Examples of such constituent systems include seaplanes and eVTOL aircraft.

- **Sub-System**: A Subsystem is an integral component of a system, yet it does not independently provide any benefit to the system or the System of Systems (SoS). Sub-systems contribute to the overall functionality and performance of the system when combined with other elements. Examples include hybrid electric propulsion, hull/floats, and vehicle-level AI technologies such as autopilot. Each sub-system, although lacking standalone utility, is essential for the comprehensive operation and efficiency of the larger system or SoS.

3.2.1 ARMADE

The **ARMADE** software is a tool designed by DLR for the structured and traceable management of key project elements, such as **stakeholders, needs, requirements,** and **success criteria**. Its primary objective is to enhance traceability among these elements, ensuring a clear association between the needs of various actors and the technical requirements to be met.

Through ARMADE, each stakeholder is directly linked to their corresponding needs, which in turn are connected to requirements and success criteria. This approach allows for effective monitoring and management of the relationships between different project levels, ensuring a systematic and detailed view of all interdependencies.

In this study, ARMADE was used to classify and analyze stakeholders and their needs, providing a structured basis for defining subsequent requirements and success criteria.

3.2.2 STAKEHOLDERS & NEEDS

Stakeholder is a neologism, derived from the expression “shareholder”, and refers to a concept of strategic management that broadens the view beyond the traditional economic roots. Stakeholders in this context can be defined as any group or individual who is affected by or can affect the achievement of the objectives of a system. The purpose of stakeholder management is to offer a strategic approach to consider and manage all relevant groups and relationships that may affect the success and performance of the system (e.g. business activity, joint project, policy implementation and so on).

Can be used also other definitions about the ‘’Stakeholder’’ such as:

- A stakeholder is a group or individual that is affected by or has a stake in the product or project.

In the context of **COLOSSUS**, primary stakeholders are groups or individuals which are actively engaged in transactions with the system, such as selling an aircraft for profit or using a service as a travelling customer.

Secondary stakeholders do not engage in direct exchange but are affected by the system or can affect its conduct or outcome, for example people living in the vicinity of airports (like noise complaints) or citizens who are protected against wildfires.

Complex systems and SoS often include a wide variety of stakeholders with different interests, expertise, and levels of understanding. This allows to develop a broader and more robust understanding of the interconnections, interdependencies, influences and other favorable or adverse effects the SoS, or products or services embedded in this SoS, will be exposed to in real-world applications.

Thus, a SoS view can facilitate the management and coherence of the various stakeholders. This necessitates a systematic approach to identifying, considering and managing the relevant stakeholders and their needs.

An example of Stakeholders is reported in Figure 9.

Figure 9: Stakeholders example

Stakeholders' express needs. A need may be defined as:

1. A type of necessity.

2. A desire or want.

3. A wish for something that is lacking.

Moreover, needs are unstructured, expressed in general (sometimes ambiguous) terms.

Some examples of needs are reported in Figure 10.

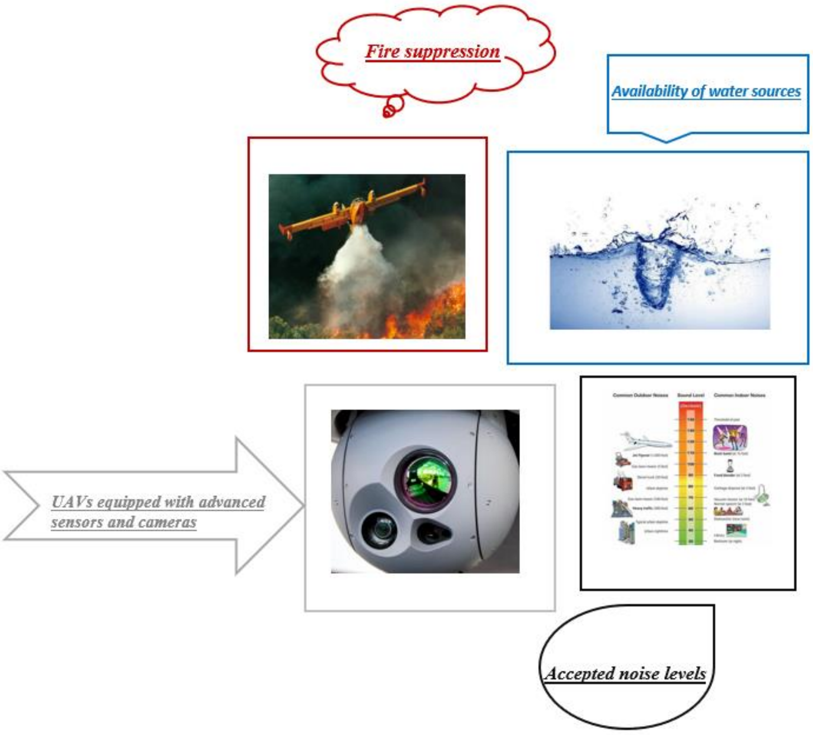


Figure 10: Needs example

In this study, Stakeholders were initially identified within the Deliverable paper [11], where they were defined alongside the scenario analysis. Subsequently, stakeholders were categorized in an Excel sheet and divided into System of Systems and Constituent Systems.

The following stakeholder categories were identified as the latter referred to the Constituent System, as follows:

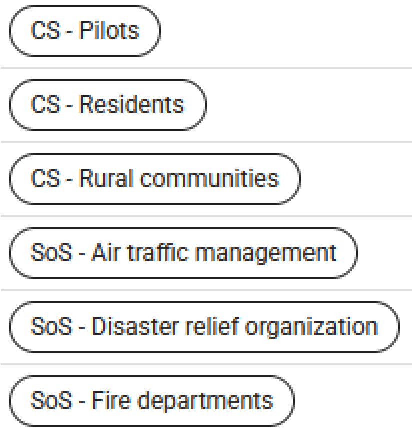
- Airport Operators
- Fire Departments
- Maintenance, Repair and Overhaul (MRO)
- Original Equipment Manufacturer (OEM)
- OEM eVTOL
- OEM Seaplane
- Pilots
- Residents
- Rural Communities

The stakeholders referred to the System of Systems:

- Air Traffic Management

- Disaster Relief Organization
- Fire Departments
- Government
- Policy Makers
- Residents

Here-after is depicted part of the mentioned stakeholders that were inserted into ARMADE:



CS - Pilots
CS - Residents
CS - Rural communities
SoS - Air traffic management
SoS - Disaster relief organization
SoS - Fire departments

Figure 11: Stakeholders into ARMADE

The needs represent the expectations of each stakeholder group. ARMADE was used to establish direct traceability between stakeholders and their associated needs, ensuring that all project requirements are properly structured and linked.

Here are some of the key needs identified, categorized according to their stakeholder groups. For some needs the implementation into ARMADE is shown:

- Minimize acquisition costs. This need is relevant for the Government and Original Equipment Manufacturers.
- Minimize operational costs. This need is associated with the Disaster Relief Organization, and Airport Operators.
- Maximize cargo load factor. This need arises from the Fire Departments.
- Optimize flight routes. This need is driven by Air Traffic Management.
- Ensure regulatory compliance. This need is a priority for the Government.
- Maximize profit. This need concerns Original Equipment Manufacturers.

Into ARMADE the implementation was in this way:

- Improve coordination and communication between fire departments and airport operators. This need is critical for Fire Departments.
- Minimize response time to extinguish fires. This need is emphasized by Fire Departments and Disaster Relief Organizations.
- Minimize fire department costs related to acquisition, operations, and human resources. This need is relevant for the Fire Departments and the Government.
- Ensure fire detection in protected areas. This need is particularly important for Disaster Relief Organizations.
- Ensure suppression of fire. This need is required by the Fire Departments and the Government.
- Minimize health damage to people affected by fire. This need is addressed by Disaster Relief Organizations and Residents.
- Ensure availability of water sources for firefighting. This need is relevant for Airport Operator.
- Minimize environmental impact, particularly CO_2 emissions. This need is supported by the Government.
- Minimize noise emissions. This need is a concern for Policy Makers and Residents.

- Reduce pollution levels. This need is addressed by Policy Makers and the Government.
- Improve energy efficiency. This need is associated with Original Equipment Manufacturers.
- Minimize maintenance costs. This need is relevant for Maintenance, Repair, and Overhaul services and Original Equipment Manufacturers.
- Minimize repair time. This need is a priority for Maintenance, Repair, and Overhaul services.

- Improve maintainability of aircraft components. This need is crucial for Maintenance, Repair, and Overhaul services and Original Equipment Manufacturers.
- Ensure a high technology readiness level (TRL). This need is emphasized by the Government.

- Equip UAVs with advanced sensors and cameras for monitoring. This need is required by the Disaster Relief Organizations.
- Minimize mission time. This need is a priority for the Fire Departments and Disaster Relief Organization.
- Improve operational efficiency. This need is relevant for Air Traffic Management and Original Equipment Manufacturers.

The structured classification of stakeholders and needs in ARMADE enables seamless traceability, ensuring that each requirement is systematically linked to the entities responsible for its fulfillment. This foundation is essential for defining requirements and success criteria, which will be addressed in the following sections.

3.2.3 REQUIREMENTS

Concerning the ‘’Requirements’’, also in this case is mandatory to define formally what are specific:

- A requirement is a well-defined statement that rephrases a need by following predetermined structures and rules, to be correct, clear, unambiguous and complete.

In other terms, thanks to the requirements, needs can be explained in a better manner. After their definition, all the needs are transformed into requirements following specific rules and patterns as well.

As mentioned before at the beginning of this paragraph, each type of requirement has a defined grammar, a set of mandatory and optional elements that ensure verifiability related to the type. [5]

The requirements are divided into different types which are:

- Functional.
- Non-functional.
- Performance.
- Design.
- Environmental.
- Suitability.

In this master thesis contemplated only the functional, non-functional and performance requirements, which are the most important for this kind of topic.

In the specific:

- Functional requirements define what functions need to be performed to accomplish the objectives.

- Non-functional requirements aren’t directly related to a specific function, but they are still important for the general informations.
- Performance requirements define how well the system needs to perform the functions.

Requirements follow patterns. For the specified requirements, the patterns are proposed here-after:

- Functional
  The **[SYSTEM]** shall **[FUNCTION]**.

- Non-functional
  The **[SYSTEM]** shall has **[PARAMETER] [CONSTRAINT]**.

- Performance
  The **[SYSTEM]** shall **[FUNCTION]** with **[PARAMETER] [CONSTRAINT] [VALUE] [UNIT]** while **[CONDITION]**.

To clarify, some practical examples can be done for each requirement’s type:

- Functional
  The **[SYSTEM OF SYSTEMS]** shall **[SUPPRESS FIRE]**.

- Non-functional
  The **[CONSTITUENT SYSTEM]** shall has **[MAINTAINABILITY] [MAXIMIZE]**.

- Performance
  The **[eVTOL]** shall **[FLY]** with **[ALTITUDE] [GREATER OR EQUAL THAN] [500] [m]** while **[CRUISE]**.

All these rules that are just explained are formulated from INCOSE (International Council on Systems Engineering), which is a no profit membership organization founded to develop and disseminate the transdisciplinary principles and practices that enable the realization of successful systems. INCOSE is designed to connect systems engineering professionals with educational, networking, and career-advancement opportunities in the interest of developing the global community of systems engineers and systems approaches to problems. [6]

In addition, INCOSE has other rules about the requirements’ statements definition, which are:

- Use the active voice in the main sentence structure with the responsible entity clearly identified.
- Define terms.
- Use appropriate units when stating quantities.
- Avoid the use of vague terms.
- Use definite article ‘’the’’ rather than the indefinite article ‘’a’’.

The following section outlines the main functional requirements and their corresponding stakeholders.

- The constituent system shall move through the air.

The CS shall move through the air

- The constituent system shall drop extinguishing substances from the air.
- The constituent system shall be equipped with foam suppression systems. This requirement pertains to the Fire Departments.
- The constituent system shall move on the ground. This requirement is relevant to the Airport Operators.

The CS shall move on the ground

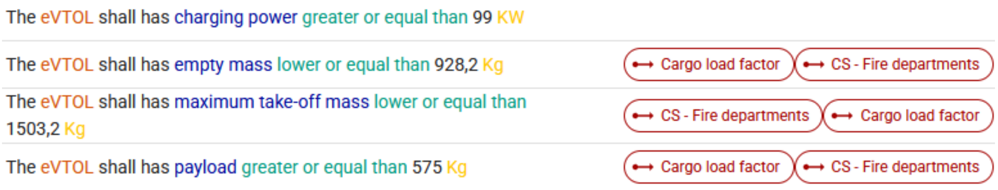
- The constituent system shall transport payload. This requirement is associated with the Fire Departments and the Disaster Relief Organization.
- The constituent system shall have water sources available. This requirement is related to the Airport Operators.
- The system of systems shall enable constituent system communication. This requirement concerns the Disaster Relief Organization and Fire Departments.
- The system of systems shall detect fire. This requirement is connected to the Disaster Relief Organization.
- The system of systems shall define flight paths. This requirement is attributed to Air Traffic Management.

The SoS shall define flight paths

- The system of systems shall guarantee the maximum safety level. This requirement is tied to the Government.
- The system of systems shall protect residents.
- The system of systems shall suppress fire. This requirement is linked to the Disaster Relief Organization.
- The system of systems shall transport water.

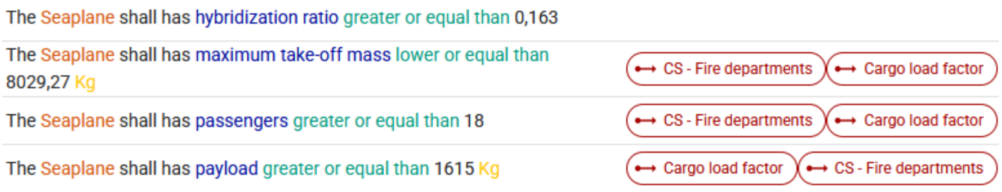
Now the section regarding the main non-functional requirements:

- The Constituent System shall maximize availability. This requirement is linked to the Airport Operator.
- The Constituent System shall maximize maintainability. This requirement came from the need for Maintenance, Repair, and Overhaul.
- The Constituent System shall minimize maintenance costs. This requirement is driven by the Maintenance, Repair, and Overhaul.
- The Constituent System shall maximize profit. This requirement originates from the Original Equipment Manufacturer.
- The eVTOL shall have a charging power greater or equal to 99 KW.
- The eVTOL shall have an empty mass lower or equal to 928.2 Kg. This requirement is influenced by the Fire Departments.
- The eVTOL shall have a maximum take-off mass lower or equal to 1503.2 Kg. This requirement is defined by the Fire Departments.
- The eVTOL shall have a payload greater or equal to 575 Kg. This requirement is based on Fire Departments.



The eVTOL shall has charging power greater or equal than 99 KW		
The eVTOL shall has empty mass lower or equal than 928,2 Kg	Cargo load factor	CS - Fire departments
The eVTOL shall has maximum take-off mass lower or equal than 1503,2 Kg	CS - Fire departments	Cargo load factor
The eVTOL shall has payload greater or equal than 575 Kg	Cargo load factor	CS - Fire departments

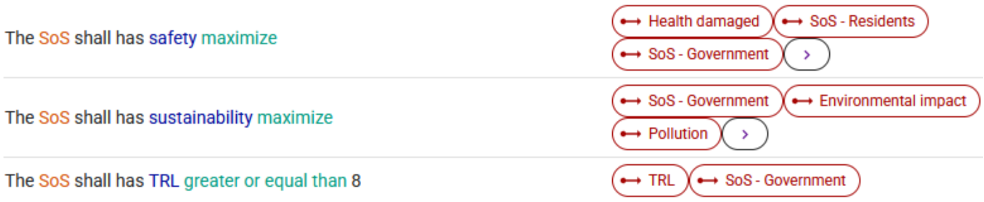
- The seaplane shall have a hybridization ratio greater or equal to 0.163.
- The seaplane shall have a maximum take-off mass lower or equal to 8029.27 Kg. This requirement stems from the Fire Departments.
- The seaplane shall have passengers greater or equal to 18.
- The seaplane shall have a payload greater or equal to 1615 Kg. This requirement is linked to the Fire Departments.



The Seaplane shall has hybridization ratio greater or equal than 0,163		
The Seaplane shall has maximum take-off mass lower or equal than 8029,27 Kg	CS - Fire departments	Cargo load factor
The Seaplane shall has passengers greater or equal than 18	CS - Fire departments	Cargo load factor
The Seaplane shall has payload greater or equal than 1615 Kg	Cargo load factor	CS - Fire departments

- The seaplane shall have a wingspan equal to 20.63 meters.
- The System of Systems shall minimize acquisition costs. This requirement is derived from the Government.
- The System of Systems shall have a lifecycle greater or equal to 30 years. This requirement is linked to Fire Departments.
- The System of Systems shall maximize safety. This requirement originates from the Government.

- The System of Systems shall maximize sustainability. This requirement is driven by the Government and the Residents.
- The System of Systems shall have a technology readiness level (TRL) greater or equal to 8. This requirement originates from the Government.



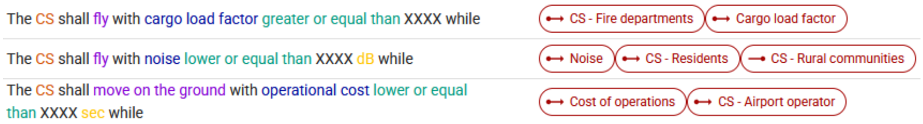
The SoS shall has safety maximize	Health damaged SoS - Residents SoS - Government
The SoS shall has sustainability maximize	SoS - Government Environmental impact Pollution
The SoS shall has TRL greater or equal than 8	TRL SoS - Government

Concerning the main performance requirements:

- The Constituent System shall fly with a cargo load factor greater or equal to a specified threshold while in operation. This requirement is linked to Fire Departments.

- The Constituent System shall fly with noise lower or equal to a defined dB threshold. This requirement is associated with Regulations and Residents.

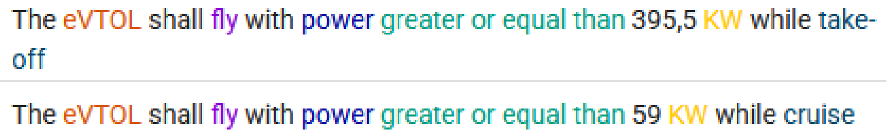
- The Constituent System shall move on the ground with operational costs lower or equal to a specific limit. This requirement is influenced by Airport Operator considerations.



The CS shall fly with cargo load factor greater or equal than XXXX while	CS - Fire departments Cargo load factor
The CS shall fly with noise lower or equal than XXXX dB while	Noise CS - Residents CS - Rural communities
The CS shall move on the ground with operational cost lower or equal than XXXX sec while	Cost of operations CS - Airport operator

- The eVTOL shall fly with power greater or equal to 395.5 KW while taking off.

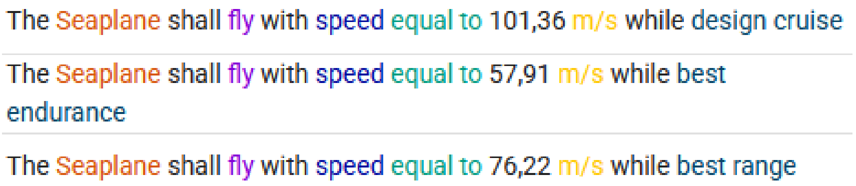
- The eVTOL shall fly with power greater or equal to 59 KW while in cruise.



The eVTOL shall fly with power greater or equal than 395,5 KW while take-off

The eVTOL shall fly with power greater or equal than 59 KW while cruise

- The Seaplane shall fly with a range equal to 500,000 m while in design phase.
- The Seaplane shall fly with a speed equal to 101.36 m/s while in design cruise.
- The Seaplane shall fly with a speed equal to 57.91 m/s while achieving best endurance.
- The Seaplane shall fly with a speed equal to 76.22 m/s while achieving best range.

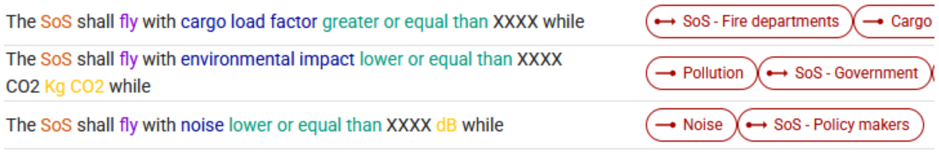


The Seaplane shall fly with speed equal to 101,36 m/s while design cruise

The Seaplane shall fly with speed equal to 57,91 m/s while best endurance

The Seaplane shall fly with speed equal to 76,22 m/s while best range

- The Seaplane shall fly with a speed greater or equal to 46.45 m/s while taking off.
- The Seaplane shall fly with a speed greater or equal to 68 m/s while loitering.
- The Seaplane shall fly with a vertical distance lower or equal to 15 m while landing.
- The System of Systems shall fly with a cargo load factor greater or equal to a specified threshold while in operation. This requirement is linked to Fire Departments.
- The System of Systems shall fly with an environmental impact lower or equal to a defined CO_2 emissions threshold. This requirement is associated with the Government.
- The System of Systems shall fly with noise lower or equal to a specified dB threshold. This requirement is influenced by policy makers' concerns.



The SoS shall fly with cargo load factor greater or equal than XXXX while	SoS - Fire departments Cargo
The SoS shall fly with environmental impact lower or equal than XXXX CO2 Kg CO2 while	Pollution SoS - Government
The SoS shall fly with noise lower or equal than XXXX dB while	Noise SoS - Policy makers

- The System of Systems shall suppress fire with damaged property lower or equal to a set threshold. This requirement is associated with Disaster Relief Organizations.

- The System of Systems shall suppress fire with extinguish time lower or equal to a specified number of seconds. This requirement is linked to Fire Departments.
- The System of Systems shall transport water with a water mass greater than 1000 Kg/h. This requirement is linked to Airport Operator.

3.2.4 SUCCESS CRITERIA

Success criteria represent a set of measurable and verifiable conditions that determine whether a system, methodology, or project has successfully met its intended goals and objectives. They serve as essential benchmarks that guide the evaluation process, ensuring that the design, development, and implementation phases align with predefined expectations. In the context of this thesis, success criteria are particularly crucial as they provide a structured framework for assessing the effectiveness, efficiency, and overall feasibility of the proposed aerospace engineering solutions.

By defining clear and quantifiable parameters, success criteria enable a systematic and objective evaluation of project outcomes, reducing ambiguity and ensuring alignment with stakeholder expectations. These criteria are intrinsically linked to system requirements, operational constraints, and performance objectives, forming a bridge between high-level conceptual goals and concrete technical achievements. Their role extends beyond simple validation, as they also facilitate iterative improvements by identifying areas that require refinement or optimization.

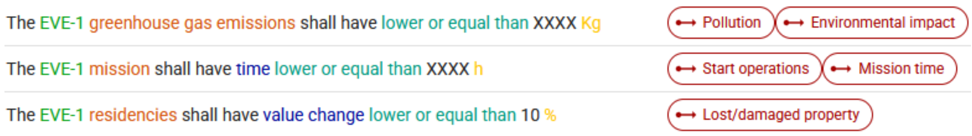
In the aerospace domain, success criteria often encompass multiple dimensions, including technical performance, economic viability, environmental sustainability, regulatory compliance, and operational effectiveness. Given the multidisciplinary nature of aircraft design and manufacturing, these criteria must capture a holistic perspective that integrates aerodynamics, structural integrity, production efficiency, and cost-effectiveness. Furthermore, the evolving landscape of digital engineering, model-based systems engineering, and multidisciplinary design optimization necessitates the definition of adaptable and scalable success criteria that can accommodate future advancements and technological shifts.

Within this thesis, success criteria play a pivotal role in evaluating the methodologies and tools developed for integrating manufacturing considerations into the early stages of aircraft design. By establishing key performance indicators, such as manufacturing costs, production times, environmental impact, and operational efficiency, it becomes possible to conduct a thorough trade-off analysis and optimize design choices accordingly. These metrics not only support data-driven decision-making but also contribute to the broader goal of enhancing sustainability, scalability, and competitiveness in modern aerospace engineering.

Ultimately, success criteria function as a foundation for continuous improvement, enabling a dynamic and adaptive approach to aircraft design and development. By rigorously defining and applying these criteria, this research ensures that the proposed methodologies are not only theoretically sound but also practically viable, fostering innovation while maintaining alignment with industry standards and stakeholder expectations.

The main success criteria for Scenario 1 are as follows:

- Greenhouse gas emissions shall be lower or equal to a specified limit (Kg).
- Mission time shall be lower or equal to a specified duration (hours).
- Residencies shall experience a value change lower or equal to 10%.



The EVE-1 greenhouse gas emissions shall have lower or equal than XXXX Kg

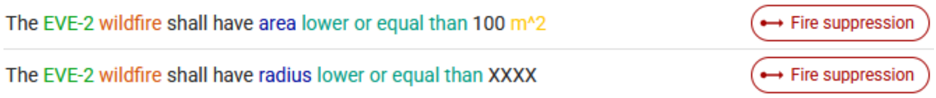
The EVE-1 mission shall have time lower or equal than XXXX h

The EVE-1 residencies shall have value change lower or equal than 10 %

- Wildfire area shall be lower or equal to 50 m².
- Wildfire radius shall be lower or equal to a specified unit.

The success criteria for Scenario 2 are as follows:

- Greenhouse gas emissions shall have a value lower or equal to a specified limit (Kg).
- Mission time shall be lower or equal to a specified duration (hours).
- Residencies shall experience a value change lower or equal to 10%.
- Wildfire area shall be lower or equal to 100 m².
- Wildfire radius shall be lower or equal to a specified limit.



The EVE-2 wildfire shall have area lower or equal than 100 m^2

The EVE-2 wildfire shall have radius lower or equal than XXXX

3.3 MANUFACTURING & DESIGN

3.3.1 METHODOLOGIES AND TOOLS FOR MANUFACTURING COST AND TIME ESTIMATION

In the aerospace industry, accurately estimating manufacturing costs and times is crucial for effective project planning and resource allocation. Various methodologies have been developed to create comprehensive datasets that inform decision-making processes. These methodologies often involve a combination of empirical data analysis, parametric modeling, and the application of advanced computational tools.

One common approach is the use of parametric cost estimation models, which rely on historical data to establish relationships between cost drivers and manufacturing expenses. By analyzing past aerospace programs, cost analysts can perform regression analyses to identify key parameters—such as weight, complexity, and production rate—that significantly impact costs. These models enable the prediction of manufacturing costs for new projects by applying the derived relationships to current design parameters.

The dataset used for the manufacturing cost and time estimation has been provided by **TECNAM**, an aircraft manufacturer. The raw data includes detailed cost breakdowns for key structural components such as frames, stringers, and skin panels. These data serve as the foundation for further calculations performed using a custom Python script.

The Python script is designed to generate all feasible combinations of materials and manufacturing processes, allowing for comprehensive costs, times, quality scores and automation scores estimation. By automating this process, the script enables rapid exploration of alternative designs while maintaining accuracy and consistency in cost estimation.

The output generated from these computational tools can be further utilized in specialized software platforms, such as **VALORISE**, to perform advanced analyses. By importing the calculated performance metrics into such platforms, engineers can conduct in-depth evaluations of different manufacturing scenarios, considering factors like cost, time, quality, and automation levels. This integration supports informed decision-making by providing a holistic view of the potential implications associated with various design and manufacturing choices.

3.3.2 VEHICLE PERFORMANCE METRICS AND COST COUPLING

The COLOSSUS project focuses on optimizing aircraft design by balancing performance efficiency with manufacturing cost-effectiveness. Key performance metrics considered include:

- **Block fuel consumption** is directly linked to weight reduction.
- **Manufacturing costs and time**.
- **Manufacturing quality score**.
- **Manufacturing automation score**.

The integration of these metrics allows for in-depth trade-off studies, determining the optimal balance between lightweight structures and cost reduction. The generated cost and performance data are subsequently analyzed to identify viable manufacturing pathways that align with both economic and environmental objectives.

Block fuel consumption is directly influenced by the aircraft's weight and aerodynamic efficiency. Reducing this metric is essential for meeting environmental objectives, as it leads to lower greenhouse gas emissions and operating costs. At the same time, minimizing manufacturing costs and time is crucial for achieving cost-effective production without compromising quality.

By coupling these performance metrics with manufacturing costs and times, the project facilitates comprehensive trade-off analyses. This approach enables the identification of optimal design solutions that meet performance targets while remaining cost-effective and efficient to produce.

3.3.3 COST MODEL ANALYSIS: FRAMES, STRINGERS AND SKIN PANELS

In this study, the structural components of a reference fuselage with a surface area of 61.33 m² were analyzed to evaluate the transition from a conventional landplane to a seaplane configuration. The investigation focused on the primary structural elements, namely frames, stringers, and skin panels, considering different material choices and manufacturing processes.

The frames were assessed using composite-carbon, alloy and titanium, while the stringers were analyzed with composite-carbon and alloy. For the skin panels, composite-carbon, composite-glass, composite-kevlar, and alloy were considered. The manufacturing processes varied depending on the material and component type. Frames in composite-carbon were fabricated using Hand Layup and Resin-Infused techniques, as well as Hand Layup Vacuum Bagging, whereas alloy and titanium frames were produced via CNC Machining. Similarly, composite-carbon stringers were manufactured using Hand Layup and Resin-Infused techniques, along with Hand Layup Vacuum Bagging, while alloy stringers were fabricated through CNC Machining. Skin panels in composite-carbon were processed using Hand Layup and Resin-Infused, as well as Hand Layup Vacuum Bagging. Composite-glass panels underwent Hand Layup and Resin-Infused or Hand Layup Vacuum Bagging Autoclave. Composite-kevlar panels were processed with Hand Layup Vacuum Bagging Autoclave, whereas alloy panels were manufactured using Calendering and Deep-Drawing techniques.

Each manufacturing process has been coupled with two different index which are the quality score and the automation score:

Process ID	Quality Score	Automation Score
Hand Layup and Resin-Infused	3	4
Hand Layup Vacuum Bagging	7	6
CNC Machining	10	9
Calendering	6	5
Deep-Drawing	8	7
Hand Layup Vacuum Bagging Autoclave	8	5

Table 1: Processes coupled with quality and automation scores

By starting from a conventional landplane configuration, this study aims to investigate the structural implications of transitioning to a seaplane, assessing how different material selections and manufacturing processes influence the overall design and performance.

Here-after is represented a simple sample regarding one combination in terms of material and process for each fuselage component. The following tables therefore illustrate the initial manufacturing costs and times distribution for key structural components:

FRAMES					
LANDPLANE					
Material	**Process**	**Mat. Cost [€]**	**Lab. Cost [€]**	**Man. Cost [€]**	**Man. Time [hr]**
Carbon	Hand Layup Res.-Infus.	5614	6228	11842	16
	Hand Layup Vac. Bag.	6175	5783	11958	16
SEAPLANE					
Material	**Process**	**Δ [€]**	**Δ [€]**	**Δ [€]**	**Δ [hr]**
Carbon	Hand Layup Res.-Infus.	580	2952	3532	8
	Hand Layup Vac. Bag.	420	1897	2317	8

Table 2: Some frames costs and times

STRINGERS					
LANDPLANE					
Material	**Process**	**Mat. Cost [€]**	**Lab. Cost [€]**	**Man. Cost [€]**	**Man. Time [hr]**
Al	CNC Machining	980	2464	3444	16
SEAPLANE					
Material	**Process**	**∆ [€]**	**∆ [€]**	**∆ [€]**	**∆ [hr]**
Al	CNC Machining	0	0	0	0

Table 3: Some stringers costs and times

SKIN PANELS					
LANDPLANE					
Material	**Process**	**Mat. Cost [€]**	**Lab. Cost [€]**	**Man. Cost [€]**	**Man. Time [hr]**
Al	Calendering	10.980 €	1.285 €	12.265 €	40
	Deep-Drawing	10.980 €	5.865 €	16.845 €	16
SEAPLANE					
Material	**Process**	**∆ [€]**	**∆ [€]**	**∆ [€]**	**∆ [hr]**
Al	Calendering	1.425 €	560 €	1.985 €	8
	Deep-Drawing	1.425 €	1.024 €	2.449 €	8

Table 4: Some skin panels costs and times

From this dataset, it is evident that skin panels represent the highest cost and labor-intensive process, while stringers have the lowest manufacturing cost. These variations provide insight into potential cost-saving opportunities by optimizing material selection and automation levels.

Always concerning this Excel data, the latter are referred to one unit for each component, like one frame, one stringer and one skin panel. Moreover, manufacturing costs are the sum between material costs and labor costs.

Starting from this dataset, some cost and time normalization relationships were applied to ensure that the results could be extended to any fuselage configuration. These relationships allowed for a standardized evaluation of manufacturing costs and production times, making the findings applicable beyond the specific reference fuselage analyzed. Practically, based on the previous relationships, have been calculated the total costs and times referred to all the frames, stringers and skin panels based on the examinated fuselage.

Done that, all the dataset has been inserted into Python code to achieve the overall costs and times, referred to the sum between frames costs, stringers costs and skin panels costs, the average quality scores and automation scores regarding the landplane which discussed before.

3.3.4 MDO FORMULATION INTEGRATING DESIGN AND MANUFACTURING

Multidisciplinary Design Optimization is a methodology that integrates various engineering disciplines to achieve optimal design solutions. In the context of aircraft design, MDO frameworks consider aerodynamic performance, structural integrity, propulsion systems, and manufacturing processes concurrently. This holistic approach allows for the exploration of design trade-offs and the identification of configurations that best satisfy multiple objectives.

The MDO formulation for the COLOSSUS project involves a multi-objective optimization strategy that seeks to minimize both the aircraft's weight and manufacturing costs. This strategy requires the development of accurate models for each discipline and their seamless integration into a unified computational framework. Advanced optimization algorithms are employed to navigate the complex design space and identify Pareto-optimal solutions that represent the best possible compromises between conflicting objectives.

Trade-off studies are conducted to compare different manufacturing techniques, materials, and design configurations. These studies assess the impact of various choices on performance metrics such as fuel efficiency, production cost, and build time. Value-driven analyses further evaluate the benefits of incorporating advanced manufacturing technologies, such as additive manufacturing and automation, into the production process. By quantifying the value added by these technologies, the project can make informed decisions about their implementation.

A crucial part of this process is the generation of quantitative performance estimates. The Python script outputs its calculated results like cost, time, quality score and automation score. These values represent performance metrics for each material-manufacturing combination and are subsequently imported into a specialized software which is **VALORISE**.

The latter plays a key role in processing these outputs by facilitating advanced trade-off analysis. It enables decision-makers to compare different manufacturing options based on predefined metrics, ensuring that selected configurations optimize both production efficiency and overall aircraft performance.

The integration of manufacturing considerations into the MDO framework ensures that the resulting aircraft designs are not only high-performing but also practical and economical to produce. This approach aligns with the industry's goals of developing innovative aircraft that meet stringent performance standards while adhering to budgetary and time constraints.

In summary, the COLOSSUS project employs a comprehensive methodology that combines empirical data analysis, computational modeling, and advanced optimization techniques to create a robust dataset of manufacturing costs and times. By integrating these datasets with vehicle performance metrics within an MDO framework, the project facilitates informed decision-making and the development of optimized aircraft designs.

3.4 VALUE-DRIVEN TRADESPACE EXPLORATION

In modern aerospace engineering, the complexity of aircraft design, manufacturing, and supply chain management has grown significantly due to increasing demands for sustainability, efficiency, and economic viability. Traditional design methodologies follow a sequential approach in which aircraft performance is optimized first, and only afterward are manufacturing feasibility and supply chain constraints considered. While this ensures that operational parameters such as fuel efficiency and aerodynamics are well-refined, it often leads to costly late-stage modifications when production or logistical challenges emerge. [12] [13]

To overcome these limitations, **Value-Driven Tradespace Exploration (VDTE)** provides a structured approach that integrates multiple decision-making criteria from the outset. Rather than treating design, manufacturing, and supply chain considerations as independent phases, VDTE enables their simultaneous evaluation, ensuring that trade-offs among different objectives—such as manufacturing cost, production time, quality score, and automation score—are explicitly accounted for.

At the heart of VDTE lies the **Value Model Theory**, a mathematical framework that enables the aggregation of multiple decision-making criteria into a single, dimensionless value metric. This approach leverages Multi-Attribute Utility Theory (MAUT) to transform various performance indicators, each with different scales and units, into a common value score that facilitates direct comparison of alternative design configurations.

Value Model Theory plays a crucial role in simplifying complex decision-making processes. It allows stakeholders to compare different aircraft configurations by aggregating four key performance parameters:

- **Manufacturing Cost** – The total cost associated with the production of the aircraft, including materials, labor, and logistical expenses.
- **Manufacturing Time** – The time required to complete the aircraft production cycle, from raw materials to final assembly.
- **Quality Score** – A measure of the final product's quality, incorporating defect rates, reliability, and compliance with safety standards.
- **Automation Score** – An index representing the degree of automation in the manufacturing process, which influences production efficiency and consistency.

Each of these attributes is assigned a weight (λ_i), which represents its relative importance in the decision-making process.

The total value of a given aircraft configuration is computed using the following formula:

$$\text{value} = \sum_{i=1}^{N} \lambda_i \, U(X_i)$$

where:

- **N** is the number of attributes (in this case, 4: manufacturing cost, manufacturing time, quality score and automation score).
- **$U(X_i)$** is the utility function that normalizes each attribute.
- **λ_i** represents the weight assigned to each attribute, indicating its relative priority.

A linear utility function is adopted for each attribute to ensure transparency and fairness across different stakeholders. This approach prevents unintended bias or nonlinear distortions that could disproportionately favor one criterion over another. By keeping the utility functions linear, VDTE ensures that the final value score accurately reflects the trade-offs involved without introducing artificial dominance of any single parameter.

To operationalize VDTE and simplify multi-criteria decision-making, the German Aerospace Center (DLR) has developed an advanced interactive dashboard called **VALORISE** which is the acronym of **Value-driven trAdespace visuaLizatiOn, exploRatIon, and aSsEssment**. This tool provides a real-time visualization and assessment environment, allowing decision-makers to dynamically explore the value-driven tradespace and compare alternative configurations.

VALORISE is designed to automate and streamline the evaluation process, enabling stakeholders to:

1. **Define Key Criteria** – Decision-makers specify the attributes (e.g., cost, time, quality, automation) to be considered in the analysis.
2. **Set Attribute Weights** – The importance of each criterion is quantified through adjustable weights (λ_i).
3. **Apply Utility Functions** – Linear utility functions are assigned to normalize each attribute's contribution to the total value score.
4. **Generate Tradespace Visualizations** – The tool computes and graphically represents different aircraft design and production alternatives.
5. **Perform Sensitivity Analysis** – Decision-makers can modify weights and parameters in real-time to explore how different prioritizations affect the optimal solution.

The main key features of VALORISE are the following:

- **Real-time scenario analysis**: Decision-makers can modify weights and immediately see the impact on rankings.

- **Multi-stakeholder alignment**: By ensuring a linear aggregation of utility functions, the tool prevents undue influence from any single decision-maker, promoting balanced outcomes.
- **Integration with Python-based analysis**: The manufacturing cost, time, quality, and automation scores are computed through Python models and seamlessly integrated into the dashboard.
- **Exportable reports**: The dashboard allows for the export of ranked solutions, helping teams document and justify their decisions.

The effectiveness of VDTE and VALORISE was demonstrated through an aeronautical case study focused on optimizing the Horizontal Tail Plane (HTP) design for a 90-passenger regional aircraft. The study aimed to determine the best supply chain configuration while balancing aircraft performance with production efficiency.

Key findings from the study include:

- When three attributes (time, quality, automation) were equally weighted, the solution that emerged is the most balanced option, offering a good trade-off between manufacturing feasibility and aircraft performance.
- When production time was given a higher priority, one parameter becomes the preferred alternative, indicating that different strategic goals lead to different optimal configurations.
- The degree of automation significantly influenced production time and cost, reinforcing the importance of integrating digital manufacturing technologies.

By integrating lifecycle considerations from the early design phases, VDTE offers several advantages over traditional aerospace design methods:

- **Transparency in Decision-Making**: Provides a quantitative and visual representation of trade-offs.
- **Cost and Time Reduction**: Minimizes the risk of late-stage redesigns, reducing unexpected expenses.
- **Enhanced Competitiveness**: Helps manufacturers select aircraft configurations that align with market needs and production capabilities.
- **Scalability to Future Technologies**: Can be applied to next-generation aircraft, including hydrogen-powered and electric aviation concepts.

CHAPTER 4: APPLICATION CASE

4.1 COST MODEL ANALYSIS APPLICATION

In this section, a detailed analysis of manufacturing cost models is conducted to evaluate different design configurations of the aircraft. The study is based on results obtained from a Python-based computational tool, which systematically assesses the manufacturing cost and production time of key structural components. The analysis focuses on two distinct cases: the landplane and the seaplane configurations, providing insights into how material and process choices influence overall cost-efficiency and manufacturability.

The assessment begins with a presentation of preliminary results obtained for the landplane configuration, highlighting key trends in manufacturing costs and production times. Subsequently, the study expands to include the seaplane variant, which introduces additional design complexities and material-process considerations.

Moreover, this section outlines the definition of stakeholders, needs, and requirements associated with aircraft manufacturing. These factors play a crucial role in aligning design choices with industrial feasibility and operational constraints. The gathered insights will be compared with the computational results to establish a comprehensive understanding of trade-offs involved in the decision-making process.

To further enhance the analysis, a trade-off study is conducted using the VALORISE platform. This tool enables the visualization and assessment of various configurations, facilitating a data-driven comparison of different manufacturing and design strategies. Through this structured approach, this section aims to bridge the gap between theoretical optimization and practical feasibility, ultimately guiding the selection of an optimal design solution.

4.1.1 PYTHON CODE RESULTS

In this subsection, are depicted some results, summarized in tabular format, that provide a clear comparison of cost and time estimates for different fuselage structural elements, which are frames, stringers and skin panels. These data points serve as a foundation for broader trade-off studies and optimization analyses conducted later in this chapter. By integrating these computational results with a structured assessment of stakeholder needs and industrial requirements, this study aims to establish a robust framework for cost-effective and efficient aircraft manufacturing.

As is shown here-after in a small sample, regarding the landplane:

Fr mat and proc	St mat and proc	Sk p mat and proc	Cost [€]	Time [hr]	Qual sc	Aut sc
C, H L Res - Inf	C, H L Res - Inf	C, H L Res - Inf	202654	65	3	4
C, H L Res - Inf	Al, CNC M.	C, H L Res - Inf	214167	57	5,33	5,67
Ti, CNC M.	C, H L Res-Inf	Al, Cal	1247097	195	6,33	6
Al, CNC M.	Al, CNC M.	Al, Deep-Dr.	190885	76	9,33	8,33
Ti, CNC M.	Al, CNC M.	C-K, H L Vc Bg At	1286550	183	9,33	7,67

Table 5: Some landplane's materials and processes combinations

The materials used for the frames include composite-carbon, alloy, and titanium, while the stringers are made of composite-carbon and alloy. The skin panels incorporate composite-carbon, composite-glass, composite-kevlar, and alloy. In the depicted sample skin panels refer to composite-carbon (C) and composite-kevlar (C-K).

The applied manufacturing processes vary depending on the material and component type. Hand Layup & Resin-Infused (H.L Res-Inf), CNC Machining (CNC M.), Hand Layup Vacuum Bagging Autoclave (H L Vc Bg At). Additional techniques were Deep-Drawing (Deep-Dr.) and Calendering (Cal).

The table also reports key performance indicators:

- **Cost [€]**: The total estimated production cost for each configuration.
- **Time [hr]**: The manufacturing time required for production.
- **Quality score (Qual sc)**: A numerical value representing the quality of the final product.
- **Automation score (Aut sc)**: A metric indicating the level of automation involved in the process.

Concerning the seaplane, some following data are shown:

Fr mat and proc	St mat and proc	Sk p mat and proc	Cost [€]	Time [hr]	Qual sc	Aut sc
C, H L Res - Inf	C, H L Res - Inf	C, H L Res - Inf	246138	82	3	4
C, H L Res - Inf	Al, CNC M.	C, H L Res - Inf	227105	74	6	5,67
Ti, CNC M.	C, H L Res-Inf	Al, Cal	1369793	229	6,33	6
Al, CNC M.	Al, CNC M.	Al, Deep-Dr.	220159	101	9,33	8,33
Ti, CNC M.	Al, CNC M.	C-K, H L Vc Bg At	1410898	217	9,33	7,67

Table 6: Some seaplane materials and processes combinations

This dataset provides a comprehensive evaluation of material-process combinations, aiding in the assessment of structural efficiency and production feasibility for the transition from a landplane to a seaplane configuration.

4.1.2 VALORISE ANALYSIS

In this section and in the following, a representation of the different plots and a trade-off analysis is conducted using the VALORISE platform to assess and compare different manufacturing strategies for both the landplane and seaplane configurations.

The VALORISE tool enables a structured, value-driven assessment by integrating multiple decision-making criteria into a unified framework. By leveraging the results obtained from the Python-based cost model, this analysis provides a comprehensive comparison of alternative manufacturing configurations, ensuring an optimal balance between cost-effectiveness, efficiency, and industrial feasibility.

The key objectives of this trade-off study include:

- Identifying the most cost-efficient and time-effective manufacturing pathways.
- Evaluating the impact of automation levels and quality scores on manufacturability.
- Comparing trade-offs between landplane and seaplane configurations in terms of feasibility and cost-effectiveness.

The findings from this analysis will provide valuable insights into the optimal manufacturing strategies that best align with stakeholder requirements while maintaining competitive performance metrics.

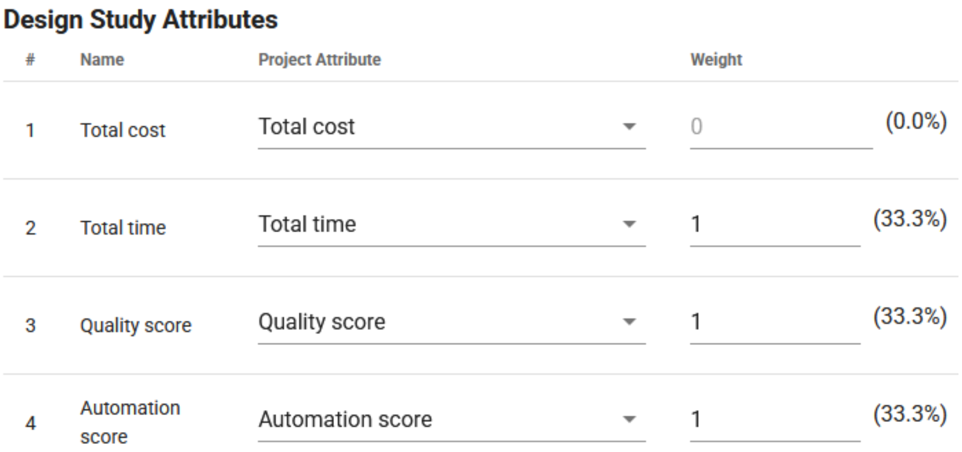
For analysis, the representation of all achieved plots is required. As follows, all the VALORISE analysis is shown, firstly for the landplane, then for the seaplane. First, based on the different wanted comparisons, and considered the cost as the independent variable, the remaining 3 attributes were setted in different ways, as follows in the next subsections.

4.1.2.1 LANDPLANE CASE

Time, quality score and automation score merged evaluation

Here-after the evaluation of the time, quality score and automation score in one combined Value.

As follows are shown the design study attributes, on VALORISE:



Design Study Attributes

#	Name	Project Attribute	Weight	
1	Total cost	Total cost	0	(0.0%)
2	Total time	Total time	1	(33.3%)
3	Quality score	Quality score	1	(33.3%)
4	Automation score	Automation score	1	(33.3%)

Figure 12: Design study attributes

Since there are 3 attributes merged in one Value, these 3 have the same weight, as in figure, equal to 33.3%. It may also be useful to allow the assignment of different weights to each parameter, should the user consider certain criteria to be more important than others.

All the attributes were represented with a linear model, so the trend is a straight line. At this point, as follows, the plot is shown:

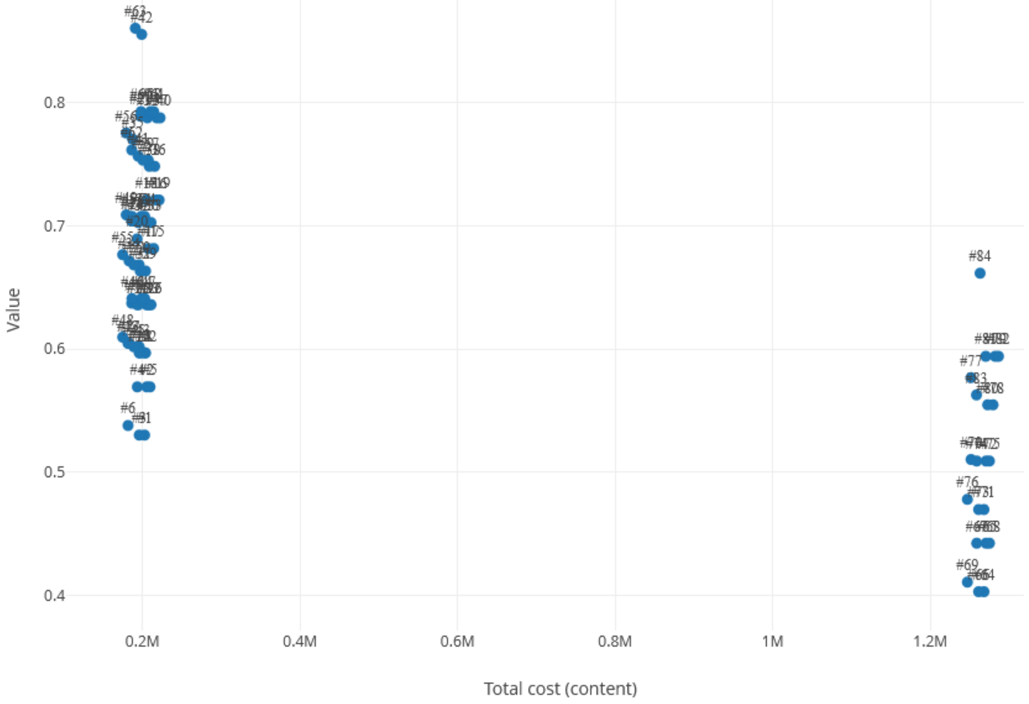


Figure 13: General plot - Value: Time, quality and automation score

Is it possible to see two different values clusters, which derive from the material which is used during the manufacturing process.

In particular, the cluster on the left is represented by all the values that refer to the following combination of materials: composite-carbon, composite-glass, composite-kevlar, alloy. This cluster is identified as ID_L_TQA where L is referred to the left cluster position and TQA are the Values considered that are time, quality score and automation score.

The cluster on the right is represented by all the values that refer to the titanium material with the remaining materials. This cluster is identified as ID_R_TQA where R is referred to the right cluster position and TQA are the Values considered that are time, quality score and automation score.

Therefore, it is possible to say that the values on the right have a higher cost than the values on the left, cause the titanium is more difficult to extract and work with. Furthermore, it is possible to notice that the ID_R_TQA has lower Values than the ID_L_TQA. The reason for that is the major manufacturing time related to titanium material, so the quality grade related to titanium material is lower. Since in the represented clusters the final value is the merge among time, quality score and automation score, it is important to mention that time affects mostly than the two scores, due to its high order of magnitude. This is the reason why despite the high numbers in terms of the two scores the final Value is lower with respect to the ID_L_TQA. For instance, the manufacturing time related to the titanium starts from 171 hours to 195 hours. For the other material combinations, the manufacturing time goes from 49 hours to 108 hours, so is it possible to notice that the reduction could be of 50% as well. It is important to remember that the Value represents the quality grade of the specific combination.

As follows is represented a clearer representation of all the values, to define the minimum Value, the maximum Value and the average Value of both clusters. The ID_L_TQA is the following:

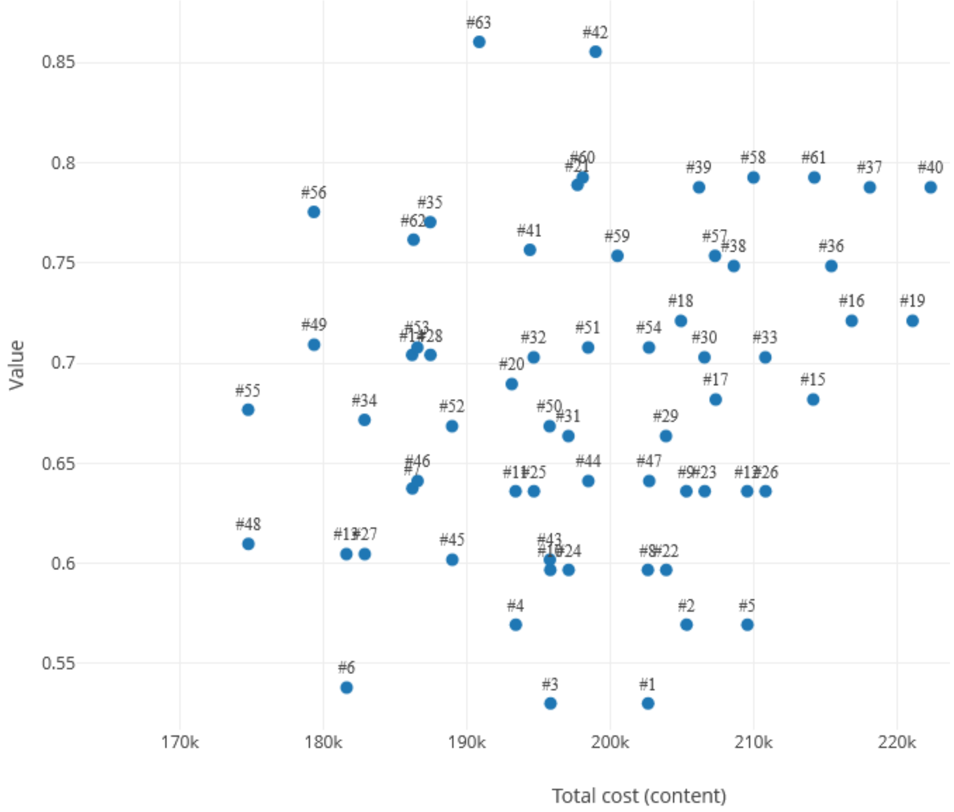


Figure 14: Left cluster plot – Value: Time, quality and automation score

Figure 14 shows that the maximum Value corresponds to the following combination:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 190885 €.
- Total time: 76 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,860.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one, in the specific that with the major cost, because is the worst between the two. The same aspect will be contemplated for the next possible multiple combinations:

- Frames material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.

- Total cost: 202654 €.
- Total time: 65 hours.
- Quality score: 3.
- Automation score: 4.
- Value: 0,530.

The average Value is equal to 0,679.

The ID_R_TQA is the following:

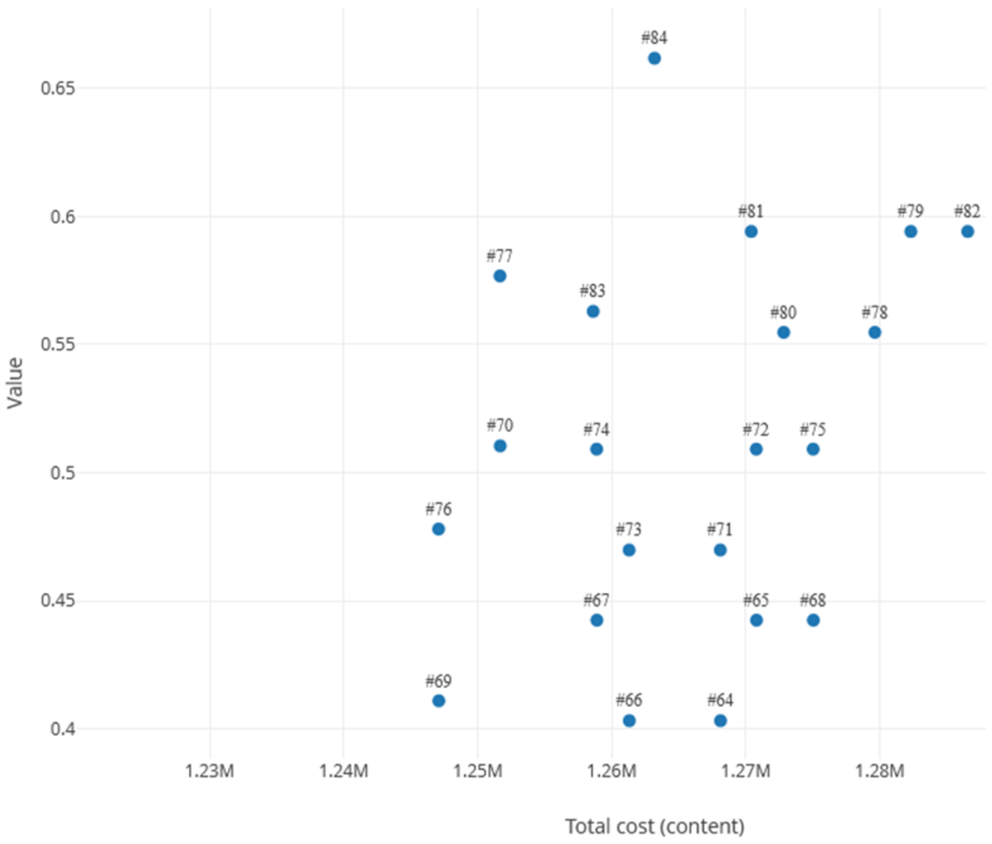


Figure 15: Right cluster plot – Value: Time, quality and automation score

Figure 15 illustrates that the maximum Value corresponds to the following combination:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 1263190 €
- Total time: 163 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,662.

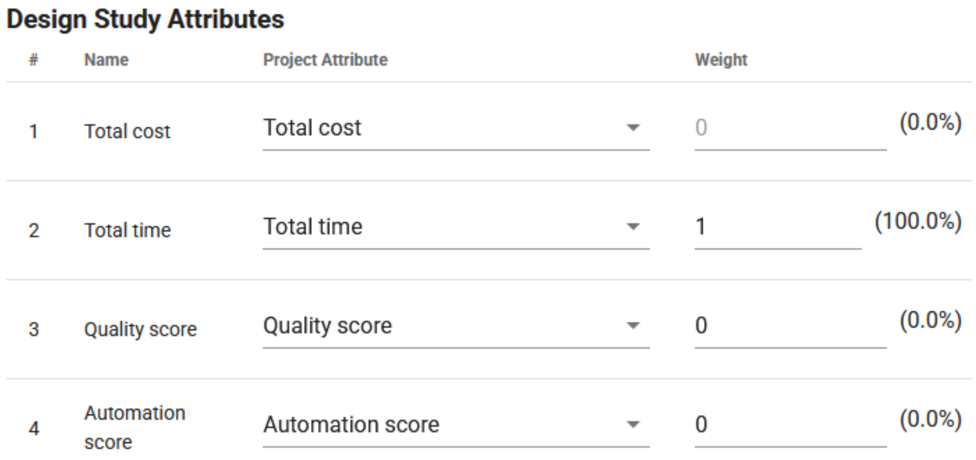
The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Total cost: 1268111 €.
- Total time: 179 hours.
- Quality score: 5,33.
- Automation score: 5,67.
- Value: 0,403.

The average Value is equal to 0,509.

Time evaluation

Here-after the evaluation of the time as one only Value. As follows are shown the design study attributes, on VALORISE:



Design Study Attributes

#	Name	Project Attribute	Weight	
1	Total cost	Total cost	0	(0.0%)
2	Total time	Total time	1	(100.0%)
3	Quality score	Quality score	0	(0.0%)
4	Automation score	Automation score	0	(0.0%)

Figure 16: Design study attributes

Since there are only 1 attribute merged in one Value, his weight is equal to 100%. The plot is shown as follows:

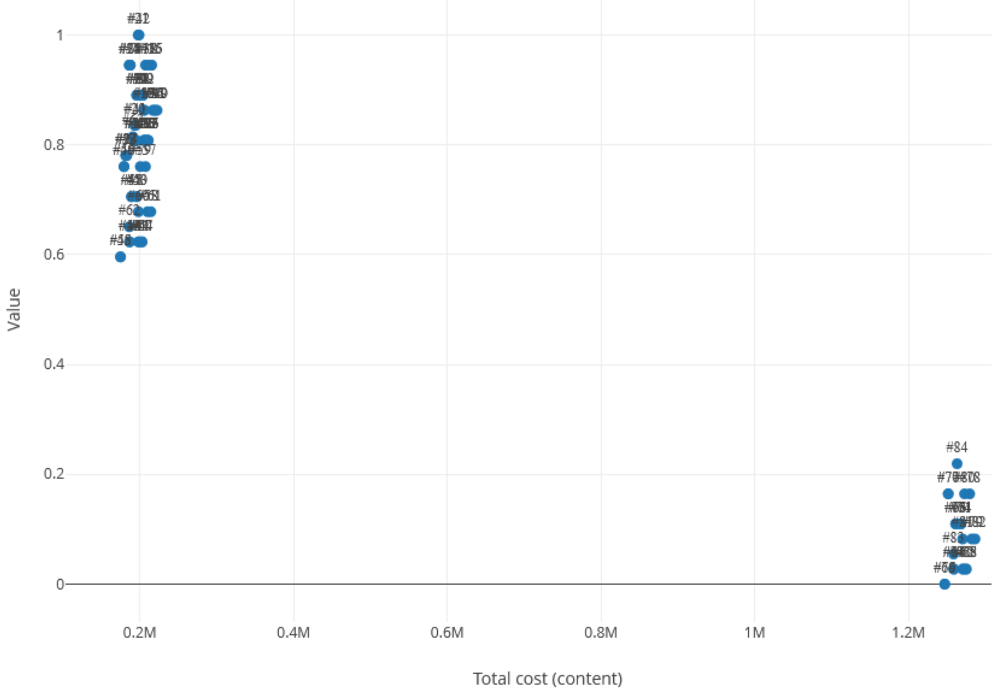


Figure 17: General plot – Value: Time

Also here is it possible to see two different values clusters, which derive from the material which is used during the manufacturing process.

As in the previous case, it is possible to notice that the cluster on the right has lower values than the cluster on the left. These clusters are identified as ID_L_T and ID_R_T, following the same model that was mentioned before. The reason for that is the major manufacturing time related to the titanium material. Being the time the only Value, which was considered, the final one is lower with respect to the ID_L_T and respects the previous case.
As follows is represented a clearer representation of all the values, to define the minimum Value, the maximum Value and the average Value of both clusters, as the previous case. The ID_L_T is the following:

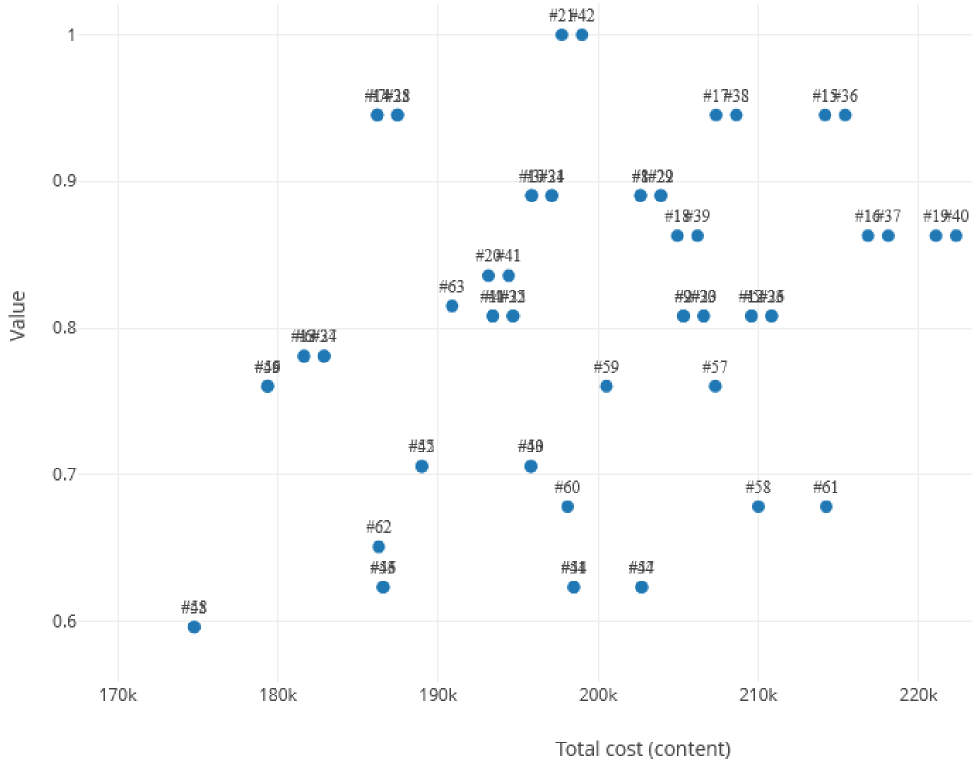


Figure 18: Left cluster plot – Value: Time

The maximum Value corresponds to two different combinations, but for simplicity here only one is represented:

- Frames material and process: Composite-Carbon, Hand Layup Vacuum Bagging.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 198996 €.
- Total time: 49 hours.
- Quality score: 8,33.
- Automation score: 7,33.
- Value: 1.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Alloy, Calendering.
- Total cost: 174792 €.
- Total time: 108 hours.
- Quality score: 6,33.
- Automation score: 6.
- Value: 0,596.

The average Value is equal to 0,804.
The ID_R_T is the following:

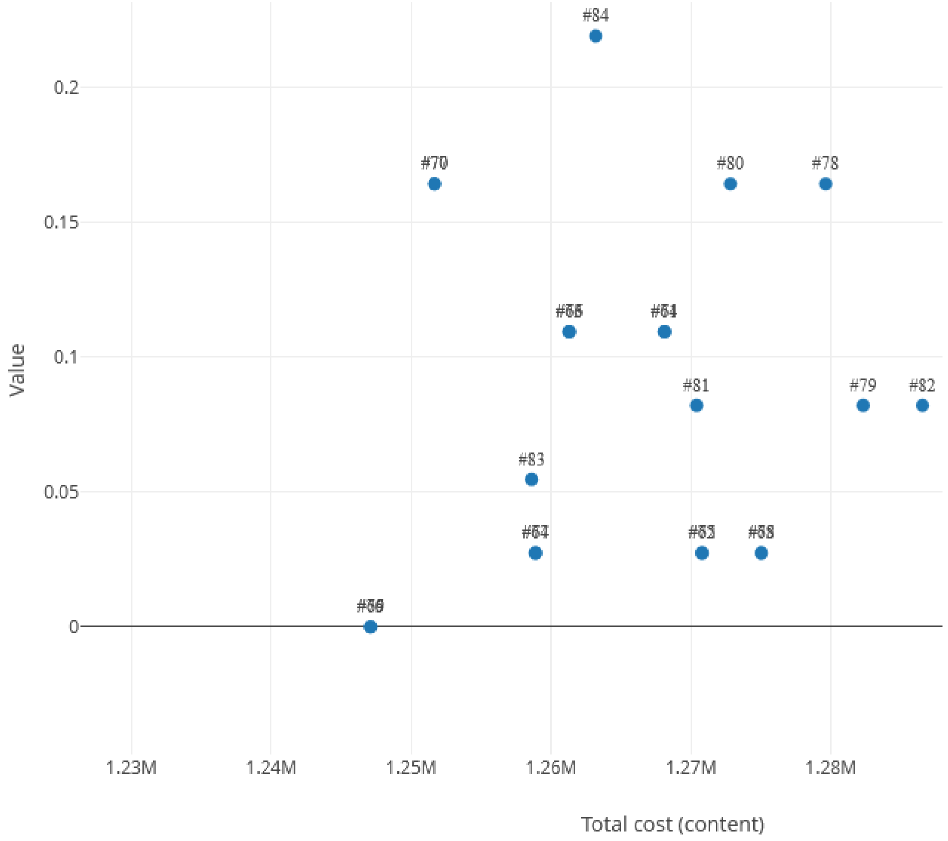


Figure 19: Right cluster plot – Value: Time

Figure 19 shows that the maximum Value corresponds to the following combination:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 1263190 €
- Total time: 163 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,219.

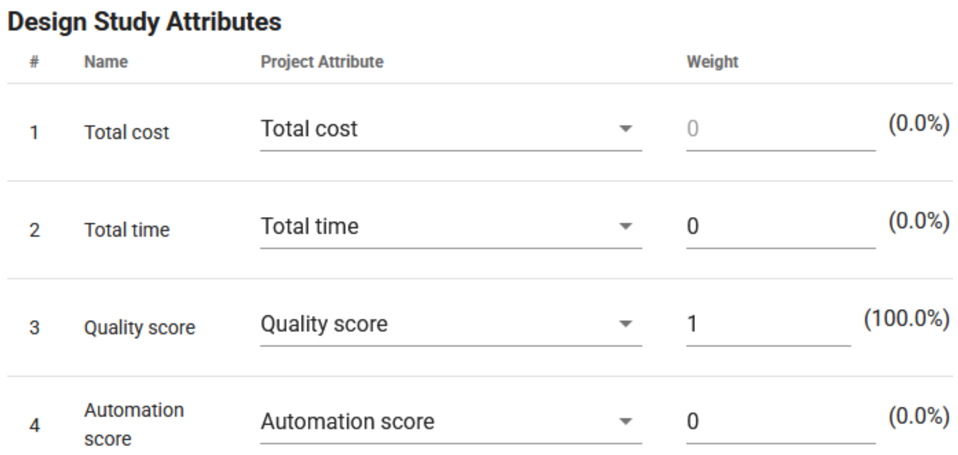
The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Alloy - Calendering.
- Total cost: 1247097 €.
- Total time: 195 hours.
- Quality score: 6,33.
- Automation score: 6.
- Value: 0.

The average Value is equal to 0,085.

Quality score evaluation

Here-after the evaluation of the quality score as one only Value. As follows are shown the design study attributes, on VALORISE:



Design Study Attributes

#	Name	Project Attribute	Weight	
1	Total cost	Total cost	0	(0.0%)
2	Total time	Total time	0	(0.0%)
3	Quality score	Quality score	1	(100.0%)
4	Automation score	Automation score	0	(0.0%)

Figure 20: Design study attributes

The plot is shown as follows:

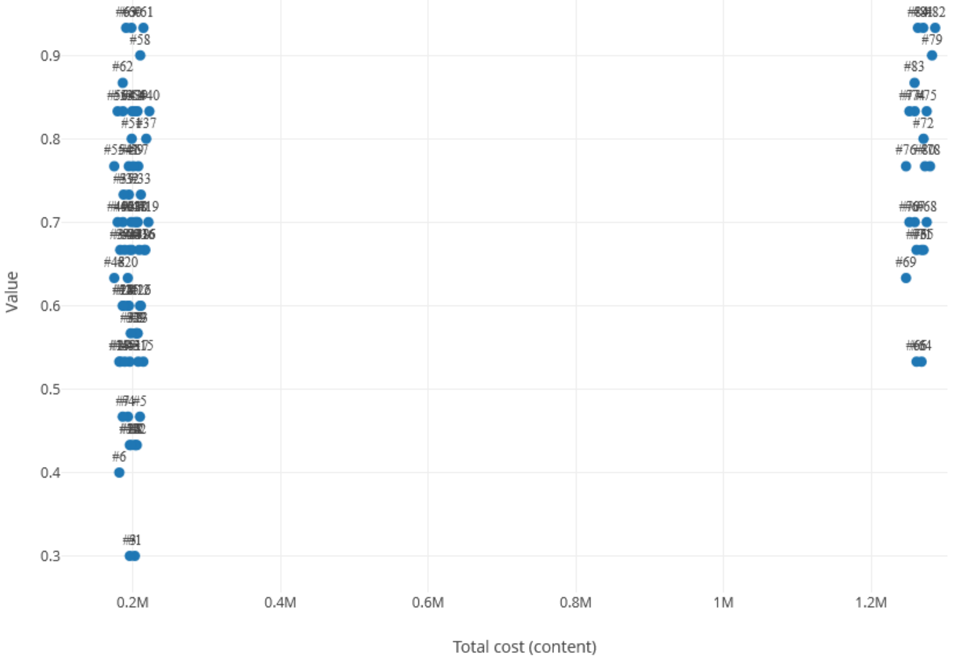


Figure 21: General plot – Value: Quality score

Also here is it possible to see two different values clusters, which derive from the material which is used during the manufacturing process.

In this case, it is possible to notice that the ID_R_Q has a similar average Value with respect to the ID_L_Q, so the quality score values have similar order of magnitude, regardless of the material.
The ID_L_Q is the following:

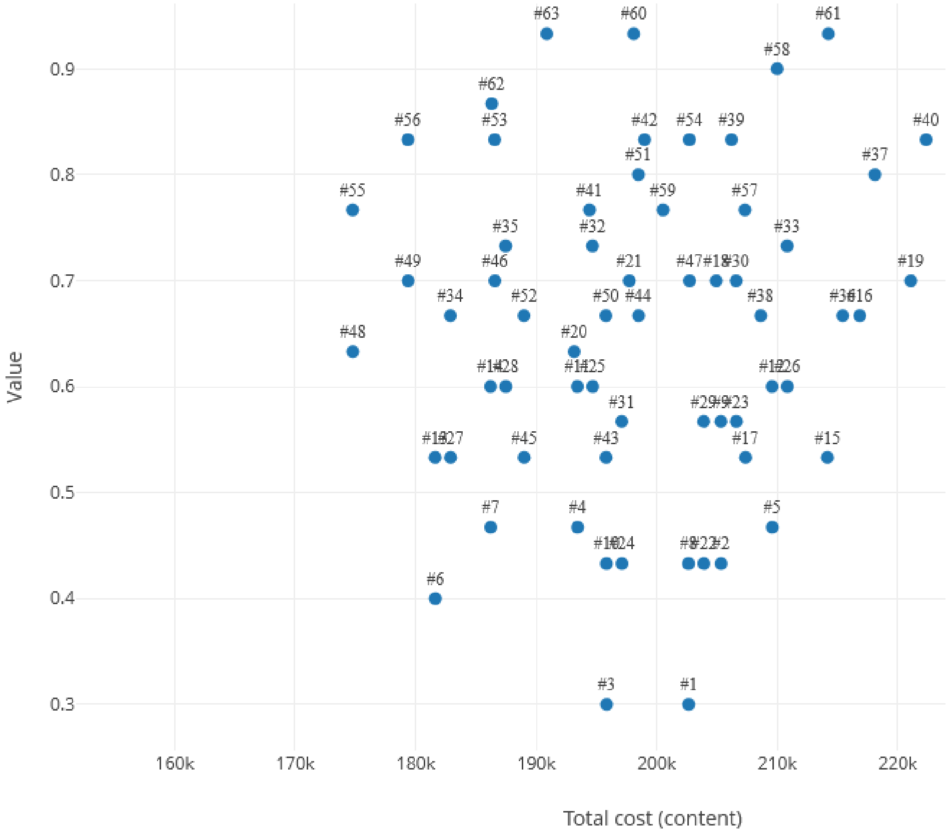


Figure 22: Left cluster plot – Value: Quality score

The maximum Value corresponds to three different combinations, but for simplicity here only one is represented:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Composite-Kevlar, Hand Layup Vacuum Bagging Autoclave.
- Total cost: 214245 €.
- Total time: 96 hours.
- Quality score: 9,33.
- Automation score: 7,67.
- Value: 0,933.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Composite-Carbon, Hand Layup and Resin – Infused.

- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Total cost: 202654 €.
- Total time: 65 hours.
- Quality score: 3.
- Automation score: 4.
- Value: 0,300.

The average Value is equal to 0,648.

The ID_R_Q is the following:

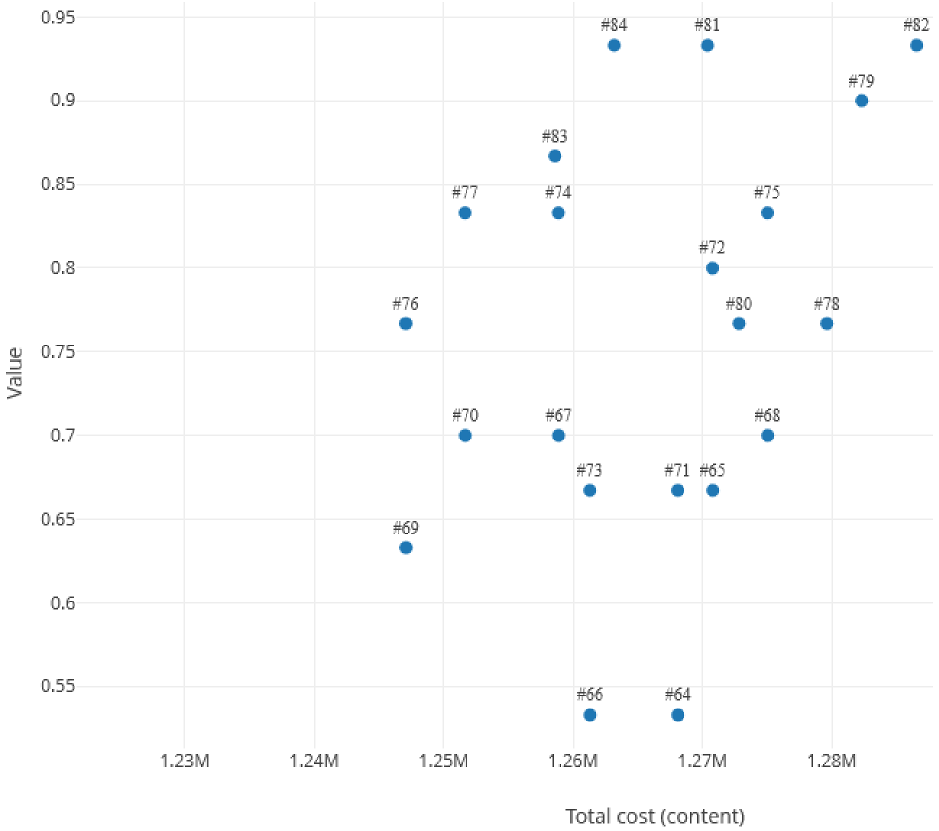


Figure 23: Right cluster plot – Value: Quality score

Figure 23 illustrates that the maximum Value corresponds to three different combinations, but for simplicity here only one is represented:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Composite-Kevlar, Hand Layup Vacuum Bagging Autoclave.
- Total cost: 1286550 €
- Total time: 183 hours.
- Quality score: 9,33.

- Automation score: 7,67.
- Value: 0,933.

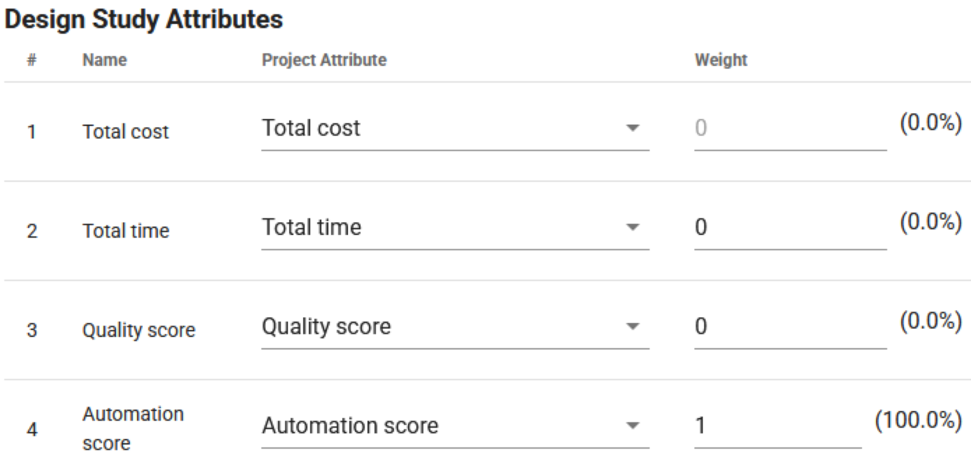
The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Alloy - Calendering.
- Total cost: 1268111 €.
- Total time: 179 hours.
- Quality score: 5,33.
- Automation score: 5,67.
- Value: 0,533.

The average Value is equal to 0,760.

Automation score evaluation

Here-after the evaluation of the quality score as one only Value. As follows are shown the design study attributes, on VALORISE:



Design Study Attributes

#	Name	Project Attribute	Weight	
1	Total cost	Total cost	0	(0.0%)
2	Total time	Total time	0	(0.0%)
3	Quality score	Quality score	0	(0.0%)
4	Automation score	Automation score	1	(100.0%)

Figure 24: Design study attributes

The plot is shown as follows:

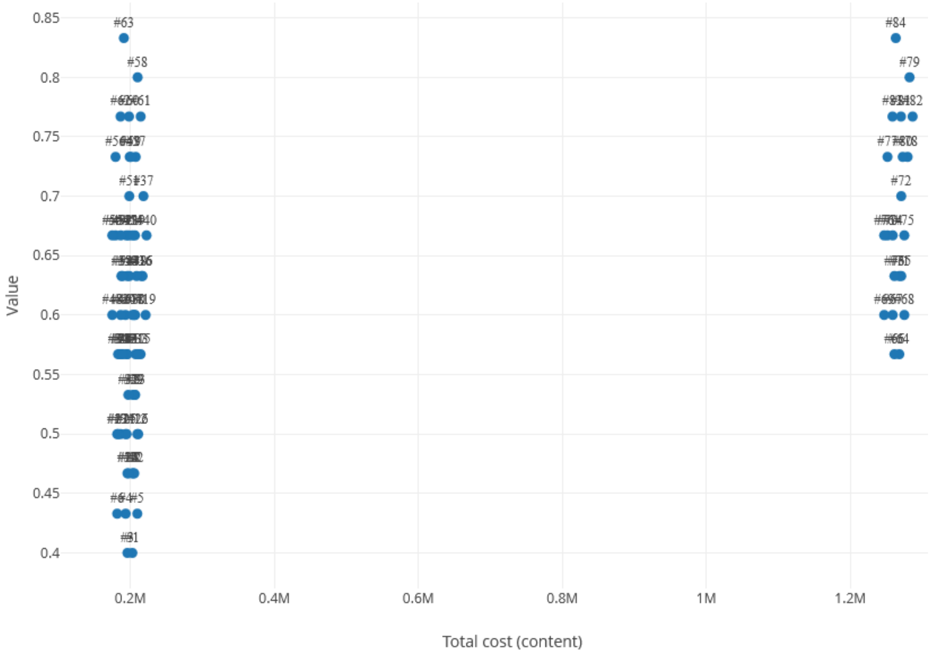


Figure 25: General plot – Value: Automation score

Also here is it possible to see two different values clusters, which derive from the material which is used during the manufacturing process.
In this case as well, it is possible to notice that the ID_R_A has a similar average Value with respect to the ID_L_A, so the automation score values have similar order of magnitude, regardless of the material.

The ID_L_A is the following:

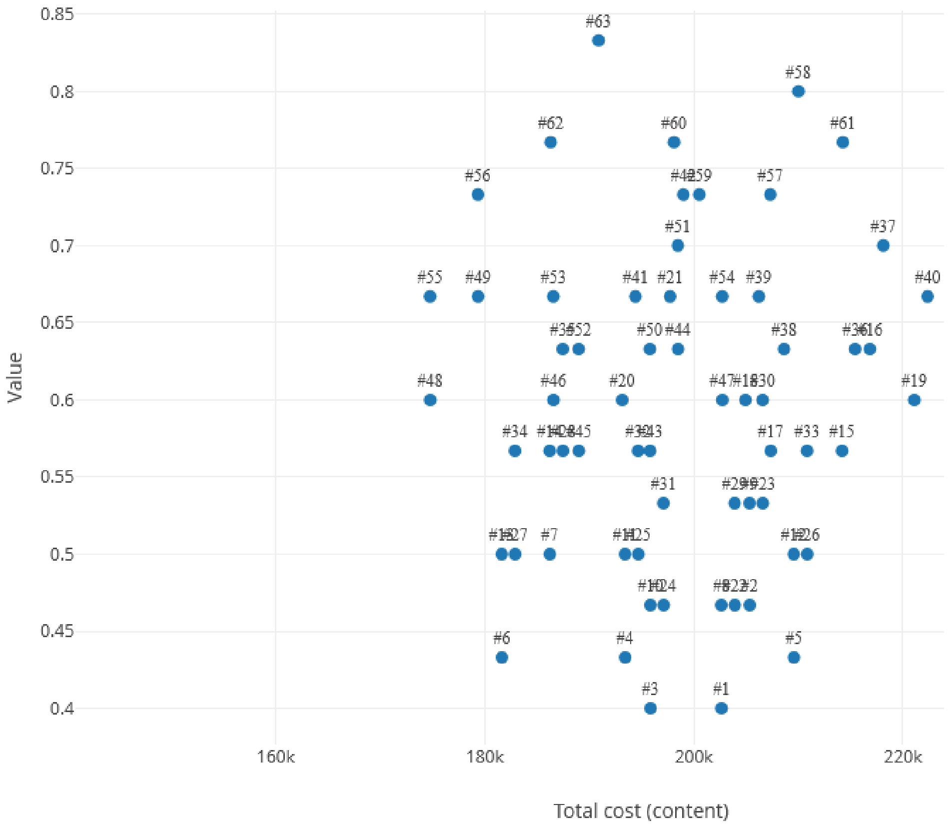


Figure 26: Left cluster plot – Value: Automation score

The maximum Value corresponds to the following combination:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 190885 €.
- Total time: 76 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,833.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.

- Total cost: 202654 €.
- Total time: 65 hours.
- Quality score: 3.
- Automation score: 4.
- Value: 0,400.

The average Value is equal to 0,590.

The ID_R_A is the following:

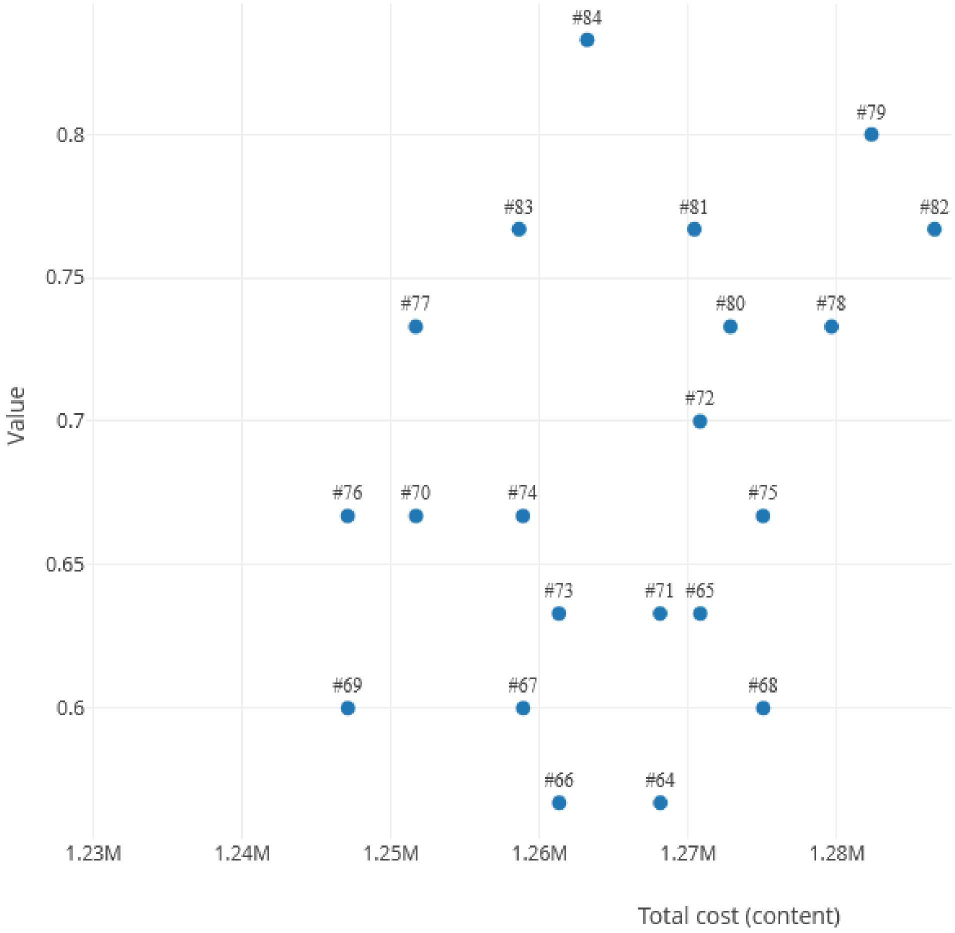


Figure 27: Right cluster plot – Value: Automation score

Figure 27 shows that the maximum Value corresponds to the following combination:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 1263190 €
- Total time: 163 hours.
- Quality score: 9,33.
- Automation score: 8,33.

- Value: 0,833.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Alloy - Calendering.
- Total cost: 1268111 €.
- Total time: 179 hours.
- Quality score: 5,33.
- Automation score: 5,67.
- Value: 0,567.

The average Value is equal to 0,683.

Quality scores and automation scores comparisons

To make a good comparison between both scores, it is necessary to depict firstly the VALORISE plot:

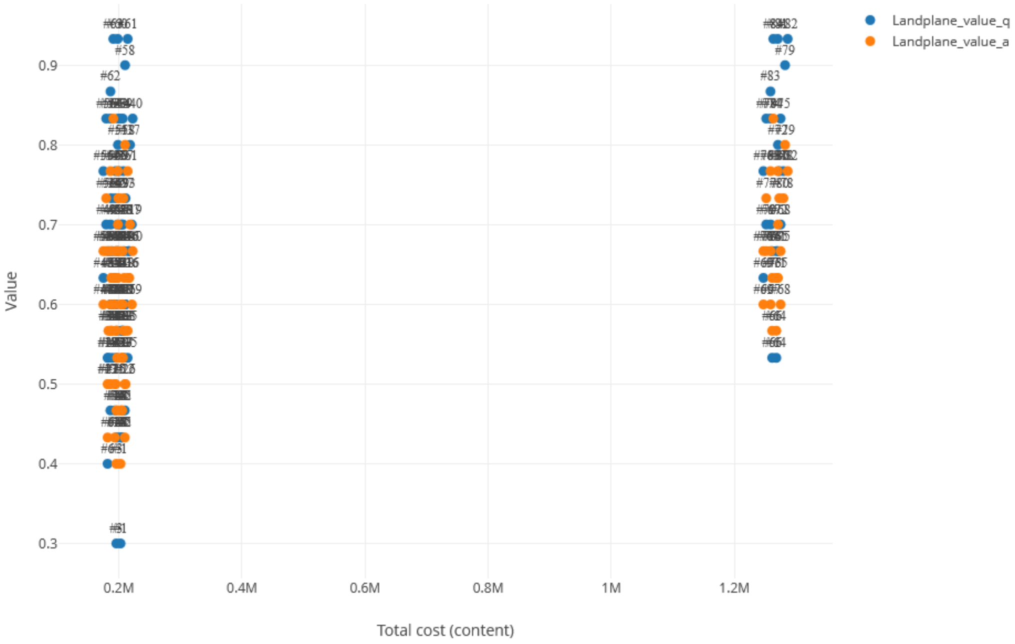


Figure 28: General plot – Quality score and automation score comparison

As described before, the average Values of the quality scores and of the automation scores, for both clusters are the following:

- Quality score average Value regarding the ID_L_Q: 0,648.

- Quality score average Value regarding the ID_R_Q: 0,760.
- Automation score average Value regarding the ID_L_A: 0,590.
- Automation score average Value regarding the ID_R_A: 0,683.

It is possible to notice that the average Values of the quality scores are higher than the average Values of the Automation scores, for both clusters. This difference is related to the higher quality scores orders of magnitude. Besides, for the clusters ID_L_Q and ID_L_A, the average Value remains similar regardless of the chosen metric. This indicates that, for all material and process combinations within these clusters, the selection of one metric over another does not significantly impact the outcome. In contrast, for the combinations grouped under ID_R_Q and ID_R_A, the average Value varies noticeably depending on which metric is prioritized whether time or quality score. This suggests that, in these cases, the choice of metric plays a more critical role in determining the final value. For the next case and for the seaplane as well the same aspect can be traced.

Times and quality scores comparisons

To make a good comparison between time and quality score, it is necessary to depict firstly the VALORISE plot, as the previous case:

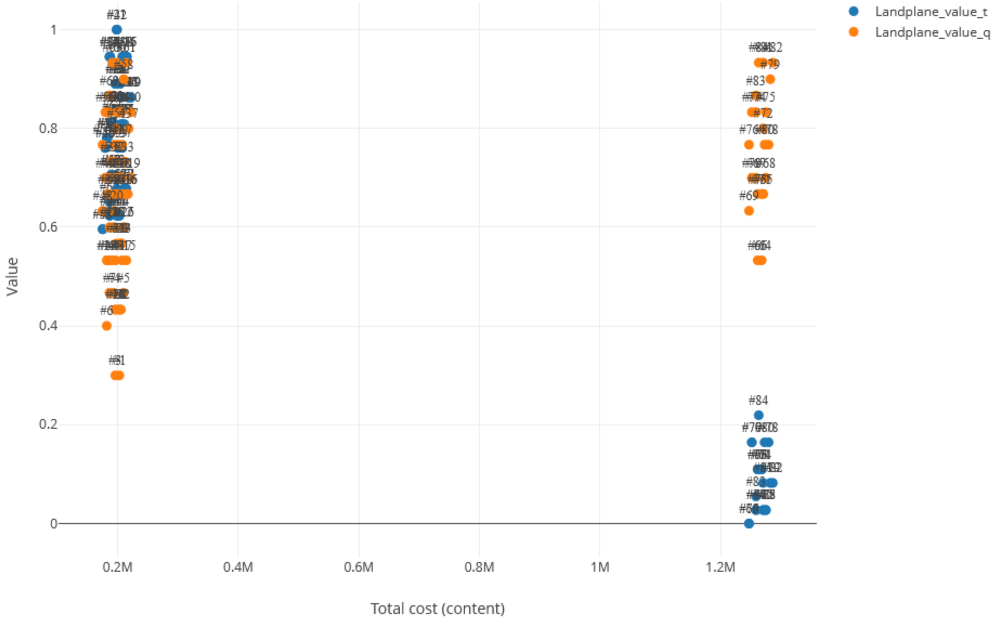


Figure 29: General plot – Time and automation score comparison

As described before, the average Value for the times and for the quality scores, for both clusters, are the following:

- Time average Value regarding the ID_L_T: 0,804.
- Time average Value regarding the ID_R_T: 0,085.
- Quality score average Value regarding the ID_L_Q: 0,648.
- Quality score average Value regarding the ID_R_Q: 0,760.

It is possible to notice that for the ID_L_T and ID_L_Q the average Values of the times are higher than the average Values of the quality scores. This is related to the fact that the times orders of magnitude are lower relative to how high the quality scores are, considering that the goal is to minimize time and maximize quality. This indicates that time is closer to its optimal range, which explains why its mean value is higher and reflects better performance.

For the ID_R_T and ID_R_Q, it is possible to notice that the average Values of the quality scores are higher than the average Values of the times. This is related to the fact that the quality scores orders of magnitude are much higher relative to how high the times are. Since the goal is to maximize quality and minimize time, this indicates that quality scores are closer to their optimal range, while times orders of magnitude remain high and therefore less desirable. This explains why the mean Value of the quality scores is higher, reflecting better performance in that aspect.

The same considerations can be made for the times and automation scores comparisons.

4.1.2.2 SEAPLANE CASE

Time, quality score and automation score merged evaluation

Adopting the same criteria used for the landplane, as follows is represented the seaplane case. Here-after the evaluation of the time, quality score and automation score in one combined Value.

As in the landplane case, is it possible to see two different values clusters as well, which derive from the material which is used during the manufacturing process.
In particular, the ID_L_TQA is represented by all the values that refer to the following combination of materials: composite-carbon, composite-glass, composite-kevlar, alloy.
The ID_R_TQA is represented by all the values that refer to the titanium material with the remaining materials.
As follows are represented the minimum Value, the maximum Value and the average Value of both clusters.

Regarding the ID_L_TQA, the maximum Value corresponds to the following combination:

- Frames material and process: Composite-Carbon, Hand Layup Vacuum Bagging.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 226670 €.
- Total time: 66 hours.
- Quality score: 8,33.
- Automation score: 7,33.
- Value: 0,855.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Total cost: 246138 €.
- Total time: 82 hours.
- Quality score: 3.
- Automation score: 4.
- Value: 0,534.

The average Value is equal to 0,684.

Regarding the ID_R_TQA, the maximum Value corresponds to the following combination:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 1386350 €
- Total time: 197 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,654.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.

- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Total cost: 1393854 €.
- Total time: 213 hours.
- Quality score: 5,33.
- Automation score: 5,67.
- Value: 0,399.

The average Value is equal to 0,506.

Time evaluation

Here-after the evaluation of the time as one only Value.
Also, here will be evaluated two different values clusters, which derive from the material which is used during the manufacturing process.
As in the previous case, it is possible to notice that the ID_R_T has lower values than the ID_L_T.
As follows is represented a clearer representation of the minimum Value, the maximum Value and the average Value of both clusters, as in the previous case. Regarding the ID_L_T, the maximum Value corresponds to two different combinations, but for simplicity here only one is represented:

- Frames material and process: Composite-Carbon, Hand Layup and Resin-Infused.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 238634 €.
- Total time: 66 hours.
- Quality score: 7.
- Automation score: 6,67.
- Value: 1.

The minimum Value corresponds to the following combination:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Alloy, Calendering.
- Total cost: 203602 €.
- Total time: 133 hours.
- Quality score: 6,33.
- Automation score: 6.
- Value: 0,589.

The average Value is equal to 0,771.

Regarding the ID_R_T, the maximum Value corresponds to the following combination:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 1386350 €
- Total time: 197 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,196.

The minimum Value corresponds to the following combination:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Vacuum Bagging.
- Skin panels material and process: Alloy - Calendering.
- Total cost: 1369777 €.
- Total time: 229 hours.
- Quality score: 7,67.
- Automation score: 6,67.
- Value: 0.

The average Value is equal to 0,0665.

Quality score evaluation

Here-after the evaluation of the quality score as one only Value.

Also here is it possible to evaluate two different values clusters, which derive from the material which is used during the manufacturing process.
In this case, it is possible to notice that the ID_R_Q has a similar average Value with respect to the ID_L_Q, so the quality score values have similar order of magnitude, regardless of the material.

Regarding the ID_L_Q, the maximum Value corresponds to three different combinations, but for simplicity here only one is represented:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Composite-Kevlar, Hand Layup Vacuum Bagging Autoclave.
- Total cost: 244707 €.
- Total time: 121 hours.
- Quality score: 9,33.
- Automation score: 7,67.
- Value: 0,933.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Total cost: 246138 €.
- Total time: 82 hours.
- Quality score: 3.
- Automation score: 4.
- Value: 0,300.

The average Value is equal to 0,651.

Regarding the ID_R_Q, the maximum Value corresponds to three different combinations, but for simplicity here only one is represented:

Frames material and process: Titanium – CNC Machining.

- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Composite-Kevlar, Hand Layup Vacuum Bagging Autoclave.
- Total cost: 1410898 €
- Total time: 217 hours.
- Quality score: 9,33.
- Automation score: 7,67.
- Value: 0,933.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Total cost: 1393854 €.
- Total time: 213 hours.
- Quality score: 5,33.
- Automation score: 5,67.
- Value: 0,533.

The average Value is equal to 0,733.

Automation score evaluation

Here-after the evaluation of the quality score as one only Value.

Here as well is it possible to evaluate two different values clusters, which derive from the material which is used during the manufacturing process. In this case as well, it is possible to notice that the ID_R_A has a similar average Value with respect to the ID_L_A, so the automation score values have similar order of magnitude, regardless of the material.

Regarding the ID_L_A, the maximum Value corresponds to the following combination:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 220159 €.
- Total time: 101 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,833.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Total cost: 246138 €.
- Total time: 82 hours.
- Quality score: 3.
- Automation score: 4.
- Value: 0,400.

The average Value is equal to 0,579.

Regarding the ID_R_A, the maximum Value corresponds to the following combination:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 1386350 €
- Total time: 197 hours.
- Quality score: 9,33.
- Automation score: 8,33.

- Value: 0,833.

The minimum Value corresponds to two different combinations, but for simplicity here is represented only one:

- Frames material and process: Titanium – CNC Machining.
- Stringers material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Skin panels material and process: Composite-Carbon, Hand Layup and Resin – Infused.
- Total cost: 1393854 €.
- Total time: 213 hours.
- Quality score: 5,33.
- Automation score: 5,67.
- Value: 0,567.

The average Value is equal to 0,679.

Quality scores and automation scores comparisons

This type of comparison is the same with respect to the landplane case, since both scores are equal for the same material combination.

Times and quality scores comparisons

Even if the times orders of magnitude are different with respect to the landplane case, the conclusions that are possible to trace are the same.

In the specific, the average Value for the times and for the quality scores, for both clusters, are the following:

- Time average Value regarding the ID_L_T: 0,771.
- Time average Value regarding the ID_R_T: 0,0665.
- Quality score average Value regarding the ID_L_Q: 0,651.
- Quality score average Value regarding the ID_R_Q: 0,733.

The same considerations can be made for the times and automation scores comparisons.

4.1.3 STAKEHOLDERS, NEEDS & REQUIREMENTS

A crucial aspect of this study is identifying the key stakeholders in the aircraft manufacturing process and defining their needs and requirements. This ensures that the design choices align with industry feasibility and meet operational expectations. The stakeholders considered in this analysis are:

1. Original Equipment Manufacturer (OEM)

- Need: Minimize manufacturing costs.
- Requirement: The landplane's total manufacturing cost shall not exceed 634000 USD.

Here-after is explained why the boundary that was setted is 634000 USD.

Starting with the following data, some calculations were made:

Aircraft	Pax	Fuselage length [m]	Price [USD]	Engine
Tecnam P2012 Traveller	11	14,00	2350000	Pistons
Pilatus PC-6 Porter	11	11,00	1200000	Pistons
Beechcraft King Air 350	11	14,20	7200000	Turboprop
Pilatus PC-12 NGX	11	14,40	5000000	Turboprop
Beechcraft 1900D	19	17,63	1700000	Turboprop

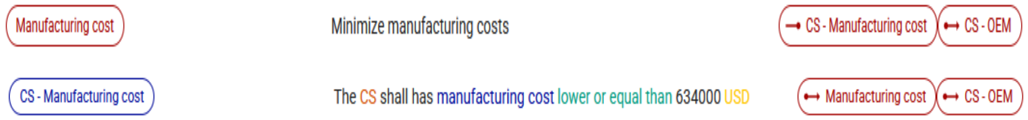
Table 7: Some aircrafts data

The average price of the selected fleet is calculated as 3490000 USD. According to Roskam's assumption [14], to estimate the average cost of the aircraft, the formula is applied:

Average aircraft cost = 3490000 USD / 1.1 = 3170000 USD. Beltramo's assumption [15] suggests that the fuselage cost is equal to 20% with respect to the total cost of the average aircraft cost. This calculation provides the following results:

Fuselage cost = 0.2 × 3170000 USD = 634000 USD = 564672 €.

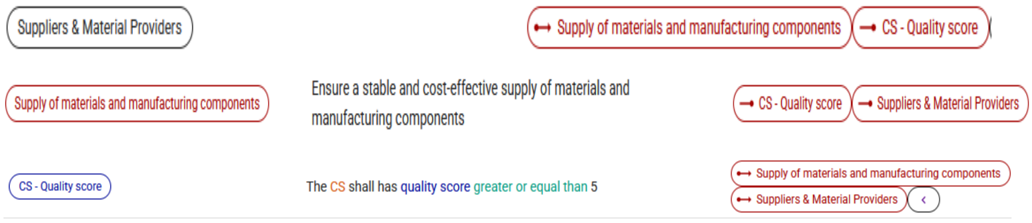
Here-after is shown the stakeholder – need - requirement implementation into ARMADE. For the next stakeholders – needs - requirements were made the same thing.



Manufacturing cost	Minimize manufacturing costs	CS - Manufacturing cost CS - OEM
CS - Manufacturing cost	The CS shall has manufacturing cost lower or equal than 634000 USD	Manufacturing cost CS - OEM

2. Suppliers & Material Providers

- Need: Ensure a stable and cost-effective supply of materials and manufacturing components.
- Requirement: The selected material-process combinations shall achieve a minimum value for the quality score. Since the latter goes from 0 to 10, the medium was chosen as a minimum value, so 5 for both landplane and seaplane configurations. This consideration was made in the absence of feedback from TECNAM.

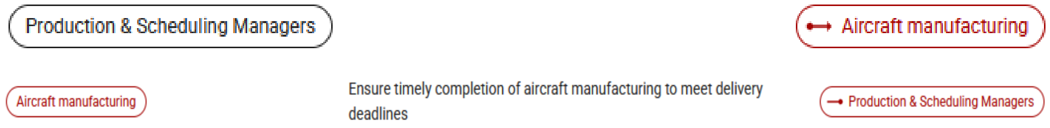


Suppliers & Material Providers		Supply of materials and manufacturing components CS - Quality score
Supply of materials and manufacturing components	Ensure a stable and cost-effective supply of materials and manufacturing components	CS - Quality score Suppliers & Material Providers
CS - Quality score	The CS shall has quality score greater or equal than 5	Supply of materials and manufacturing components Suppliers & Material Providers ‹

3. Production & Scheduling Managers

- Need: Ensure timely completion of aircraft manufacturing to meet delivery deadlines.

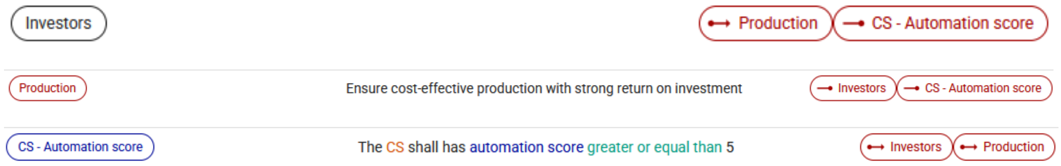
For this metric there isn't a particular requirement since times were already verified by TECNAM.



Production & Scheduling Managers		Aircraft manufacturing
Aircraft manufacturing	Ensure timely completion of aircraft manufacturing to meet delivery deadlines	Production & Scheduling Managers

4. Investors

- Need: Ensure cost-effective production with strong return on investment.
- Requirement: The manufacturing automation score shall be at least 5 for both landplane and seaplane configurations to ensure economic scalability. The same logic as the quality score was adopted.



Investors

⟷ Production ⟶ CS - Automation score

Production

Ensure cost-effective production with strong return on investment

⟶ Investors ⟶ CS - Automation score

CS - Automation score

The CS shall has automation score greater or equal than 5

⟷ Investors ⟷ Production

Therefore, these stakeholders' requirements will be assessed in comparison with the results obtained from the Python-based cost model analysis, ensuring that all critical constraints and targets are satisfied within the optimized design framework. The subsequent trade-off analysis will further evaluate how well the proposed manufacturing strategies align with these expectations.

4.1.4 TRADE-OFF ANALYSIS

In this paragraph, as mentioned before, a trade-off analysis will be treated in VALORISE. It is analyzed how the application of stakeholders' requirements leads to a reduction in the space of feasible solutions, as represented within the value space on VALORISE. In the specific, will be eliminated all the combinations that overcome the cost equal to 564672 €, quality score and automation score less than 5. Is it possible to say that all the combinations referred to the titanium will be discarded, since the price overcome widely the setted requirement. This type of analysis will be done for both landplane and seaplane, making a comparison between them and highlighting the main differences and important considerations for both aircraft. Besides will be considered all the cases described above.

Time, quality score and automation score merged trade-off

Here after the evaluation of the time, quality score and automation score in one combined Value. Is possible to compare plots post trade-off analysis. Here-after the plot analysis, before regarding the landplane, after concerning the seaplane, and then the considerations between them:

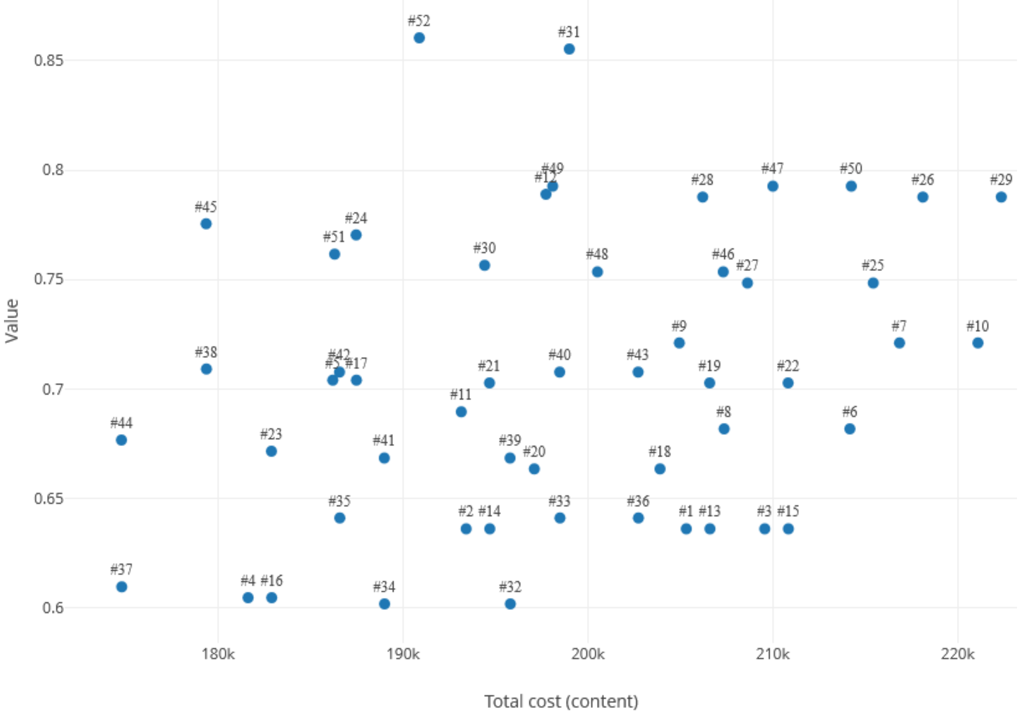


Figure 30: Landplane trade-off plot - Value: Time, quality and automation score

Is it possible to specify that the requirements didn’t affect the maximum value for both landplane and seaplane. Indeed, the latters remained because they satisfy all the requirements. In particular, for the landplane the best materials combination is the following:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 190885 €.
- Total time: 76 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,860.

ID #63 before the trade-off analysis now is ID #52. All the data are clearly the same.

Now the seaplane plot:

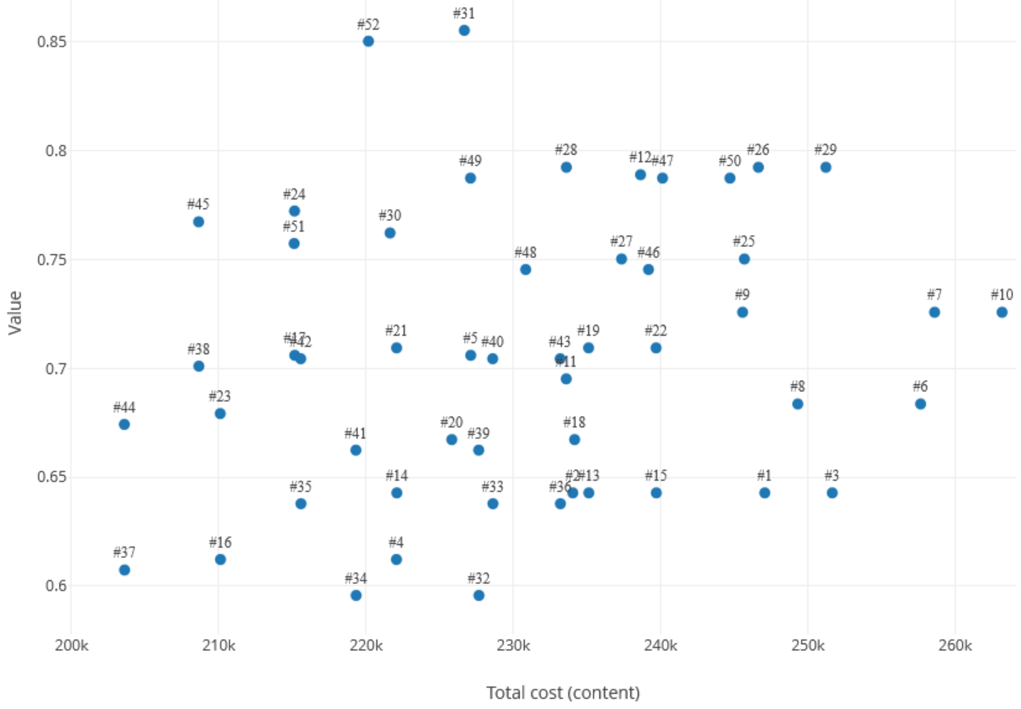


Figure 31: Seaplane trade-off plot - Value: Time, quality and automation score

Instead, for the seaplane the best materials combination is the following:

- Frames material and process: Composite-Carbon, Hand Layup Vacuum Bagging.
- Stringers material and process: Alloy – CNC Machining.

- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 226670 €.
- Total time: 66 hours.
- Quality score: 8,33.
- Automation score: 7,33.
- Value: 0,855.

ID #42 before the trade-off analysis now is ID #31.

Is it possible to notice that the final Value regarding the maximum value of the landplane case is higher with respect to the seaplane case, so is the best solution.

Time trade-off

Here-after the evaluation of the time as one only Value. As follows the landplane plot:

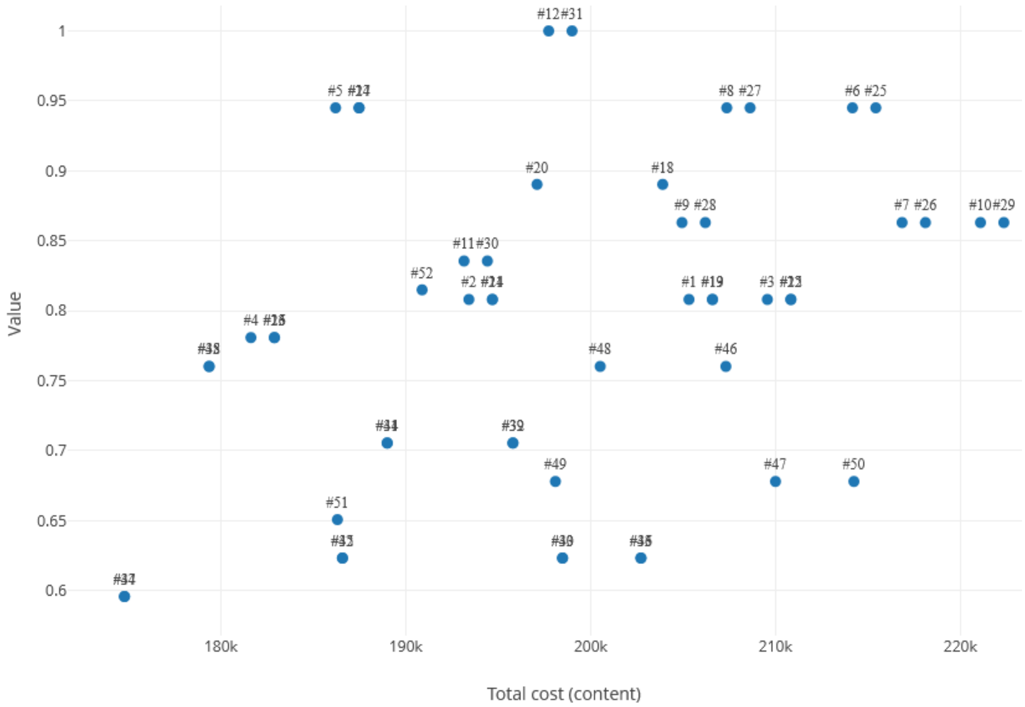


Figure 32: Landplane trade-off plot - Value: Time

Also, in this case is it possible to specify that the requirements didn’t affect the maximum value for both landplane and seaplane.

In the specific, for the landplane the best materials combinations are two, but here the point that has lower cost is chosen, and it is the following:

- Frames material and process: Composite-Carbon, Hand Layup and Resin - Infused.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 197733 €.
- Total time: 49 hours.
- Quality score: 7.
- Automation score: 6,67.
- Value: 1.

ID #21 before the trade-off analysis now is ID #12.

Now the seaplane case:

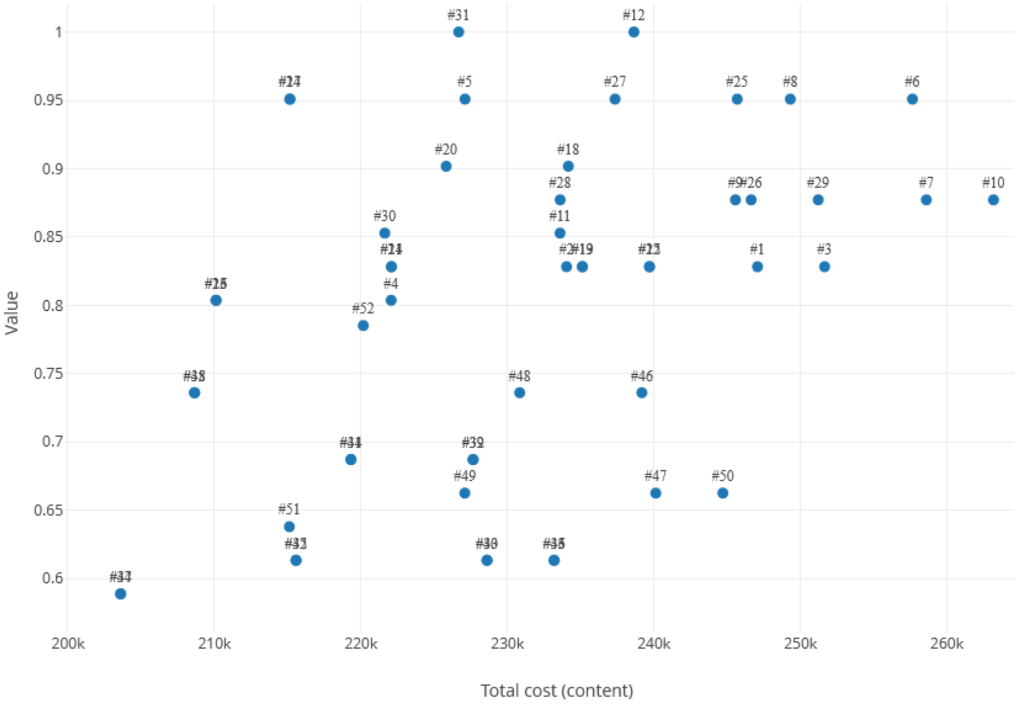


Figure 33: Seaplane trade-off plot - Value: Time

Instead, for the seaplane the best materials combinations are two as well, but with the same considerations mentioned before, the best one is the following:

- Frames material and process: Composite-Carbon, Hand Layup Vacuum Bagging.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 226670 €.
- Total time: 66 hours.

- Quality score: 8,33.
- Automation score: 7,33.
- Value: 1.

ID #42 before the trade-off analysis now is ID #31.

Is it possible to notice that the final Value regarding the maximum value of the landplane case is equal with respect to the seaplane case, so the best solution is the one that has lower cost. In this case, the landplane case solution.

Quality score trade-off

Here-after the evaluation of the quality score as one only Value. As follows the landplane plot:

Figure 34: Landplane trade-off plot - Value: Quality score

Also, in this case is it possible to specify that the requirements didn't affect the maximum value for both landplane and seaplane. In the specific, for the landplane the best materials combinations are three, but here the point that has lower cost is chosen, as mentioned before, and it is the following:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.

- Total cost: 190885 €.
- Total time: 76 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,933.

ID #63 before the trade-off analysis now is ID #52.

Now the seaplane case:

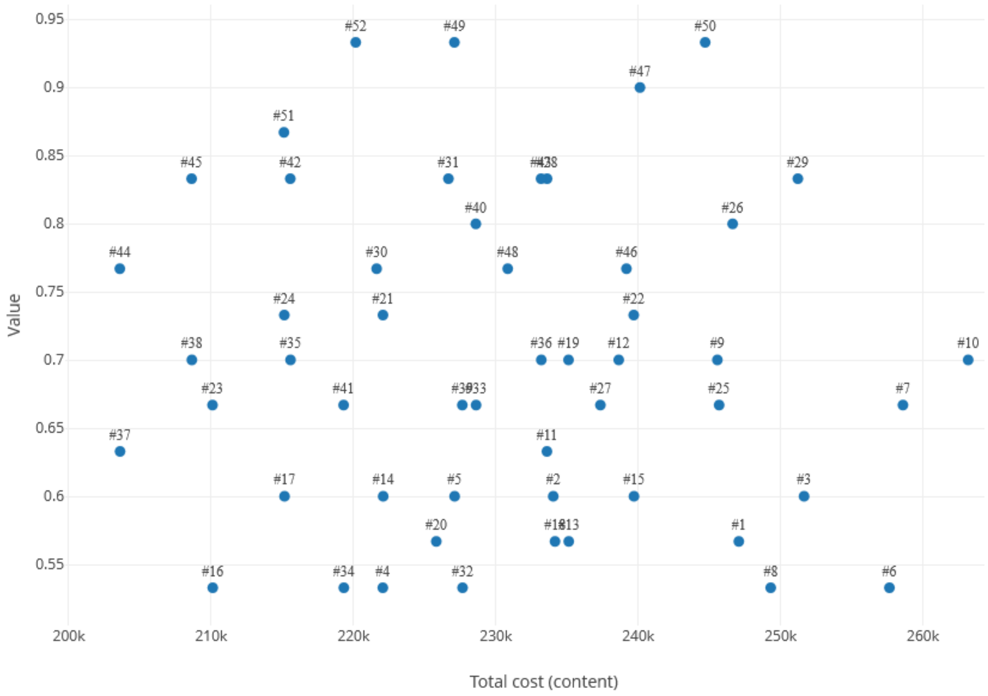


Figure 35: Seaplane trade-off plot – Value: Quality score

Instead, for the seaplane the best materials combinations are three as well, but with the same considerations mentioned before, the best one is the following:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 220159 €.
- Total time: 101 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,933.

ID #63 before the trade-off analysis now is ID #52.

Is it possible to notice that the final Value regarding the maximum value of the landplane case is equal with respect to the seaplane case, as before, so the best solution is the one that has lower cost. In this case, the landplane case solution.

Automation score trade-off

Here-after the evaluation of the automation score as one only Value. As follows the landplane plot:

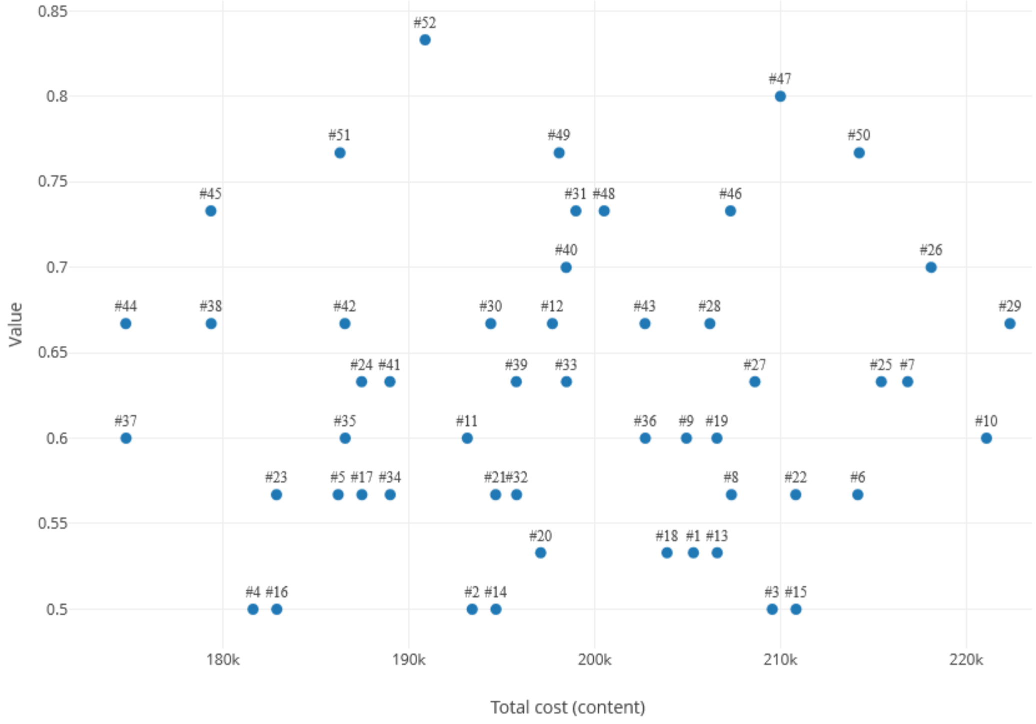


Figure 36: Landplane trade-off plot - Value: Automation score

Also, in this case is it possible to specify that the requirements didn't affect the maximum value for both landplane and seaplane. In the specific, for the landplane the best materials combination is the following:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 190885 €.
- Total time: 76 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,833.

ID #63 before the trade-off analysis now is ID #52.

Now the seaplane case:

Figure 37: Seaplane trade-off plot - Value: Automation score

Instead, for the seaplane the best materials combination is the following:

- Frames material and process: Alloy – CNC Machining.
- Stringers material and process: Alloy – CNC Machining.
- Skin panels material and process: Alloy – Deep Drawing.
- Total cost: 220159 €.
- Total time: 101 hours.
- Quality score: 9,33.
- Automation score: 8,33.
- Value: 0,833.

ID #63 before the trade-off analysis now is ID #52.

Is it possible to notice that the final Value regarding the maximum value of the landplane case is equal with respect to the seaplane case, as before, so the best solution is the one of the landplane case.

CONCLUSIONS

This thesis developed an integrated approach for incorporating manufacturing considerations to support configuration trade-offs early in the conceptual aircraft design phase, following a model-based and value-driven approach. By combining empirical data, computational tools, and stakeholder analysis, a more holistic and collaborative design process was achieved.

The use of the ARMADE tool ensured full traceability between stakeholder needs, technical requirements, and success criteria, aligning design choices with operational and regulatory constraints. The EVE use case, focused on aerial wildfire suppression, demonstrated how complex stakeholder demands can be translated into structured technical specifications.

On the manufacturing side, the Python-based tool enabled detailed analysis of costs and production times for various material and process combinations in key structural components. These results, examined through the VALORISE platform, highlighted how cost, time, quality and automation influence overall system value, supporting informed trade-off decisions.

Integrating multidisciplinary design optimization (MDO) with real-time manufacturing evaluation and stakeholder-driven modeling bridges the gap between conceptual design and industrial feasibility. This approach improves the alignment between performance goals and production constraints.

While the results are promising, future work could expand the analysis to other subsystems, integrate dynamic operational data, and include environmental and lifecycle impact metrics. The proposed approach contributes to the COLOSSUS project's vision, offering a replicable model for sustainable and agile aerospace system development.

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LIST OF FIGURES

LIST OF TABLES

THANKSGIVINGS

Vi avevo già avvisati del fatto che la storia sarebbe continuata. È giunta, purtroppo o per fortuna, la fine del mio percorso universitario. E adesso che si fa? Si vedrà. La vita è troppo imprevedibile per permettersi il lusso di predire i futuri accadimenti. Nel frattempo, non resta che godersi il momento. Per evitare di essere prolisso, andrò diritto al punto e ai ringraziamenti finali.

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Basta così, preferirei continuare a scrivere su un giornale, un giorno, sperabilmente!