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Doctoral Thesis in Industrial Engineering

Systems Engineering holistic approach for aircraft, manufacturing and supply chain concurrent design

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Research is what I´m doing when
I don´t know what I´m doing.
Werher von Braun

Declaration of Authorship

I, Giuseppa Donelli, declare that this thesis, titled "Systems engineering holistic approach for aircraft, manufacturing and supply chain concurrent design" is a product of my original research.

I hereby confirm that:

- I performed the research and writing of this thesis entirely or mainly while pursuing a research degree at this University;
- I made it explicitly clear when sections of this thesis have been previously submitted for a degree or any other qualification at this or another institution;
- I clearly cited the published works of other authors when reviewing them;
- I properly cited any quotations from the works of other authors and, except of these quotations, the thesis is entirely the product of my own effort;
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- I clearly distinguished the contributions made by others from those of my own in the context of collaborative activities.

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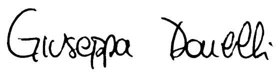

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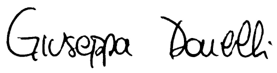
Naples, December 2024
Giuseppa Donelli



Abstract

Over years, public perception of aviation has evolved, placing greater emphasis on climate change, sustainable solutions and fastest and most affordable connections. This has led in the Flightpath 2050, a comprehensive vision for European aviation aiming at achieving climate neutrality, global leadership and meeting citizen needs. To realize these goals, a fundamental shift is necessary in the way aeronautical systems are conceived, built and sustained. The key aspect of this fundamental shift is the integration of manufacturing and supply chain decisions from the early design stages. This integrated approach is crucial for overcoming the limitations of traditional sequential method, which prevented adaptability to market changes and increased costs. Companies like Airbus, Boeing, Toyota, and Honda have faced these challenges. By adopting an integrated approach and leveraging digital transformation, companies can instead enhance innovation, efficiency, and competitiveness throughout the aircraft life cycle. This research activity, framed in this context, investigate the following research question:

Can making more decisions in the early life-cycle stage increases the value of complex aeronautical systems?

Real-world cases have demonstrated how production-related decisions are often made after the aircraft design has been completed and the related challenges faced. To overcome these issues, and in relation to the identified research question, this work aims to demonstrate that:

The concurrent conceptual design, manufacturing and supply chain leads to more competitive, affordable and resilient aeronautical systems.

The objective is to formalize, implement and apply a holistic systems engineering framework to demonstrate this hypothesis and provide an answer to the research question. In line with this objective, the literature review covers three key research areas: architectural frameworks, methodologies for the concurrent design and optimization evaluation, value model techniques. This in-depth review highlights key gaps in existing research regarding the use of a systems engineering approach to formalize the concurrent design of the three systems and demonstrate how this can enhance the value of aeronautical systems. In addition, literature still lacks of methodologies enabling the concurrent design evaluation and optimization of architectures integrating product and production choices.

In this frame, a Systems for System Framework, shortly S4S Framework, is proposed to allow the concurrent conceptual design of the manufacturing, supply chain and aircraft systems. The S4S formalizes the processes of the life-cycle concept stage for the three systems. Based on the ISO 15288, it encompasses the definition of stakeholders’ needs and requirements, generation of architecture alternatives and their evaluation to aid decision-making. To execute the processes of the S4S Framework, a model-based approach is used. This approach provides a structured, integrated, and dynamic way of modelling, representing and analyzing complex systems throughout their life cycle. Information is captured in centralized digital models that are continuously updated improving accuracy and consistency, enhancing collaboration, scalability and flexibility leading to faster iterations and solutions innovation. The application of the S4S Framework in two case studies demonstrates its use advantages. The most efficient and competitive aeronautical systems can be identified in the solutions tradespace, in alignment with design and production requirements and stakeholders´needs. Aeronautical systems are so designed to increase the cost-effectiveness, by anticipating the evaluation of later stages. By integrating production performance assessments into the design phase, designers can make informed decisions that enhance manufacturability and supply chain efficiency. This integrated approach also helps proactively identifying and addressing potential production bottlenecks, reducing costs and increasing the overall value of the aeronautical systems. All the activities performed in this study are summarized in the conclusions with the main findings and key recommendations for the future.

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Nomenclature

Acronyms and Abbreviations

Acronym	Description
3DCE	Three-dimensional Concurrent Engineering
A350XWB	A350 Extra Wide Body
ACARE	Advisory Council for Aviation Research and Innovation in Europe
ADSG	Architecture Design and Optimization Graph
AGILE	Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
AHP	Analytic Hierarchy Process
AR	Aspect Ratio
CBA	Cost Benefit Analysis
DoDAF	Department of Defense Architecture Framework
ES	Enabling System
GBOM	Generic Bills of Materials
H2020	Horizon 2020
HTP	Horizontal Tail Plane
ID	Identifier
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISA	International Standard Atmosphere
ISO	International Organization for Standardization
LA	Least Acceptable
LB	Low Boundary
LHS	Latin Hypercube Sampling
MAC	Mean Aerodynamic Chord
MAUT	Multi Attribute Utility Theory
NPV	Net Present Value
MBSE	Model Based Systems Engineering
MD	Max Desirable
MDAO	Multidisciplinary Design Analysis and Optimization
MDO	Multidisciplinary Design Optimization
MODAF	British Ministry of Defence Architecture Framework
MfG	Manufacturing
MTOW	Mass Take Off Weight
MZFW	Max Zero Fuel Weight
MOEW	Mass Operative Empty Weight
MEW	Mass Empty Weight
MPAYLOAD	Mass Payload
NAF	NATO Architecture Framework
OEMs	Original Equipment Manufacturer(s)
PAX	Passengers
PD	Product Design
QoI	Quantity of Interest

S4S	Systems for System
SC	Supply Chain
SoI	System of Interest
SoS	System of Systems
SoTA	State of The Art
SV	Surplus Value
TF	Technology Factor
TOGAF	The Open Group Architecture Framework
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UB	Upper Boundary
VDD	Value-driven Design
WTO	Weight Take-off

Symbols

Symbol	**Units**	**Description**
W	kg	system mass
S	m^2	wing surface
b	m	wing span
lf	m	fuselage lenght
MAC	m	mean aerodynamic chord lenght
C_L	dimensionless	lift coefficient
C_D	dimensionless	drag coefficient
C_{d0}	dimensionless	zero-lift Drag
$C_{d0_{Cruise}}$	dimensionless	zero-lift Drag in Cruise
a	dimensionless	air
r	dimensionless	road
rl	dimensionless	railway
w	dimensionless	water
g	dimensionless	means of transportation
e_j	dimensionless	enterprise j of supply chain
q_{i,e_j}	dimensionless	production quantity of the component i manufactured/assembled by the enterprise e_j
d_{e_j,e_i}	dimensionless	distance between the production site i and the assembly site j
w_g	dimensionless	percentage of path carried out by the selected transportation mode
Cost($\sum_{j,i} d_{e_j,e_i}$)	dimensionless	cost to transport goods from production site i to the assembly site j using the mean of transportation g
Time$\sum_{j,i} d_{e_j,e_i}$)	dimensionless	time to transport goods from production site i to the assembly site j using the mean of transportation g
Risk($\sum_{j,i} d_{e_j,e_i}$)	dimensionless	risk to transport goods from production site i

		to the assembly site j using the mean of transportation g
Cost_{MfG_j}	dimensionless	manufacturing cost of each enterprise
Time_{MfG_j}	dimensionless	manufacturing time of each enterprise
Risk_{MfG_j}	dimensionless	manufacturing risk of each enterprise
Quality_{MfG_j}	dimensionless	manufacturing quality of each enterprise
Cost_{tr}	dimensionless	transportation cost of each enterprise
Time_{tr}	dimensionless	transportation time of each enterprise
Risk_{tr}	dimensionless	transportation risk of each enterprise
Cost_{SC}	dimensionless	supply chain cost of each enterprise
Time_{SC}	dimensionless	supply chain time of each enterprise
Risk_{SC}	dimensionless	supply chain risk of each enterprise
Quality_{SC}	dimensionless	supply chain quality of each enterprise
Cost_{fixed}	dimensionless	supply chain cost of each enterprise
Time_{fixed}	dimensionless	supply chain time of each enterprise
Risk_{fixed}	dimensionless	supply chain risk of each enterprise
Quality_{fixed}	dimensionless	supply chain quality of each enterprise
N	dimensionless	number of attributes
λ_i	dimensionless	weight associate with attributes
$\text{U}(\text{X}_i)$	dimensionless	single attribute utility function
TF_{Drag}	dimensionless	Technology Factor for Drag
TF_{Weight}	dimensionless	Technology Factor for Mass

1
Introduction

Contents

1.1 European Frame & High-level Goals

Over years, public perception of aviation has evolved, placing greater emphasis on climate change, local air quality, noise, punctuality, pricing, health, and the fastest and most affordable connections.

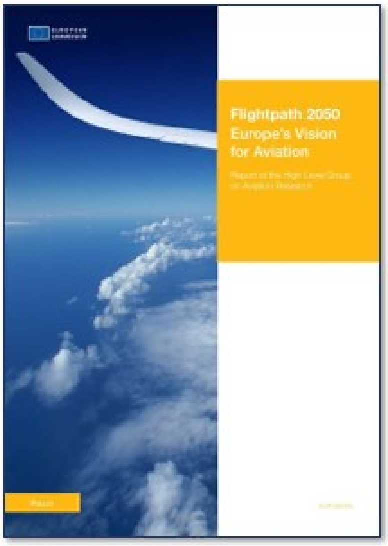


Figure 1.1: FlightPath 2050

These societal priorities, along with the visions, strategies, and road-maps of various aviation stakeholders, have been consolidated into a unified and holistic vision for the future of European aviation: the Flightpath 2050 (Figure 1.1). Developed by the European Commission, namely by the Advisory Council for Aviation Research and Innovation in Europe (ACARE), this plan outlines milestones for the transition from aviation's Era of Growth (1990-2020) to its Era of Transformation (2020-2050), aiming to achieve climate-neutral aviation, enhance global leadership and prioritize citizens' needs [1]. The achievement of these goals involves a range of activities aimed at tackling key challenges, grasping emerging opportunities, and fostering collective action across the aerospace ecosystem. These activities encompass research and development initiatives focused on advancing critical technologies for a more efficient and environmentally friendly aviation sector, regulatory harmonization to streamline processes and eliminate barriers to innovation, and education and training programs designed to equip students and professionals with the necessary knowledge, skills, and mindset (Figure 1.2).

Figure 1.2: Flightpath 2050: Challenges and Goals for Aviation in 2050 [2].

Realizing these aspirations however demands more than just innovative engineering and technological breakthroughs. It necessitates a fundamental shift in the way aeronautical systems are conceived, built and sustained. A key aspect of this shift is the imperative to integrate manufacturing and supply chain decisions into the early design stage of an aircraft: from the selection of materials and production processes to the sourcing of components and logistics management to customers delivery (Figure 1.3). The early selection of materials, processes and suppliers facilitates the adoption of innovative manufacturing techniques, materials and supply chain strategies enabling streamlined production processes. It allows for the identification and mitigation of risks associated with production scalability, supplier dependencies and material availability minimizing production expenses and ensuring competitive pricing for aeronautical systems. Engineers can so design components and systems that are not only technologically feasible but also cost-effective to produce. In fact, the early identification of potential bottlenecks or resources constraints empowers organizations to proactively address these challenges avoiding delays downstream, prevent costly redesigns later in the process leading to shorter lead times and faster time-to-market.

This approach, however, not only enhances system competitiveness but also boosts continuous improvement throughout the development process encouraging collaboration with global partners, including suppliers, manufacturers and regulatory bodies. By fostering interdisciplinary cooperation, stakeholders can unlock new synergies, accelerate technological advancements, and drive continuous improvement towards the shared goal of sustainable aviation. In fact, aerospace engineers and industry stakeholders can leverage the full spectrum of opportunities to optimize efficiency, minimize waste, and enhance sustainability across the entire life-cycle of an aircraft: from lightweight composite materials that reduce fuel consumption to modular assembly techniques that streamline production processes. Therefore, aerospace stakeholders can contribute to building a sustainable, competitive, and technologically advanced aviation sector envisioned for the future.

Figure 1.3: Concurrent Aircraft Design and Production, [3].

In conclusion, the concurrent design of manufacturing and supply chain processes in the early aircraft design phase is not just a strategic choice; it's a necessity in today's competitive aerospace landscape. By embracing this integrated approach and prioritizing early decision-making, companies can unlock new opportunities for innovation, efficiency, and success in bringing cutting-edge aircraft to market. In this frame, the digital transformation represents a key enabler for achieving such objectives. Disruptive technologies are needed to manage complexity, facilitate the data exchange, optimize the entire aircraft life-cycle and accelerate the decision-making at all the stages of the aircraft life-cycle to quickly define cutting edge solutions and remain competitive in the global market. This perfectly aligns with Flightpath 2050´s goals (Figure 1.2) of boosting a financially sustainable aviation industry capable of driving economic growth and innovation, maintaining a competitive edge in the global aviation market ensuring timely introduction of innovative aviation solutions to address societal and market needs and realizing the international collaboration and partnerships to drive progress toward common aviation goals fostering a culture of innovation and collaboration within the aerospace industry.

1.2 Research Question, Hypothesis & Objective

Considering manufacturing and supply chain aspects in the early phase of aircraft design aligns with the overarching goals and principals outlined in Flightpath 2050. By embracing this integrated approach, aerospace stakeholders can contribute to building a sustainable competitive and technologically advanced aviation sector envisioned for the future. A consistent integration of design, manufacturing and supply chain therefore emerges as a critical imperative nowadays to overcome the limits of the sequential approach, adopted by aeronautical companies over years. Indeed, the manufacturing and supply chain have been always addressed once defined the design of the aeronautical system. This limits the ability to adapt to market changes, technological advancements or unexpected disruption causing a drastically increase of cost. Indeed, once the design is frozen, making changes becomes extremely costly and time-consuming, as stressed in Figure 1.4.

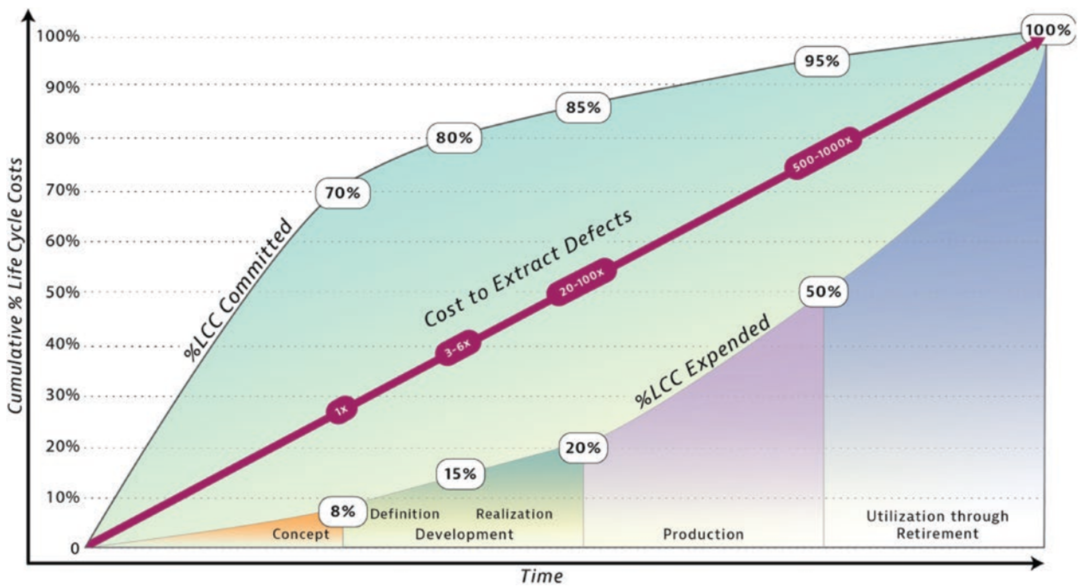


Figure 1.4: Costs of changes during system life-cycle, [4].

Several aeronautical companies faced these problems. Among others, Boeing with the 787 Dreamliner in which required changes in the design lead to production bottlenecks and delays with significant cost overruns [5]. Instead, the Concorde, a supersonic passenger jet developed jointly by Brithish Aerospace and Aérospatiale, faced challenges due to its unique design and technologies. As the aircraft aged, sourcing spare parts became increasingly difficult, ultimately contributing to its retirement. Without considering that technology evolves rapidly and components that are state-of-the-art during the design phase may become obsolete by the time production starts leads to higher costs for sourcing or even unavailability of critical parts [6]. In addition, global events, such as natural disasters, geopolitical tensions, or pandemics, can disrupt the supply chain. Once the design is frozen, it's difficult to quickly adapt to these disruptions, leading to production delays or increased cost. For instance, the Fukushima earthquake and tsunami in 2011 had a significant impact on the automotive industry's supply chain, affecting companies like Toyota and Honda [7, 8]. The rigid supply chain designs meant that even minor disruptions at critical suppliers could halt production lines for weeks [8, 9]. Also, Airbus with the A380, the largest passenger airliner, and the A350XWB (Extra Wide Body) introduced in 2004 as derivative of A330, faced challenges due to their ambitious design and production scales. Issues with suppliers and unexpected design changes led to massive delays, cost overruns, ultimately causing Airbus to rethink its production strategy [10, 11]. Finally, once the design is frozen, maintaining consistent quality becomes more challenging, especially if suppliers encounter issues or changes are required late in the production process. That´s what´s happened with the Bombardier's CSeries aircraft which faced delays and quality control issues during its development phase. Changes in suppliers and design modifications contributed to these challenges, highlighting the importance of robust quality control processes in complex supply chains [12]. Therefore, the need of considering production aspects in the early conceptual stage. By involving supply chain and manufacturing experts during the design phase, potential constraints and limitations can be identified early. This allows designers to make informed decisions that optimize the product for manufacturability and supply chain efficiency, than only the overall product performance. By involving supply chain and manufacturing experts in the design phase, companies can foster collaboration and communication between cross-functional teams and leverage their expertise to drive innovation and differentiate their products in the market. In addition, design decisions that take into account material availability, production processes, supply chain logistics can help mitigate risks associated with production delays, supply chain disruptions and quality issues leading to more cost-effective solutions, reduce the time to market, giving companies a competitive advantage in the fast-paced aerospace industry.

This research activity is framed in this context. Specifically, the research question being investigated is:

Research Question

Can making more decisions in the early life-cycle stage increase the value of complex aeronautical systems?

Each system, indeed, has a life-cycle that can be defined in terms of stages that mark progress in achieving the system characteristics. A general example of life-cycle stages, also according to ISO15288, is proposed in Figure 1.5 .

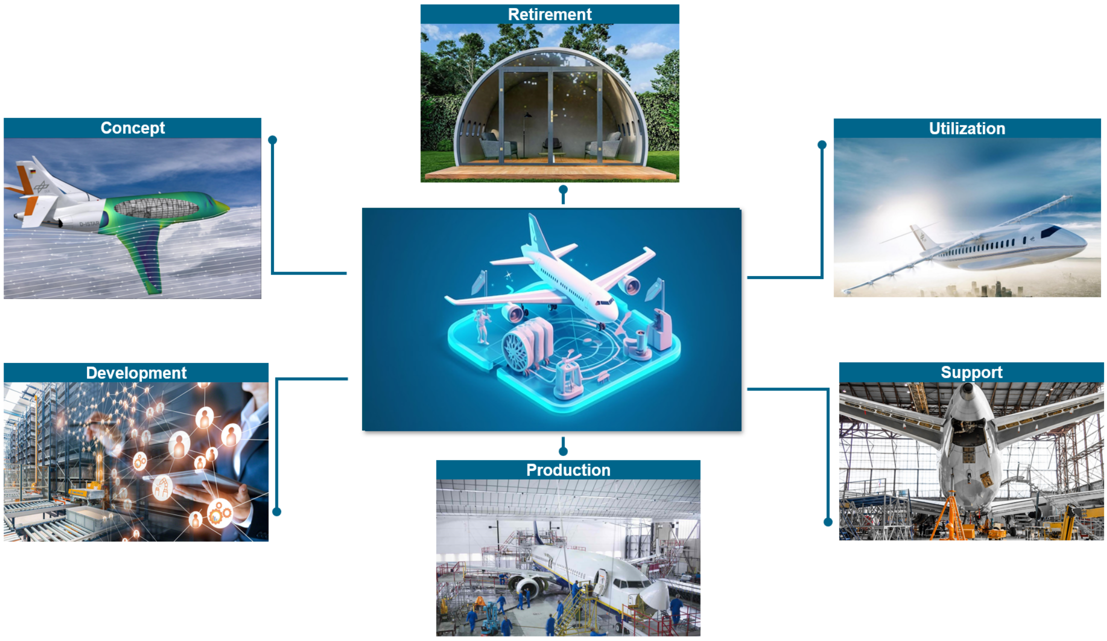


Figure 1.5: System life-cycle stages according to ISO15288.

These stages do not necessarily occur in a sequential order. However, decisions related to the system's life-cycle are typically made while the system is in that specific stage. This has been demonstrated in the real-world cases previously mentioned, showing how decisions related to production are often made after the aircraft design has already been finalized. These cases have also highlighted the issues associated with this approach. To overcome these issues, and in relation to the identified research question, this work aims to demonstrate that:

Hypothesis

The concurrent conceptual design, manufacturing and supply chain leads to more competitive, affordable and resilient aeronautical systems.

High competitiveness, efficiency and resilience can be indeed seen as way to enhance the value of aeronautical systems. Proving this hypothesis requires, however, addressing several sub-questions. Among others, for instance, how to enable the concurrent conceptual design of the aircraft, manufacturing and supply chain; how to formalize and quantify the value of aeronautical systems when considering design and production; what role decision-makers play and how they come into play. Indeed, the objective of this research activity is:

Objective

Increase the value of aeronautical systems by formalizing, implementing and applying a holistic systems engineering methodology ensuring the concurrent supply chain, manufacturing, and aircraft systems conceptual design.

To achieve the objective of this research, which is essential for validating the proposed hypothesis and thus answer to the research question under investigation, several activities are carried out: from a literature review to identify the current state of these topics and the main existing gaps, to developing a formal and consistent approach, followed by its implementation and application.

1.3 Thesis Structure

To address the research question posed in this study and support the proposed hythesis, several tasks have been performed and organized according to the following structure:

- **Chapter 1**: Introduction
  The high-level objectives and challenges at the European level are introduced to highlight the importance of this research activity with respect to the European context. Then, the research question is identified as well as the hypothesis and main objective of this study.
- **Chapter 2**: Literature Review
  The literature review is performed to have a clear idea on the main activities related with this study. Three key research areas are investigated: Architectural framework, methodologies for the concurrent design and optimization evaluation, value model techniques. The main gaps are highlighted.
- **Chapter 3**: Methodology Formulation
  Clarifications on the meaning of the main activities and terms of this study are provided for a clear understanding of all the activities performed. In addition, the proposed systems engineering holistic approach enabling the concurrent aircraft design, manufacturing and supply chain is explained in details.

- **Chapter 4**: Methodology Implementation
  The technologies leveraged to implement the proposed systems engineering approach are briefly described. These technologies are necessary to accelerate the execution of the approach, enable the collaboration with other partners and increase traceability when designing multiple systems at the same time.
- **Chapter 5**: Methodology Application
  The proposed systems engineering approach and the relative technologies are applied in the context of two European projects aiming respectively to identify the best alternative for the design, manufacturing and supply chain of a horizontal tail plane for a 90-passenger aircraft and the best alternative for the design and manufacturing of a fuselage seaplane.
- **Chapter 6**: Conclusions
  A brief overview of the activities conducted is presented, highlighting the key findings related to each task in this study. Additionally, recommendations for future activities are included.

2

Literature Review

Contents

2.1 Architectural Frameworks

The management of the development complexity requires a shift to a novel development paradigm for complex systems and to the development of novel design systems. The organization of all the data produced during the design process can be guided through an architectural Framework. The ISO/IEC/IEEE 42010 standard defines an architectural Framework as a set of conventions, principles and practices for the description of architectures established within a specific domain of application and/or community of stakeholders [13]. The architecture in this definition represents the structure and behavior of a system, where a system is a set of entities and their relationships, whose functionality is greater than the sum of the individual entities [14]. In other words, an aircraft is a system, since all its entities, e.g. wings, fuselage, engines and on-board systems, are joined together to make possible the flight and transport of payload. Therefore, an architecture describes different aspects of the system. A system architecture can represent for instance all the parts that compose the system, its life-cycle, how it is operated by external users and a lot of other information. An architectural Framework provides the guidelines for the standard representation of the multiple system architectures.

Several architectural Frameworks are available in literature, e.g. Zachman's Framework [15], DoDAF [16], MODAF [17], NAF [18], TOGAF [19] and Ciampa

[20]. All of them promote standardization and consistency in system development and share the common goals of improving systems architecture, ensuring alignment with organizational gaols and emphasizing interoperability and system integration. However, while DoDAF, MODAF and NAF are more military and defence-focused, Zachman, TOGAF and Ciampa´s MBSE-MDAO Development Framework are more flexible and address a wider range of application cases. Among all, Ciampa´s architectural Framework, shown in Figure 2.1, inspired this study representing the starting point on which the holistic systems engineering approach enabling the concurrent design of aircraft, manufacturing and supply chain has built.

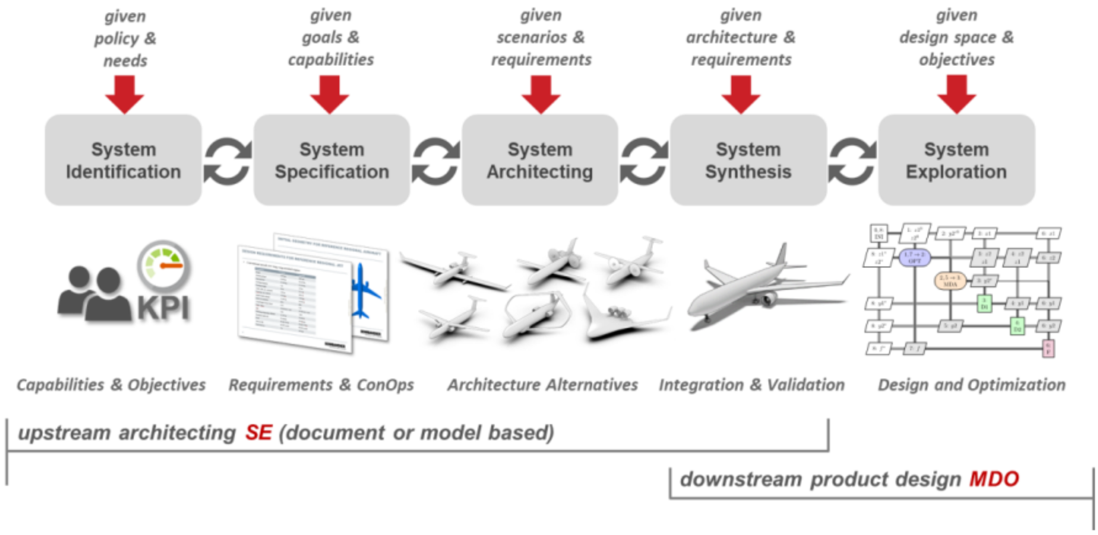


Figure 2.1: MBSE-MDAO Development Framework connecting the upstram architecting System Engineering (SE) and the downstream product design MDAO phases, adapted from [20].

This MBSE-MDAO Development Framework aims at connecting two phases of the complex system development process:

- **upstream architecting phase** that includes the identification of stakeholders and their needs within a scenarios (System Identification Process), the system requirements elicitation from stakeholders´needs (System Specification Process), the design and modeling of the architecture of the system of interest under development, for instance an aircraft (System Architecting Process);
- **downstream product design and optimization phase** that addresses the design and eventually optimization for a given architecture and a given set of requirements. This includes the selection of the design competence, e.g. disciplinary simulations, the integration into a design processes, the deployment of design system, the exploring of the design space and the decision

making about the optimum solutions (System Synthesis and Exploration Processes).

The Framework provides guidelines supporting the definition and modelling of these processes [21–23]. In addition, several technologies have been developed to implement the MBSE-MDAO Development Framework to support the processes, enhance design quality, system specification and communication within the design team [24]. More details on the processes characterizing the upstream and downstream architecting phases are provided in the following sections.

2.1.1 System Identification and Specification

The ontology of the MBSE-MDAO Framework defining the stakeholders, needs and requirements is reported in Figure 2.2. It represents the key concepts and their relationships for the definition of system stakeholders, needs and requirements.

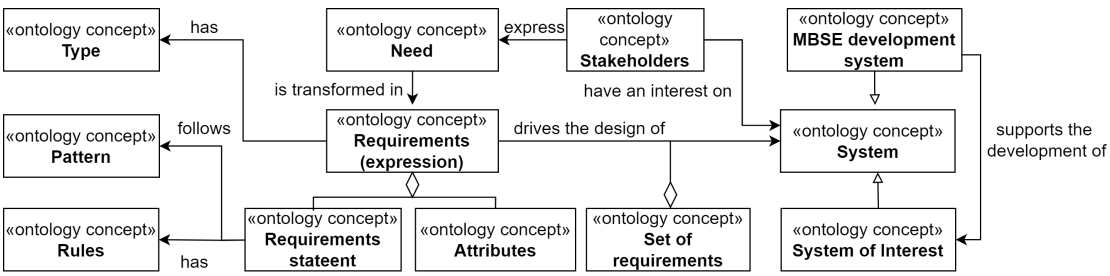


Figure 2.2: Ontology for the definition of system stakeholders, needs and requirements, modified from [21].

The first process targets the identification of all the stakeholders that have an interest on the system. A stakeholder is indeed, per definition, an individual or organization having a right, share, claim, or interest in a system or in its possession of characteristics that meet their needs and expectations [4]. All the stakeholders express different needs that are wishes, necessities and desires from the system. These needs are generally unstructured and expressed in fuzzy or general, ambiguous terms, and therefore they must be translated into requirements, which instead should follow precise patterns and rules to assure characteristics as completeness, feasibility, verifiability and correctness. A requirement is a statement which translates or expresses a need and its associated constraints and conditions. Each requirement consists of a statement, i.e. the text, and attributes that are used for the management of the requirement like ID, author and means of compliance [25].

Requirements can also be categorized according to their type. Depending on the requirement type, the requirement statements follow different patterns (that define the structure of the requirements) as following:

- **Functional Requirements** define what functions need to be performed to accomplish the objectives [26]
  Pattern: The SYSTEM shall [exhibit] FUNCTION [while in CONDITION]
- **Performance Requirements** define how well the system needs to perform the functions [26]
  Pattern: The SYSTEM shall FUNCTION with PERFORMANCE [and TIMING upon EVENT TRIGGER] while in CONDITION
- **Design Constraint Requirements** limit the options open to a designer of a solution by imposing immovable boundaries and limits [27]
  Pattern: The SYSTEM shall [exhibit] DESIGN CONSTRAINTS [in accordance with PERFORMANCE while in CONDITION]
- **Environmental Requirements** define which characteristics the system should exhibit when exposed in specific environments (e.g. acoustic/thermal loads, atmospheric conditions) [26]
  Pattern: The SYSTEM shall [exhibit] CHARACTERISTIC during/after exposure to ENVIRONMENT [for EXPOSURE DURATION]
- **Suitability Requirements** include a number of the "-ilities" in requirements to include, e.g. transportability, survivability, flexibility, portability, reusability, reliability, maintainability, and security [26]
  Pattern: The SYSTEM shall exhibit CHARACTERISTIC with PERFORMANCE while CONDITION [for CONDITION DURATION]

2.1.2 System Architecting

The activities of the System Architecting Process aim at defining all the possible components that should be part of the system architectures in order to provide all the system functions as demanded by the functional requirements. Multiple system architectures can be identified in this step, representing conventional but also innovative solutions. The ontology of the MBSE-MDAO Framework describing the key concepts and their relationships about system architecture is reported in [22]. The designer chooses the boundary functions from the defined functional requirements. These functions are fulfilled by components. Each component described in the design space defines the functions it fulfills and the functions it needs (i.e. induces [28]) in order to fulfill its functions. In a system architecture, only one component can fulfill a function. This means that if there are multiple components specifying that they can fulfill a function, there is a design choice to be made. Mapping components to functions is the first step in the architecting process, and these decisions are therefore also the first decisions to be taken. Once components have been associated to functions, the next step in the architecting process is the characterization of the components. These can be characterized in two ways: by number of instances and the amount of instances can be a design decision or/and by attributes and the selection of values for the attributes is a design decision. In addition, quantifiable performance metrics can be assigned to functions or components to compare architectures instances. In an optimization problem, these metrics can also represent the objectives functions, the design variables or the constraints. An example showing the described tasks related to the system architecting is shown in Figure 2.3.

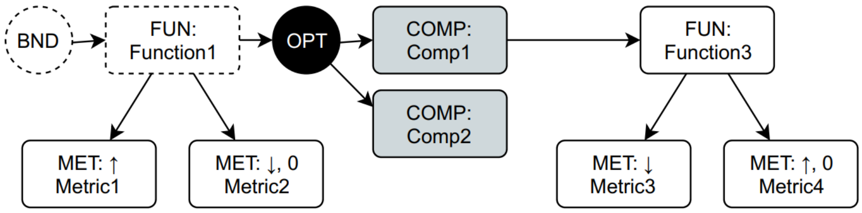


Figure 2.3: Example of main system architecting tasks, modified from [29].

2.1.3 System Synthesis and Exploration

During the downstream Multidisciplinary Design and Optimization (MDO) phase, the design and optimization of a given architecture and a given set of requirements is addressed. During these processes, the disciplinary competences needed to quantify the main performance metrics of the architecture are therefore identified. Structure, aerodynamic, weights and balance are some examples of disciplinary competence related to the design of the aircraft. To analyse the architecture, these competences are integrated into the same design process. The design of the nowadays aircraft system, however, requires the integration of an increasing number of connected disciplines in order to find the overall benefit. In addition, the complete design is not the endeavor of a single actor anymore, but rather the results of collaboration among hundreds of engineers, distributed among multiple specialized organizations. For this reason, the MBSE-MDO Framework proposes to adopt the AGILE Paradigm based on the 3rd generation MDO systems [30].In this case the distribution does not involve only the analysis capabilities, but the distribution of the overall design task. Research has focused on the development of decomposition methods, and approaches, such as concurrent engineering and collaborative optimization, which promise to enable the reality of participant engineering. Due to the complex interactions, one of the priorities of the 3rd generation MDO is to support the human judgment, and lessen the aforementioned complexities.

2.2 Concurrent Design & Optimization Methodologies

Concurrent engineering, also known as simultaneously engineering, refers to a method of designing in which different stages of product development run at the same time, rather than consecutively. Here, the domains of interest for the concurrent coupling are: product design (PD) dealing with the product´s specifications; supply chain (SC) including in-sourcing and outsourcing, logistical channels, suppliers and the type of relationship among supply chain members; manufacturing (MfG) focusing on the facilities, equipment and methods used to manufacture the product. Addressing optimization of Product Design and Supply Chain simultaneously via mathematical models allows to overcome the limits of the sequential approach in which product design is analysed independently from the production plan, impacts, and constraints [31]. Including supply chain decisions during the product design leads to a reduction in the production cost [32], higher product quality [33, 34] and strategic partnership between Original Equipment Manufacturers (OEMs) and their suppliers [35]. A close link between Product Design and Manufacturing results, instead, in a better overall operating performance [36], cost reduction [37, 38], increased quality and reliability, shorter manufacturing time with better responsiveness to market changes [39–41] with optimized the net cash flows over time [42]. Finally, integrating Manufacturing and Supply Chain simultaneously reduces production cost [43–45], boosts the relationship between supplier and customer [46, 47] and improves the logistic organization in the exchange of information among the supply chain members [48, 49]. Survey and conceptual works, however, provide preliminary evidence that decisions made simultaneously accounting for Product Design, Manufacturing and Supply Chain can help companies to achieve even more competitive advantages [50, 51]. To make a potential benefit of the final product as whole, it is necessary to enlarge the concurrent analyses to more than two domains and consider the manufacturing and supply chain information simultaneously in the early stage of product design [52, 53]. In this context, several activities have been found in literature related to the modelling of the three-dimensional concurrent engineering paradigm (3DCE), defined as the simultaneous developments of products, processes and supply chains [54–57]. A different approach is proposed by Fixson [58], who suggests the functional architecture of a product as the link between the product design, manufacturing and supply chain domains. Although it might be complicated to adapt for complex systems [54], Blackhust et al. [59] formalize a short network approach, called Product Chain Decision Model, to analyse the impact of product design and manufacturing decisions on the supply chain. An extension of the concept Generic Bills of Materials (GBOM) is instead proposed by Wang et al. [60] to qualitatively and quantitatively capture the integration among product configurations, manufacturing processes and supply chains. Finally, further insights on motivations, approaches and trade-off studies that can be performed by coordinating product design, manufacturing and supply chain are provided by papers collected in [61, 62].

2.3 Value-driven Decision-making Techniques

To meet the nowadays stringent requirements, for instance the greenhouse reduction for aviation system, new variables not strictly related to the product design have to be considered in the early stage of product development. Integrating new aspects enlarges the solutions design space complicating even more the decision-making process. Identify the best solution in the design phase is nevertheless essential since decisions made during this phase mostly determine the product cost. Studies in systems engineering highlights that up to the 70% of product development cost is already committed in preliminary design and that the cost to remove defects radically increases afterward [63]. As consequence, define which criteria lead stakeholders to value the system has to be clear since the early stage of product design in order to balance these criteria and optimize the system design value. Over years, the concept of value has assumed different meaning being defined as the ratio between performance and cost [64]; amount of money a customer is willing to pay [65,66]; individual satisfaction of a user in using the product [67]. In the last decades, however, researchers in the field of systems engineering identified the need of having a definition of value as numerical quantification of stakeholder 'expectations in order to enhance the decision-making process. With the introduction of value-driven design (VDD) [68], the definition of value switches to a numerical estimation of stakeholders 'preferences including but not limited to the feasibility and technical performance of the product under design [69, 70]. Nowadays, all the methodologies leveraging value models to identify the best possible outcome based on a right comprise among all the criteria important for stakeholders are under the VDD term [71]. These methodologies range from Tradespace Exploration [72–75], to Value Centric Design [76] and Value Driven Optimization [77, 78]. While in the last case the objective is to optimize a system towards its best value, in the first cases the aim is to increase the decision-makers ‘awareness during trade-off studies involving multiple criteria. Different value models support these methodologies having each one a unique interpretation, quantification and representation of the term value. Net Present Value (NPV), Surplus Value (SV), Cost-Benefit Analysis (CBA) are the mostly used value models in system engineering. In this case, the value function represents the discounted cash flows generated over time and thus the profits gained in investing in a specific design of the system [77,79,80]. The Multi-Attribute Utility Theory (MAUT) instead uses utility curves of system attributes, derived from a set of probabilistic lotteries, to aggregate monetary and not-monetary stakeholder perceived value to obtain a ranked ordering of system design alternatives [81]. This theory provides the same output of another value model, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [82]. TOPSIS is also based on a systematic decomposition of a system design into a hierarchy of desirable attributes, aggregated in an overarching goal. However, decision trees or matrixes are used and system attributes are pairwise compared by the use of a simple algorithm within each node or within each cell in the matrix. Analytic Hierarchy Process (AHP) [83] is another value model sharing the same TOPSIS approach but it is more similar to NPV and CBA in mapping alternatives to a cardinal scale [72].

2.4 Research Gap and Original Contribution

Several research studies have been reviewed to identify the current state of the art (SoTA) of activities related to the technical objective of this study: enhance the value of aeronautical systems by formulating, implementing, and applying a systems engineering approach that facilitates the concurrent conceptual design of the supply chain, manufacturing, and aircraft systems. In line with this objective, the literature review covered three key research areas: Architectural Frameworks, Methodologies for the Concurrent Design and Optimization, Value Model Techniques. The results of the literature review are summarized in Table 2.1. This table highlights the SoTA of the these three research areas and the main identified gaps.

Architectural Frameworks, usually based on industry standards, offer designers structured guidelines for the system development processes. Although some Frameworks are mainly used in the military sector, Ciampa’s MBSE-MDO Framework can be applied across various field. As mentioned, it provides a clear approach for system development, including identifying stakeholders and their needs, converting those needs into validated requirements, creating system architectures, and evaluating them to determine the best solution. The guidelines provided by this Framework can be applied to the conceptual design development of each individual system

Table 2.1: Literature Review Summary.

Research Area	References	SoTA	Gaps
Architectural Framework	[15–30]	Several Available; System of Interest and Military Applications	Applications to enabling systems; Guidelines for decision-making
Concurrent Methodologies	[31–62]	Few on concurrent design of all Systems	Formalized methodology
Value model Techniques	[63–83]	Several methods available	Few aeronautical applications; Link with Systems Engineering

(aircraft, manufacturing, supply chain). However, the goal of this study is to implement the processes of the Framework concurrently for the three systems rather than individually, by following the ISO/IEC/IEEE15288. For instance, one of the objectives, is to establish an architectural design space in which decisions result in architectures that integrate the design variables of the three systems at the same time. Therefore, while the logical architecture process of each individual system follows the approach outlined in Section 2.1.2, this study goes further by formalizing the integrated logical architecture across aircraft, manufacturing, and supply chain systems. The main modifications, however, are related with the processes characterizing the downstream phase and thus related with the design and optimization evaluation analysis. This study, in fact, aims at enabling the simultaneous design and optimization of aircraft, manufacturing and supply chain systems for the identification of the best solution according to decision-makers´expectations. Therefore, also decision-making elements are included in the approach and a simple ontology on how to integrate these new elements is presented. In addition, a new methodology for the concurrent design, optimization and best solution identification while considering the supply chain, manufacturing and aircraft systems is proposed. In this methodology, the terms domains are used instead of systems since the focus shifts to the competences and tools needed for evaluating these architectures. As highlighted in the literature review, some studies address concurrent methodologies for product design, manufacturing, and supply chain. However, a well-defined and formalized methodology for performing evaluations in the aeronautical sector is still lacking. To bridge this gap, a new value-driven methodology is proposed to clearly identify the key models of each domain (aircraft, manufacturing, supply chain) and the links existing among them. Among the available value-model techniques, the Multi-Attribute Utility Theory (MAUT), widely used in the space sector, is applied in this study. This technique is embedded in a systems engineering Framework, to enable the concurrent design and optimization evaluation and ensure that the best architecture trading stakeholders´expectations with respect to aircraft, manufacturing and supply chain criteria is correctly identified. A Systems for System Framework, shortly S4S, is therefore proposed in this study to close the key gaps existing in literature and demonstrate the advantages of leveraging a systems engineering approach to formalize the concurrent design of the supply chain, manufacturing and aircraft systems to enhance aeronautical systems value.

3
Methodology Formulation

Contents

3.1 Glossary

Before introducing the proposed systems engineering approach for the concurrent conceptual design of aircraft, manufacturing, and supply chain, it is beneficial to clarify the terminology used in this study and the respective meaning.

According to the ISO/IEC/IEEE 15288 (2023):

«a **System** is an arrangement of parts or elements that together exhibit or meaning that the individual constituents do not.»

The concept of an aircraft as a system is well-defined. An aircraft is a system designed to fly, consisting of components like wings, the horizontal tail plane, fuselage, and other parts. Each component has a specific function, such as the wing providing lift for flight. The aircraft serves as the **System of Interest (SoI)** meaning it is the system under analysis, development, or consideration for a particular purpose. In contrast, the characterization of the supply chain and manufacturing as systems may be less clear or not as well established as that of the aircraft.

In this study, the **Supply Chain system** is defined as a network of enterprises responsible for aircraft production, with each enterprise representing a constituent of the supply chain system. While individual enterprises may specialize in producing certain aircraft components, the supply chain as a whole has the capability to produce the entire aircraft. The **Manufacturing system**, on the other hand, is defined as a combination of machines necessary to transform raw materials into the final product, that is the aircraft. In this context, the individual constituents are the machines responsible for specific manufacturing processes related to the aircraft components. The proposed definitions of supply chain and manufacturing as systems align closely with the ISO definition. However, these systems are specifically related to the aircraft, as they support its development or production. Therefore, they are classified as enabling systems. In general, enabling systems are those that facilitate the development, operation, or maintenance of the System of Interest. According to the ISO/IEC/IEEE 15288:2015:

«**Enabling Systems (ES)** are systems that facilitate the development, production, deployment, operation, or disposal of a system of interest but do not necessarily contribute directly to its operational capability. Enabling Systems provide essential support functions such as development environments, training systems, maintenance systems, and logistics support.»

A schematic view representing the SoI (aircraft) and the enabling systems (supply chain, manufacturing) is reported in Figure 3.1.

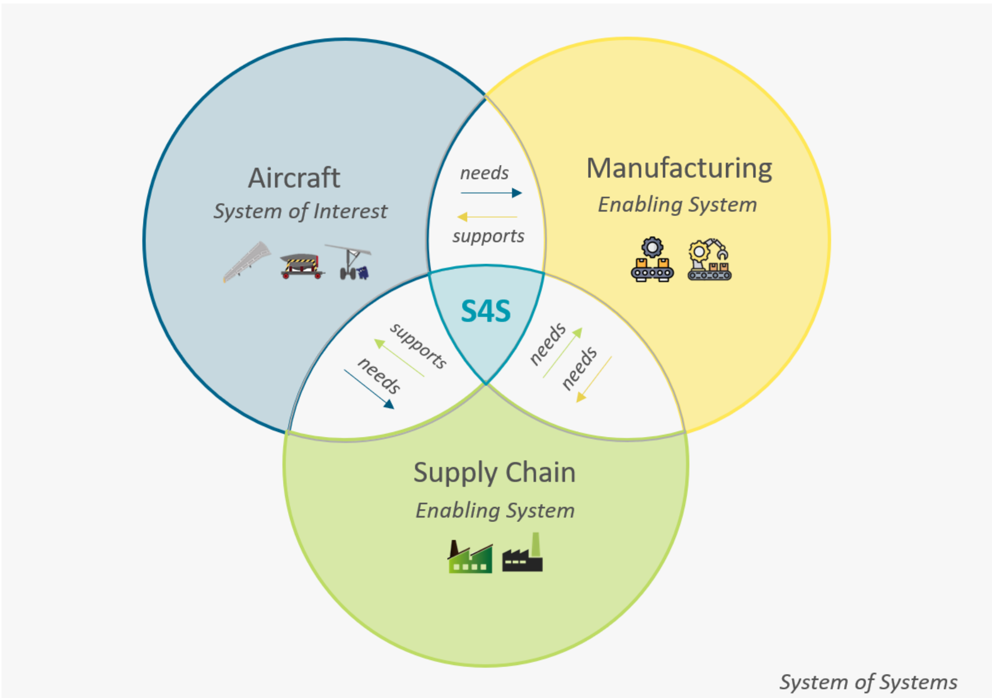


Figure 3.1: Enabling Systems (Supply Chain and Manufacturing) supporting the System of Interest (Aircraft). The Systems for System (S4S) indicates their relationships, also in a broader System of Systems Context.

In this picture, the **Systems for System (S4S)** is also proposed to indicate the System of Interest and the Enabling Systems relationships. In this definition, Systems refer to the Enabling Systems that supports the System of Interest (for System). S4S can be part of the System of Systems (SoS) concept defined, according to ISO/IEEE/IEC 15288, as follow:

«A **System of Systems (SoS)** is a system-of-interest whose elements are themselves systems. A SoS brings together a set of systems for a task that none of the systems can accomplish on its own. Each constituent system keeps its own management, goals, and resources while coordinating within the SoS and adapting to meet SoS goals.»

3.2 S4S Concurrent Conceptual Design

Traditionally, the design of manufacturing and supply chains starts when the aircraft configuration is established. This research activity aims at overcoming the limits of the traditional sequential design and enhance the value of complex aeronautical systems by proposing a systems engineering approach that enables the concurrent design of aircraft, manufacturing, and supply chain. But what does concurrent design actually mean? A formalized definition from a systems engineering perspective, beginning with the characterization of the life cycles of the systems involved is here proposed.

Life cycles are defined in terms of the stages that mark progress in achieving the system characteristics. Each system has therefore an its own life-cycle, meaning that based on the purpose and functionalities of the system under design, some stages might not be present. In this study, the common life-cycle model proposed by ISO/IEC/IEEE 15288:2023 and ISO/IEC/IEEE 24748:2018 is assumed for all the systems. It consists of six stages: concept, development, production, utilization, support and retirement that can overlap or run in parallel [63].

The concept stage is the initial phase. It generally begins with an exploratory research in which stakeholders´needs are analyzed to identify the technical requirements of the system under design. During this exploration research, in-depth studies are conducted and engineering models are used to evaluate multiple candidate concepts (architectures) and eventually provide a substantiated justification for the system concept that is selected. In the development stage, these requirements are refined and the prototype of the proposed concept is built and validated. The system is then realized during the production stage, used (utilization stage) and maintained (support stage) until the disposal (retirement stage). Among all, the concept stage is a particularly critical part of the system life cycle because the decisions made during this stage shape, with increasing difficulty to change, the possibilities for all the remaining stages [4].

The main limitation of the sequential approach lies in the decisions made in the concept stage, which focus exclusively on the aircraft design. Therefore, at this stage, various analyses are performed to determine the most efficient aircraft configuration.

Decisions related to production, such as manufacturing techniques and supply chain logistics, are postponed until the production stage of the aircraft begins. As a result, analyses concerning costs, potential production issues, manufacturing and assembly methods, and partner company selection only takes place once the aircraft design is finalized. This means that the conceptual stages of the supply chain and manufacturing systems start later, specifically after the aircraft's concept stage is completed and production has started, as shown in Figure 3.2.

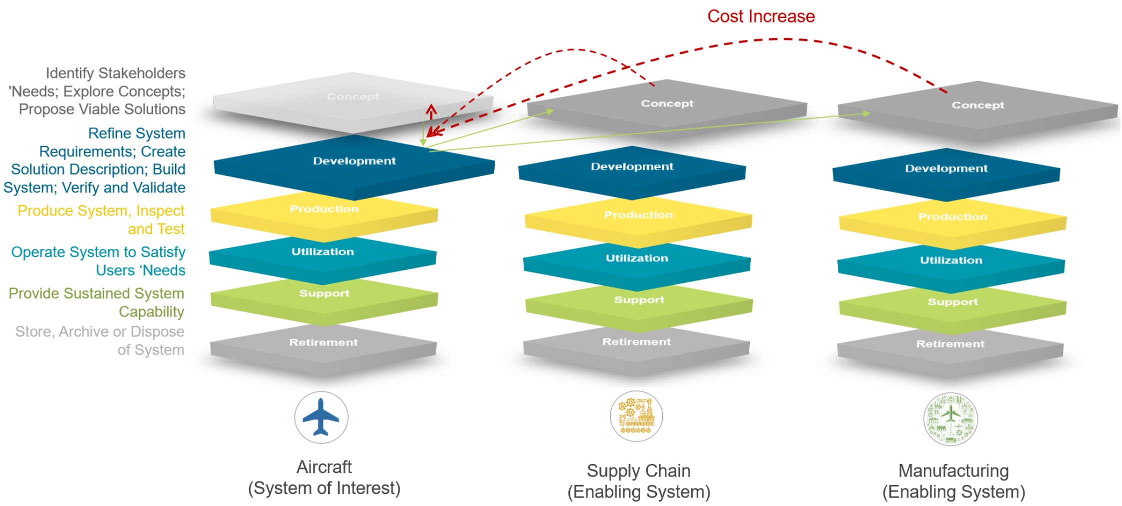


Figure 3.2: Traditional Sequential Approach in a systems engineering perspective. The concept life-cycle stages of manufacturing and supply chain systems starts after the concept stage of the system of interest (aircraf) during its development stage.

However, this approach leads to unforeseen costs if production issues occur. Therefore, the objective to overcome this traditional sequential approach with a concurrent approach in which the conceptual stage of all three systems begins simultaneously, as shown in Figure 3.3. In this case, analyses are performed to assess both the design and production performance, aiming at identifying the most efficient and competitive aircraft configuration. Therefore, production-related decisions, such as manufacturing processes and logistics considerations, are also taken into account simultaneously with those concerning aircraft configuration.

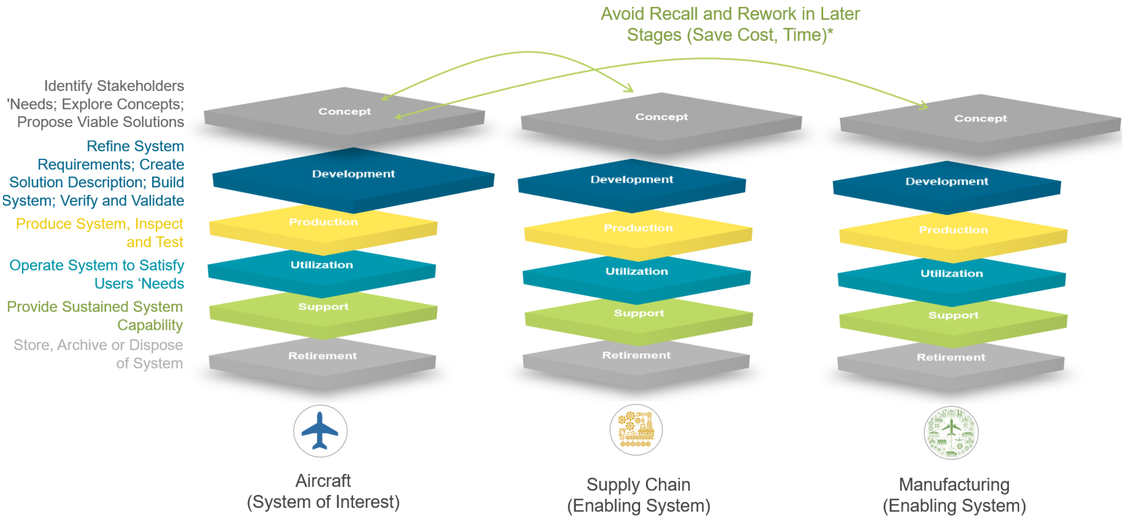


Figure 3.3: Concurrent Approach in a systems engineering perspective. The concept life-cycle stages of manufacturing, supply chain and aircraft systems start at the same time.

In conclusion, concurrently designing the manufacturing, supply chain and aircraft systems requires addressing the concept stage of these systems simultaneously. This practically means executing the processes that define the concept stage at the same time for all the systems.

3.3 S4S Framework

To enable the concurrent design of the aircraft, manufacturing, and supply chain systems, the main processes characterizing the concept stage have to be executed at the same time for the three systems. Therefore, as first step, it is necessary to identify the technical processes that characterize the concept stage.

The ISO/IEC/IEEE 15288 defines 14 technical processes throughout the life cycle stages. These processes are typically applied recursively to establish system requirements, convert those requirements into a functional product, utilize the product to deliver the necessary services, maintain it, and ultimately dispose of it when it is no longer in service [84].Among these technical processes, those related with the concept stage are:

- **Business or Mission Analysis Process** with the objective to define overall strategic problem or opportunity;
- **Stakeholders needs and requirements definition process** with the purpose to define the stakeholders´needs for a system;

- **System Requirements Definition Process** with the objective to transform the stakeholders desired capabilities into a technical view of a solution;
- **Architecture Definition Process** with the purpose to generate system architecture alternative;
- **Design Definition Process** with the objective to provide data and information about the system and its elements;
- **System Analysis Process** with the objective to provide a rigorous basis of data and information for technical understanding to aid decision-making.

These processes are integrated into the graphical and conceptual representation of the MBSE-MDO Framework introduced by Ciampa (Figure 2.1, Section 2.1) that provides, in addition, a set of guidelines that designers can follow to perform them. Nevertheless, when comparing these technical processes with those proposed in the MBSE-MDO Framework (Table 3.1), it is clear that the activities associated with the Business or Mission Analysis process are not formalized in Ciampa's Framework. Instead, they provide input data for the activities of the other processes of the Framework.

Table 3.1: Comparison between the ISO 15288 Technical Processes and MBSE-MDO Framework Processes.

ISO 15288 Technical Process	MBSE-MDO Framework Process
Business or Mission Analysis	-
Stakeholders Needs and Requirements	System Identification
System Requirements	System Specification
Architecture	System Architecting
Design Definition	System Synthesis
System Analysis	System Exploration

The MBSE-MDO Framework, assumed as reference for this study, has been modified to enable the concurrent design of the aircraft, manufacturing and supply chain systems. Indeed, the guidelines provided by this Framework can be applied to the conceptual design development of each individual system. For instance, in the case of the supply chain system, it is possible to identify stakeholders, their needs, and translate them into requirements. From these requirements, supply chain system architectures can be generated and evaluated using the right competences and tools. Therefore, modifications to the MBSE-MDO Framework are required to enable the simultaneous conceptual design of the three supply chain, manufacturing, and aircraft systems, in line with the aim of this study. The goal is to implement the processes for all three systems concurrently rather than individually. For example, the objective is to establish an architectural design space where the decisions made result in architectures that integrate the design variables of all the three systems. In this frame, the Systems for System Framework, shortly S4S Framework, is proposed as an enhancement to the MBSE-MDO Framework. As illustrated in Figure 3.4, it aims at enabling the concurrent conceptual design of the manufacturing, supply chain and aircraft systems, according with the definition provided in Section 3.2. The S4S Framework has the same processes of the MBSE-MDO Framework, grouped into an upstream and downstream phase.

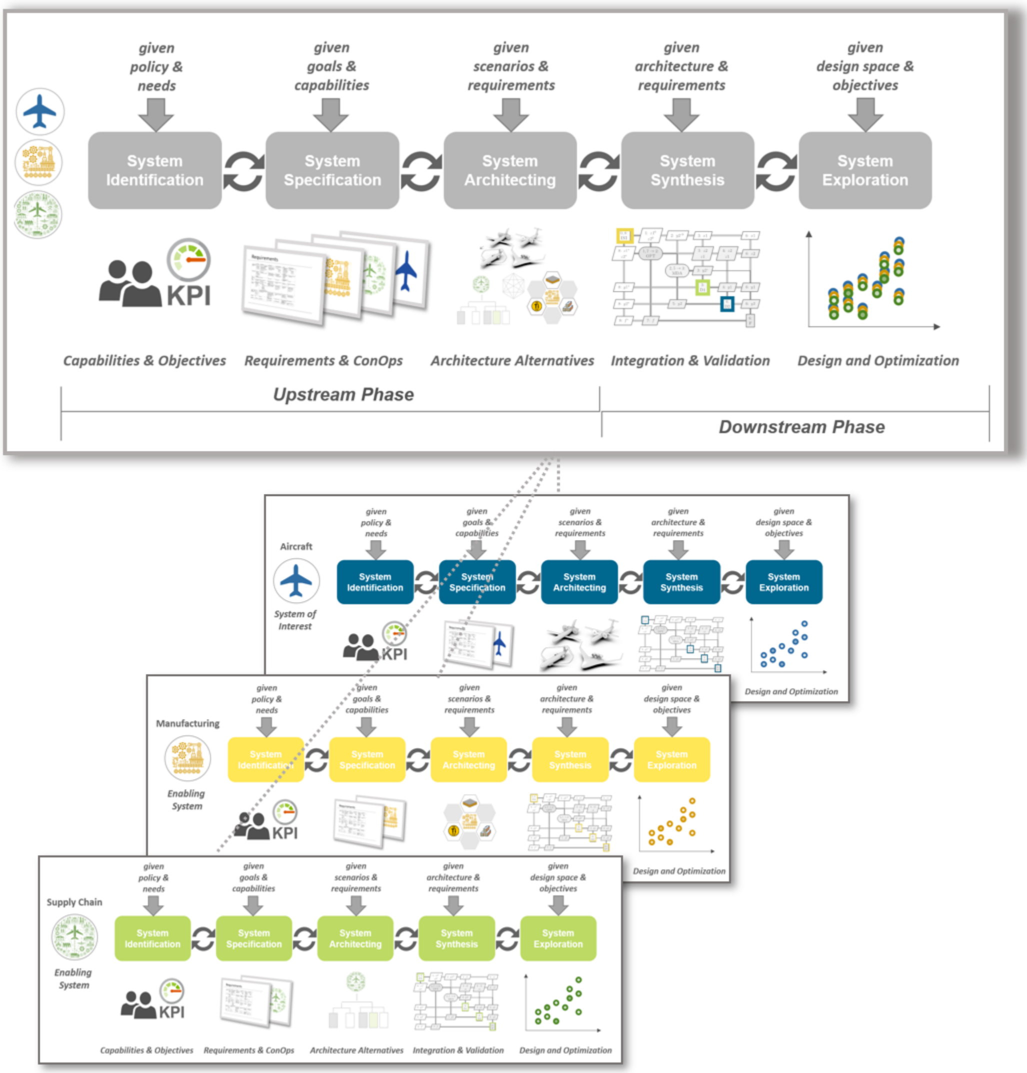


Figure 3.4: Systems for System (S4S) Framework as enhancement of the MBSE-MDO Framework to enable the concurrent conceptual design of supply chain, manufacturing and aircraft systems.

Section 3.4 demonstrates how the procedures outlined in Section 2.1.1 can be utilized in the upstream phase to model the stakeholders' needs and requirements for the three systems, as well as to formalize their logical architecture. The main modifications to the S4S Framework are instead related with the changes needed in the downstream phase processes. Decision-making elements have also been incorporated into the Framework and integrated with other process components. A simplified but representative ontology of the S4S Framework is presented in Figure 3.5.

This ontology shows the key elements of the Framework processes and their interconnections. These processes can be performed recursively. In the initial process of System Identification, stakeholders and their needs are identified for the three systems. Additionally, decision-makers, responsible for making the final decisions regarding the systems to be developed, are also identified among the stakeholders. The stakeholders' needs are then translated into requirements that follow specific rules and patterns (System Specification). These requirements relate to the aircraft, supply chain, and manufacturing systems.

By examining the requirements from an alternative perspective, illustrated in Figure 3.6, the main difference between the traditional and the proposed concurrent approaches can be identified. In the traditional approach, as mentioned, the design of manufacturing and the supply chain begins when the aircraft design is finalized. In this case, the design of the aircraft, that is the system of interest, is driven by technical requirements, such as the Top-Level Aircraft Requirements. Therefore, in the traditional approach, as shown in Figure 3.6, the technical requirements drive the design of the System of Interest. In the concurrent approach, instead, as explained the conceptual design of the three systems begins simultaneously. Therefore, production requirements (related to manufacturing and supply chain) are also collected at this stage. This implies that the system design, encompassing both the system of interest and enabling systems, is driven by a broader set of requirements, including those related to production, rather than only by technical specifications. From the functional requirements of these systems, boundary functions are derived, leading to the creation of the architectural design space for the three systems. Quantities of Interest (QoI) are assigned to the generated architectures, representing the evaluation parameters of these architectures (System Architecting). In the downstream phase, the expertise required to estimate these parameters and assess the architectures is identified, and all relevant data gathered.

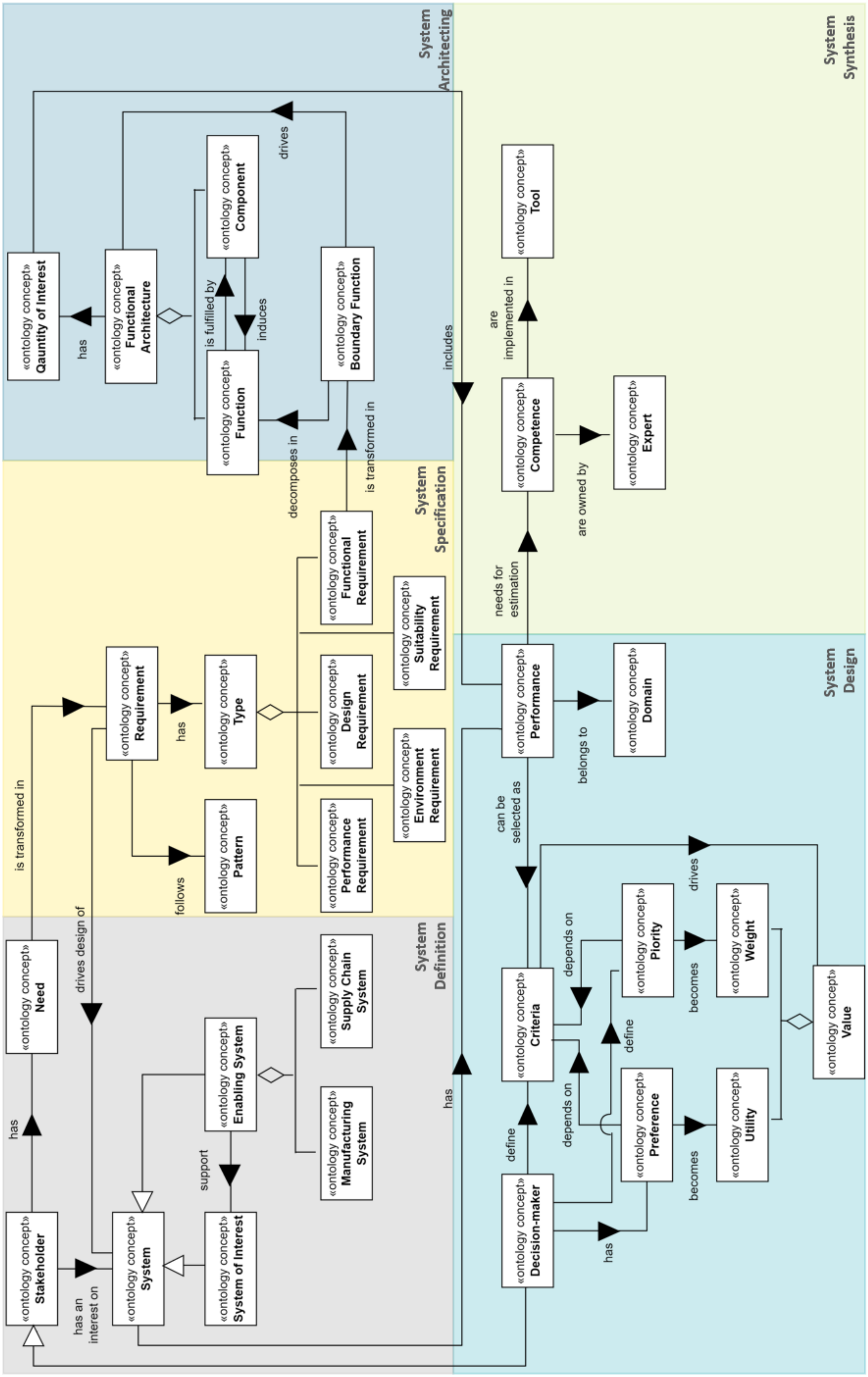


Figure 3.5: S4S Framework ontology illustrating the key elements that characterize the various processes and their relationships.

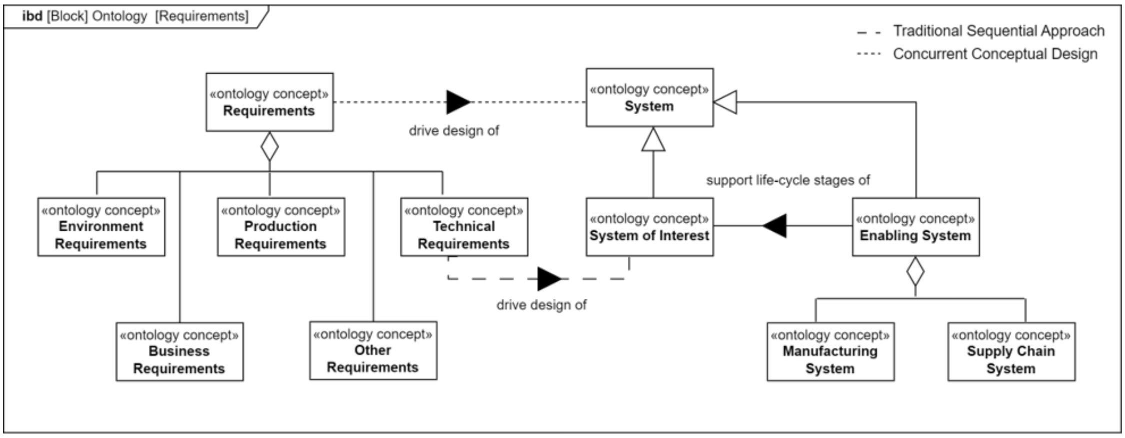


Figure 3.6: Requirements ontology focusing on the main difference between the traditional sequential and concurrent approaches - the design of the system of interest and enabling systems is driven not only by technical requirements but all the collected requirements, including production requirements.

At this stage, analyses such as optimization, decision-making, and uncertainty propagation can be performed. In particular, for decision-making analyses, it is essential the definition of the criteria that decision-makers consider critical for making decisions and defining the value of the system.

At the end of the downstream phase processes, the best alternative for the decision-makers, based on the defined criteria related to both production and design, and which meets the established requirements, is identified. To implement these downstream phase processes, this work proposes a new methodology for the concurrent evaluation and optimization of the architectures generated in the upstream phase. In this methodology, the terms domains are used instead of systems, as the focus shifts to the competencies and tools needed for evaluating these architectures.

Details of this methodology can be found in this chapter, specifically in Section 3.5.1. The introduction of optimization algorithms is addressed in Section 3.5.2. Furthermore, Section 3.5.3 explains how to facilitate the decision-making process for identifying the best solution based on design and production criteria. Additionally, a process for identifying a robust solution that incorporates uncertainty into the parameters defining the decision-making process is also proposed. These details are outlined in Section 3.5.3.

3.4 S4S Framework: Upstream Phase

The upstream phase includes, as shown in Figure 3.7, the processes of system identification, specification, and architecting. The objective of the upstream phase is to define the stakeholders, needs, and requirements of the manufacturing, supply chain and aircraft systems. In addition, the architectural design space is generated.

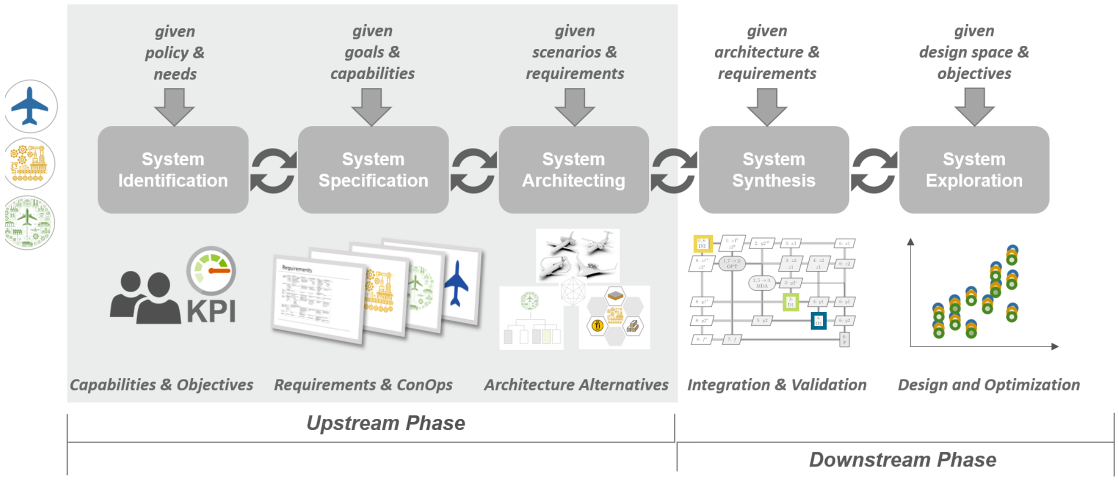


Figure 3.7: Systems for System Framework Upstream Processes.

The guidelines of the MBSE-MDO Framework regarding the definition of stakeholders, needs, and requirements (Section 2.1.1 and 2.1.2) can be easily extended and applied to the system of interest (aircraft) and the enabling systems (supply chain and manufacturing). In this context, stakeholders with an interest in production are also considered, along with their needs. The same applies to the requirements: the system to be defined in the requirement patterns can respectively be the aircraft, the supply chain, the manufacturing or their components as shown in Figure 3.8. Applications of stakeholders´needs and requirements models are shown in Chapter 5.

Regarding the formulation of the architectural design space, instead, the functions-components approach explained in Section 2.1.3 is used to model the logical architecture of the individual systems and extended to the logical architecture of the S4S. Indeed, given the boundary function of the system of interest, the boundary functions of the enabling systems can be seen as induced functions of the system of interest or another enabling system, as shown in Figure 3.9.

The aircraft, i.e. the system of interest, is selected to fulfill the boundary function 'to fly in all conditions'. This system, however, requires machines and enterprises able to perform the selected manufacturing and assembly processes. The boundary functions of the enabling systems are thus induced by the presence of

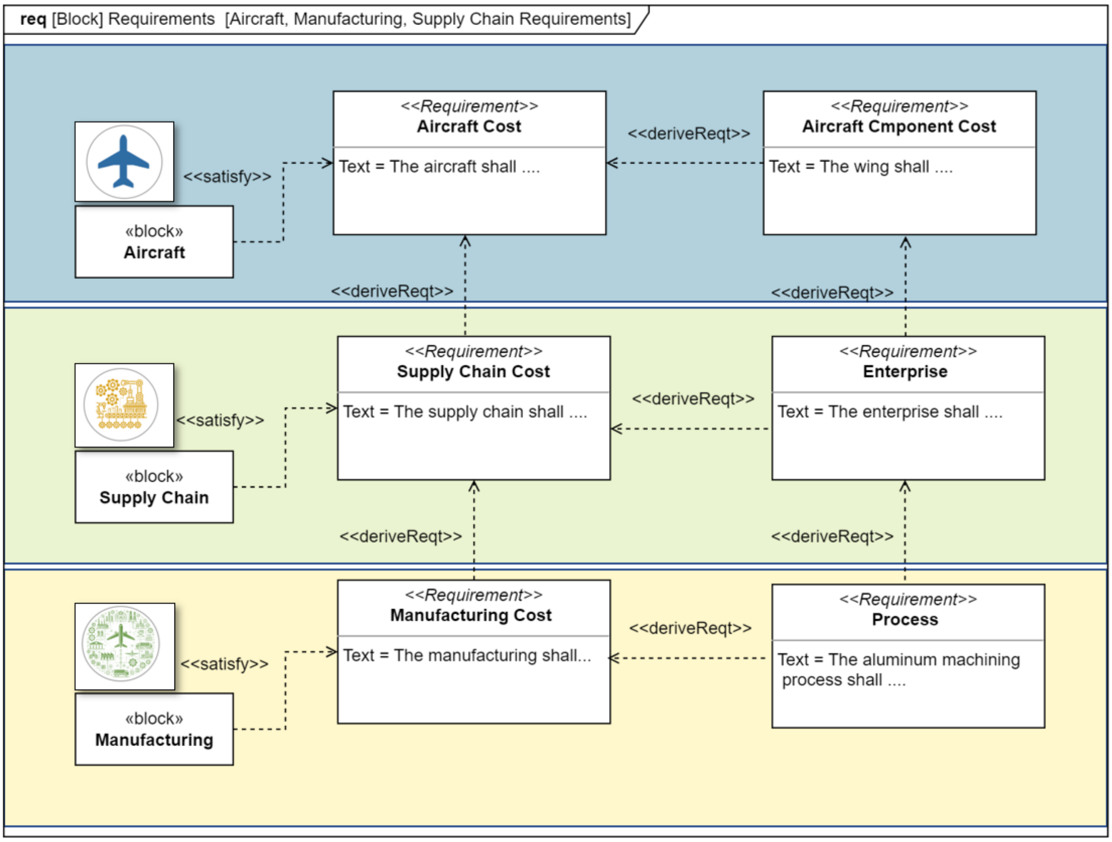


Figure 3.8: SysML Requirements Diagrams representing an example of System for Systems requirements.

the aircraft system. Additionally, the existence of the supply chain system implies the presence of manufacturing, and vice versa. This results in a logical architecture where the boundary function of each enabling system is induced by the other.

The relationships at the systems level are inherited by the components of each system, ensuring a connection between the logical architectures of these systems. In conclusion, the created architectural design space created includes alternatives generating considering both design (related to the aircraft) and production choices (related to the supply chain and manufacturing). The sequential order shown in Figure 3.9 is purely representative. It is worth noting that in the generation of the architectural design space, decisions are not made in a sequential order.

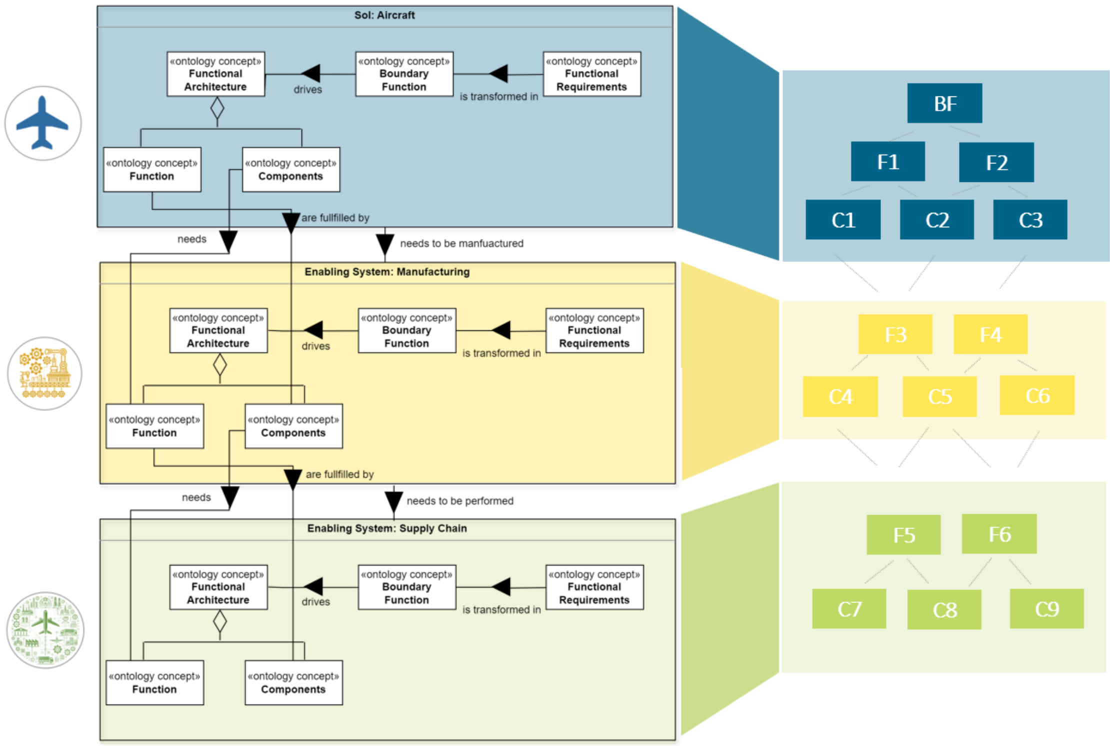


Figure 3.9: Systems for System logical architectures formulation. The boundary function of enabling systems as induced function of a system of interest or another enabling system.

3.5 S4S Framework: Downstream Phase

The downstream phase, as shown in Figure 3.10, focuses on the last two processes of the Framework, thus on activities related to the evaluation of the architectures generated in the upstream phase.

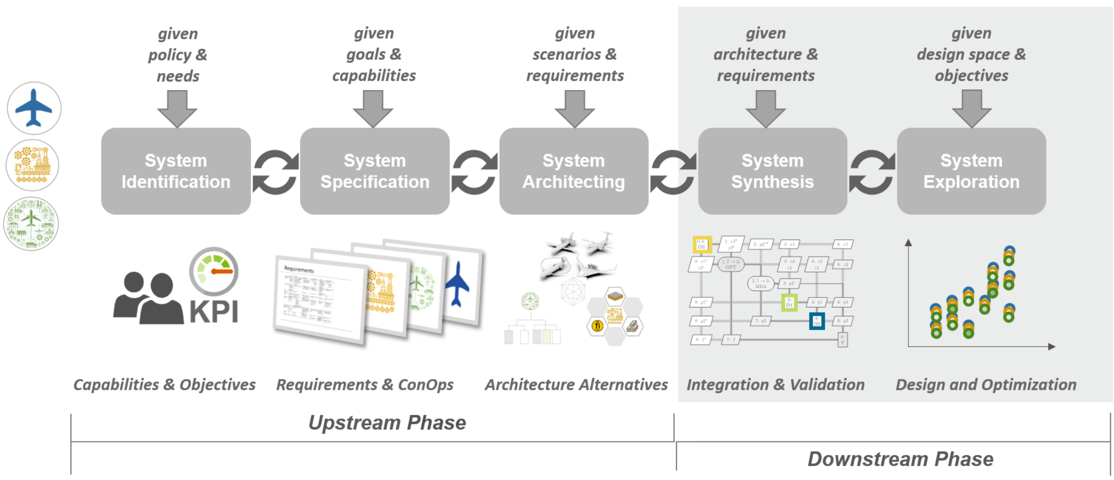


Figure 3.10: Systems for System Framework Downstream Processes.

Methodologies necessary to analyze and optimize the design of S4S architectures are therefore required. In Section 3.5.1, a value-based methodology is proposed for the concurrent design of the three systems. Additionally, in Section 3.5.2, optimization algorithms are introduced to identify the Pareto front and thus the optimal solutions when considering both design and production variables. Then, since the goal is to identify the best architecture within the design space by trading decision-makers' expectations, value-model theory is introduced to be applied in this context (Section 3.5.3). Finally, how to perform uncertainty propagation analysis on value is detailed in the last Section 3.5.3. The main outcome of this downstream phase is a value-driven design space populated by architectures generated by design and production choices. By including decision-makers´expectations with respect to the main criteria identified as key when taking decisions, the best solution according to decision-makers can be easily identified.

3.5.1 Value-driven Concurrent Design Evaluation Methodology

The proposed methodology allows for the evaluation of architectures that simultaneously consider both the design and production parameters of the aircraft. Therefore, through this methodology, it is possible to execute the design exploration process of the concept stage of manufacturing, supply chain and aircraft systems at the same time. The methodology is generically formalized, as it can be adapted to other sectors if appropriately modified. For this reason, the term 'product design' is used instead of 'aircraft design.' However, references to aircraft are provided since the case studies in this research are focused on the aeronautical sector. In addition, as already mentioned, since these methodologies belong to the downstream processes of the framework, the term 'domain' is used instead of 'system' to indicate that it refers to the competencies needed to evaluate the generated architectures.

The proposed value-driven concurrent approach coupling manufacturing, supply chain and product design is schematically represented by the flowchart in Figure 3.11.

For a given product, the value-driven concurrent approach starts with the manufacturing domain dealing with the choice of materials, manufacturing and assembly processes. Once materials and manufacturing processes are assigned to all the product components, the assembly processes are selected depending on the components to be joint. Constraints are implemented to guarantee the feasibility of the manufacturing choices. For instance, depending on the material (aluminium or composite), only a set of manufacturing processes can be selected (machining for aluminium but not infusion). The assignment of material and manufacturing process

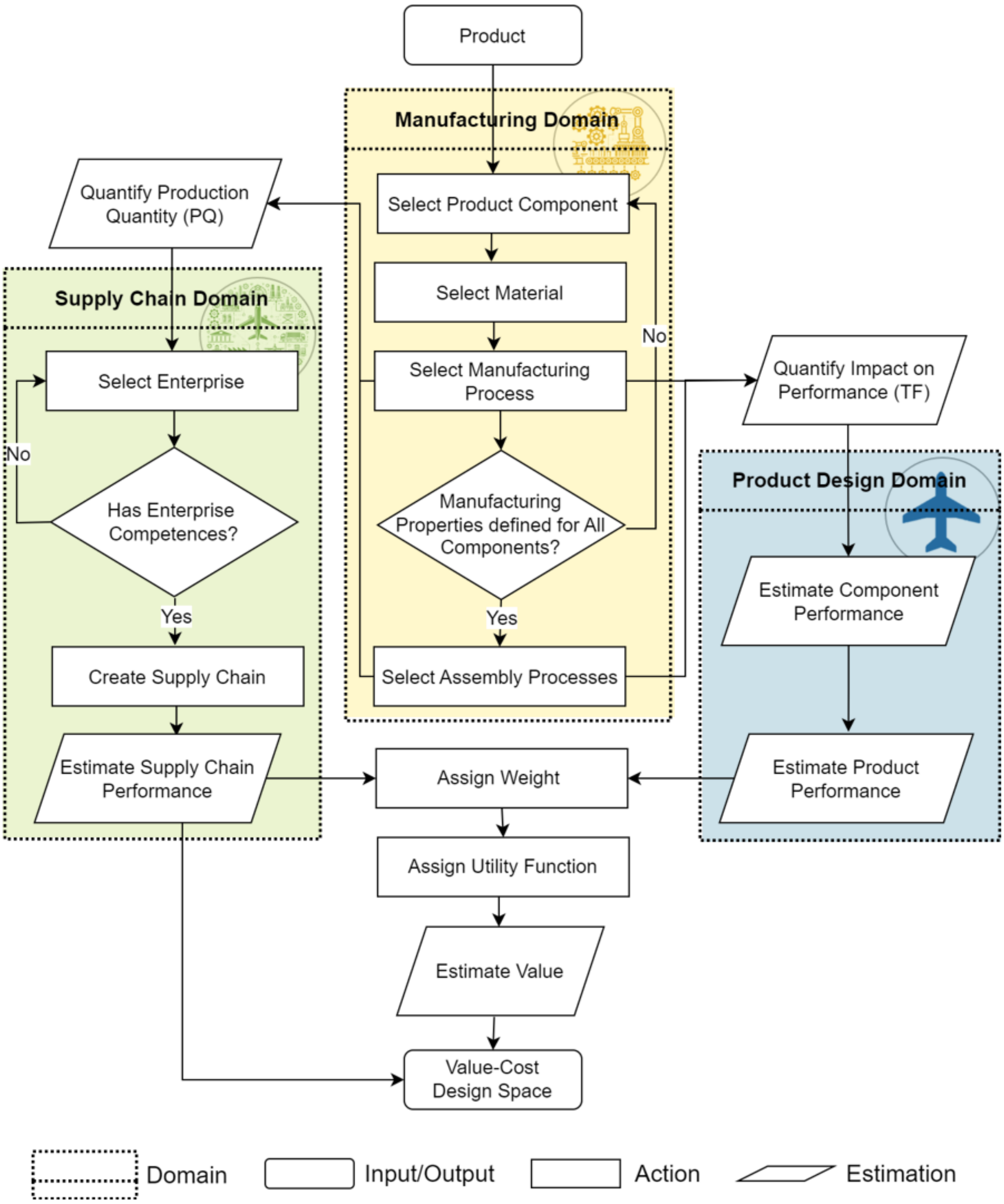


Figure 3.11: Flowchart of the value-driven approach proposed to enable the concurrent design of manufacturing, aircraft and supply chain domains.

per each product component influences the technical performance of the component itself, for instance its mass. Similarly, for the assembly processes. As shown in Figure 3.11, a technology factor (TF) is proposed as link between the manufacturing and product design domains. Defined as a dimensionless number ranging from 0 to 1, the TF quantifies the impact that the selected materials, manufacturing and assembly processes has on the technical performance of the product component.

In the product design domain, then, the impact of the manufacturing properties is propagated at the product level. Hence, the product performance is estimated based on the component performance, whose quantification is in turn based on the TF. If the TF is proposed as the link between the manufacturing and product design domains, the production quantity (PQ) is instead identified as the link between the manufacturing and supply chain domains (left side of the flowchart in Figure 3.11). The production quantity is the percentage of components to be produced with selected materials, manufacturing and assembly processes. In the supply chain domain, enterprises are selected and combined in supply chains. The selection of enterprises strongly depends on the competences and thus on the skills they have in performing the selected materials and processes. The production quantity is assigned to enterprises also considering their capacity, thus the maximum amount of quantity they can perform. Supply chains can include a single enterprise, multiple sites of the same enterprise or multiple different enterprises. Depending on the selected enterprises different production performance, meaning production cost, time, quality and risk of each supply chain are generated for each supply chain. The approach ends with the use of the MAUT value model to enable the concurrent coupling of these domains. The product and production performance are the criteria defined important for stakeholder in 'value' the system design. From the production perspective, the production cost, time, quality and risk have been selected as important criteria because of the key role they play in the supply chain management [85]. From the product perspective, the choice of important criteria for stakeholder change depending on the product under design.

Except for cost, all the other criteria are aggregated in the value through weights and utility functions. The output of the methodology is the value-cost solutions tradespace. Decisions related to the product design and, at the same, to the production aspects (manufacturing and supply chain) can be made by exploring this value-cost design space. In this way, the assessment of manufacturing and supply chain performance is part of the results of the solutions tradespace exploration rather than further analysis performed after the design phase.

The models characterizing the supply chain, manufacturing, product design domains and value model are shown in Figure 3.12 and described in details in the next sections.

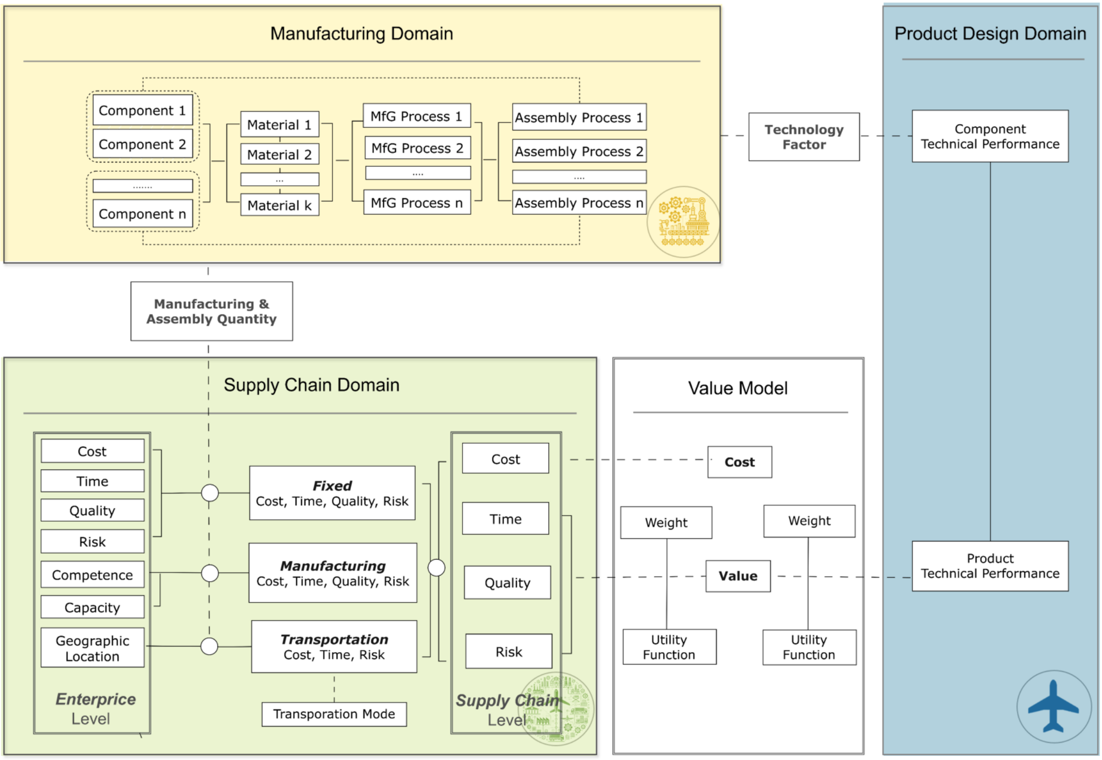


Figure 3.12: Models characterizing the manufacturing, supply chain and product design domains.

Domains Models

The equations and models characterizing the product design domain strictly depend on the product under design. The input of this domain, as shown in Figure 3.12, is a technology factor that quantifies the impact that materials, manufacturing and assembly processes has on the technical performance of the product component. The assignment of this technology factor can be based on the experience of experts when other models for the estimation are not available. Based on this TF, the technical performance of the component and consequently of the product is estimated. In case the product under design is the aircraft, many sources are available in literature to estimate the aircraft performance depending on changes related to its components. The TF of the product component is one of the main output of the manufacturing domain and input of the aircraft domain. The other output of the manufacturing domain is the number of components to manufacture and assemble. As shown Figure 3.12, this is defined as production quantity. The production quantity is the input of the supply chain domain.

The formulation of models that support the domains of manufacturing and supply chain is more complex. In this case, collaboration with experts has been necessary, and the challenge to transform their tacit knowledge into mathematical models has been faced.

The main output of the supply chain domain is the estimation of the supply chain performance, and thus of the production cost, time, quality and risk. Indicating with SC the production cost, time, quality and risk at the supply chain level, the estimation of these production performance is proposed as sum of three contributions (fixed, manufacturing, transportation) as reported in the following equations:

$$\begin{aligned} Cost_{SC} &= Cost_{fixed} + Cost_{manufacturing} + Cost_{transportation} \\ Time_{SC} &= Time_{fixed} + Time_{manufacturing} + Time_{transportation} \\ Risk_{SC} &= Risk_{fixed} + Risk_{manufacturing} + Risk_{transportation} \\ Quality_{SC} &= Quality_{fixed} + Quality_{manufacturing} \end{aligned} \tag{3.1}$$

The first addend (fixed) of these formulas depends on the fixed production time, cost, quality and risk of each enterprise as well as on the production quantity that each enterprise has to perform. Considering a supply chain made of n enterprises, the fixed production performance at the supply chain level is evaluated as:

$$\begin{aligned} Cost_{fixed} &= \prod_{j=1}^{n} Cost_{e_j} x q_{i,e_j} \\ Time_{fixed} &= \prod_{j=1}^{n} Time_{e_j} x q_{i,e_j} \\ Risk_{fixed} &= \prod_{j=1}^{n} Risk_{e_j} x q_{i,e_j} \\ Quality_{fixed} &= \prod_{j=1}^{n} Quality_{e_j} x q_{i,e_j} \end{aligned} \tag{3.2}$$

in which:

- $Cost_{e_j}$, $Time_{e_j}$, $Risk_{e_j}$, $Quality_{e_j}$ indicates respectively the fixed production cost, time, risk and quality of each enterprise depending on aspects strictly related to the enterprises (e.g. energy fees related to the geographic location). These usually represent inputs of the methodology;
- q_{i,e_j} is the production quantity of the component i manufactured/assembled by the enterprise e_j.

The second addend (manufacturing), instead, depends on the enterprise's competences, thus on the skills that each enterprise has in performing a selected manufacturing and assembly process. Competences are expressed as numbers ranging from 0 to 10. For simplicity, a linear approach can be adopted. Thus, higher is the enterprise competence, higher is the quality, while lower are the production cost, time and risk. However, also non-linear functions can be leveraged if available from experience. In this way, the manufacturing cost, time, quality and risk are estimated for the individual enterprise. Then, the manufacturing performance at the supply chain level are simply calculated as their average. The following formulas are used considering n enterprises:

$$\begin{aligned} Cost_{MfG} &= \textstyle\sum_{j=0}^{n} Cost_{MfG_j}/n \\ Time_{MfG} &= \textstyle\sum_{j=0}^{n} Time_{MfG_j}/n \\ Risk_{MfG} &= \textstyle\sum_{j=0}^{n} Risk_{MfG_j}/n \\ Quality_{MfG} &= \textstyle\sum_{j=0}^{n} Quality_{MfG_j}/n \end{aligned} \tag{3.3}$$

in which:

- $Cost_{MfG_j}$; $Time_{MfG_j}$; $Risk_{MfG_j}$; $Quality_{MfG_j}$ respectively indicate the manufacturing cost, time, risk and quality of each enterprise - e.g. linearly - depending on the its own competence (higher is the competence, higher is quality, lower are cost, risk and time).

Finally, the third addend (transportation) considers the cost, time, and risk necessary to transport goods from the manufacturing sites, in which manufacturing processes are performed, to the assembly sites, in which components are aggregated. In the model, four different means of transportation are considered: road (r), railway (rl), air (a) and water (w). Since different means of transportation can be used for the same route, in the supply chain domain the here-after formulas are integrated:

$$\begin{aligned} Cost_{tr} &= \textstyle\sum_g (Cost(\sum_{j,i} d_{e_j,e_i} x w_g)) \quad g = r, rl, a, w; \quad i = 1, ..., n; \quad j = 1, ..., k \\ Time_{tr} &= \textstyle\sum_g (Time(\sum_{j,i} d_{e_j,e_i} x w_g)) \quad g = r, rl, a, w; \quad i = 1, ..., n; \quad j = 1, ..., k \\ Risk_{tr} &= \textstyle\sum_g (Risk(\sum_{j,i} d_{e_j,e_i} x w_g)) \quad g = r, rl, a, w; \quad i = 1, ..., n; \quad j = 1, ..., k \end{aligned} \tag{3.4}$$

in which:

- d_{e_j,e_i} is the distance between the production site i and the assembly site j, estimated by using the Haversine formula [86];
- g represents the means of transportation adopted: road (r), railway (rl), water (w) and air (a);
- w_g is the percentage of path carried out by the selected transportation mode;
- $Cost(\sum_{j,i} d_{e_j,e_i})$, $Time(\sum_{j,i} d_{e_j,e_i})$, $Risk(\sum_{j,i} d_{e_j,e_i})$ are respectively the cost, time and risk to transport goods from production site i to the assembly site j using the mean of transportation g, estimated by using available linearized literature models [87, 88] or/and not-linear functions provided by experts based on the experience.

The models presented in this section enable the estimation of supply chain performance, which can be then aggregated in the value with the product performance, as explained in the next Section.

Value Model

The product and production performance are aggregated in a single dimensionless measure, i.e. the value, by applying the Multi Attribute Utility (MAU) theory [89]:

$$Value = \sum_{i=1}^{N} \lambda_i U(X_i) \tag{3.5}$$

in which:

- N is the number of attributes (criteria);
- $U(X_i)$ is the single attribute utility function;
- λ_i is the weight associate with attributes Xi:

$$0 < \lambda_i < 1 \quad : \quad \sum_{i=1}^{N} \lambda_i = 1 \tag{3.6}$$

Traditionally, this theory is used to simplify the multi-criteria decision-making process. The weights represent the relative importance, while the utility functions represent a way to translate qualitative preferences of decision-makers in quantitative functions. How to leverage the MAU theory to perform decision-making analysis is well described in Section 3.5.3. In the proposed methodology, instead, the value is used as mean to aggregate multiple criteria having different units of measures in a single dimensionless one. This use of MAU requires the hypothesis of same weights and linear functions for all the aggregated criteria. In fact, same wights assure that criteria are not prioritized. Instead, linear utility functions simply translate the unit of measure of the specific criteria in a dimensionless one, that is the utility, ranging from 0 to 1. An example of assumptions needed to use the value model theory in the methodology for the manufacturing, supply chain and product design are shown in Figure 3.13.

This figure also highlights example of utility functions. To the minimum (LB) and maximum (UB) contents (numbers) of the attributes are assigned utility 1 or 0. In this case, contents is used to express the numerical value of the attribute to avoid misunderstanding with the value, aggregation of criteria. The increasing or decreasing behaviour of the functions depends on the attributes trend. For attributes such as time, a decreasing trend is applied, meaning that the higher the time, the lower the utility associated with the solution. In contrast, for quality attribute. In this case, to higher quality correspond to higher utility. Consequently, a linear function with an increasing trend is used.

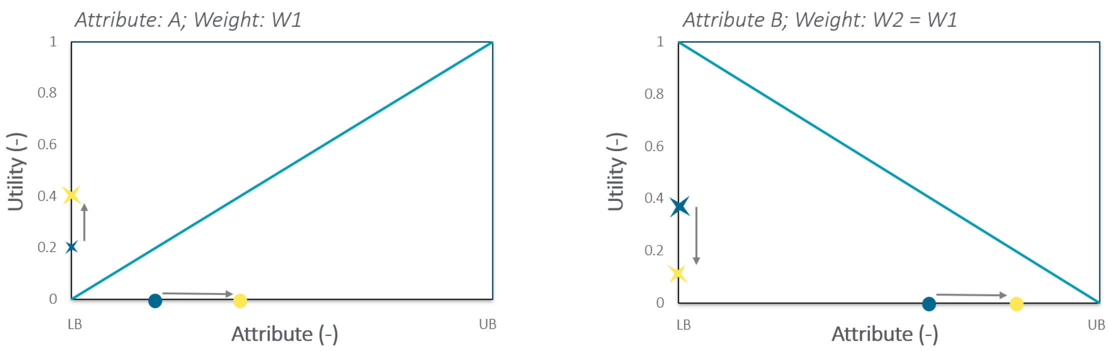


Figure 3.13: Same weights and linear utility functions as main assumption of the value-driven concurrent design methodology.

Concluding, once defined for all the criteria the same weights and the linear utility functions consistent with their trends, the value-driven tradespace is generated. In this tradespace, solutions can be easily compared through the value while considering multiple criteria. The higher the value, the better the solution in terms of the parameters aggregated within it. Generally, cost are then used as other independent variable to perform trade-off studies between value and cost. It is worth noting that this generated value-cost tradespace is **not** influenced by decision-makers. It is instead an analytical representation of solutions.

3.5.2 Value-driven Concurrent Optimization

Optimization algorithms are introduced in the methodology discussed in the previous section with the objective to optimize architectures while considering at the same time design and production variables. Several mMDO problems of increasing complexity can be so formalized and executed. These MDO problems are collected in three MDO Cases depending on the optimized domains, as shown in Figure 3.14. In details:

- The MDO Case I includes problems addressing the concurrent optimization of the supply chain and manufacturing domains;
- the MDO Case II the concurrent optimization of manufacturing and product design domains;
- the MDO Case III the concurrent optimization of manufacturing, product design and supply chain domains.

The aim and consequently the set-up of the MDO problems in terms of objective functions (quantities to maximize/minimize), design variables (quantities to vary) and constraints (quantities to limit) strictly depends on the optimized domains, thus on the MDO Case. For instance, the production performance are the objective

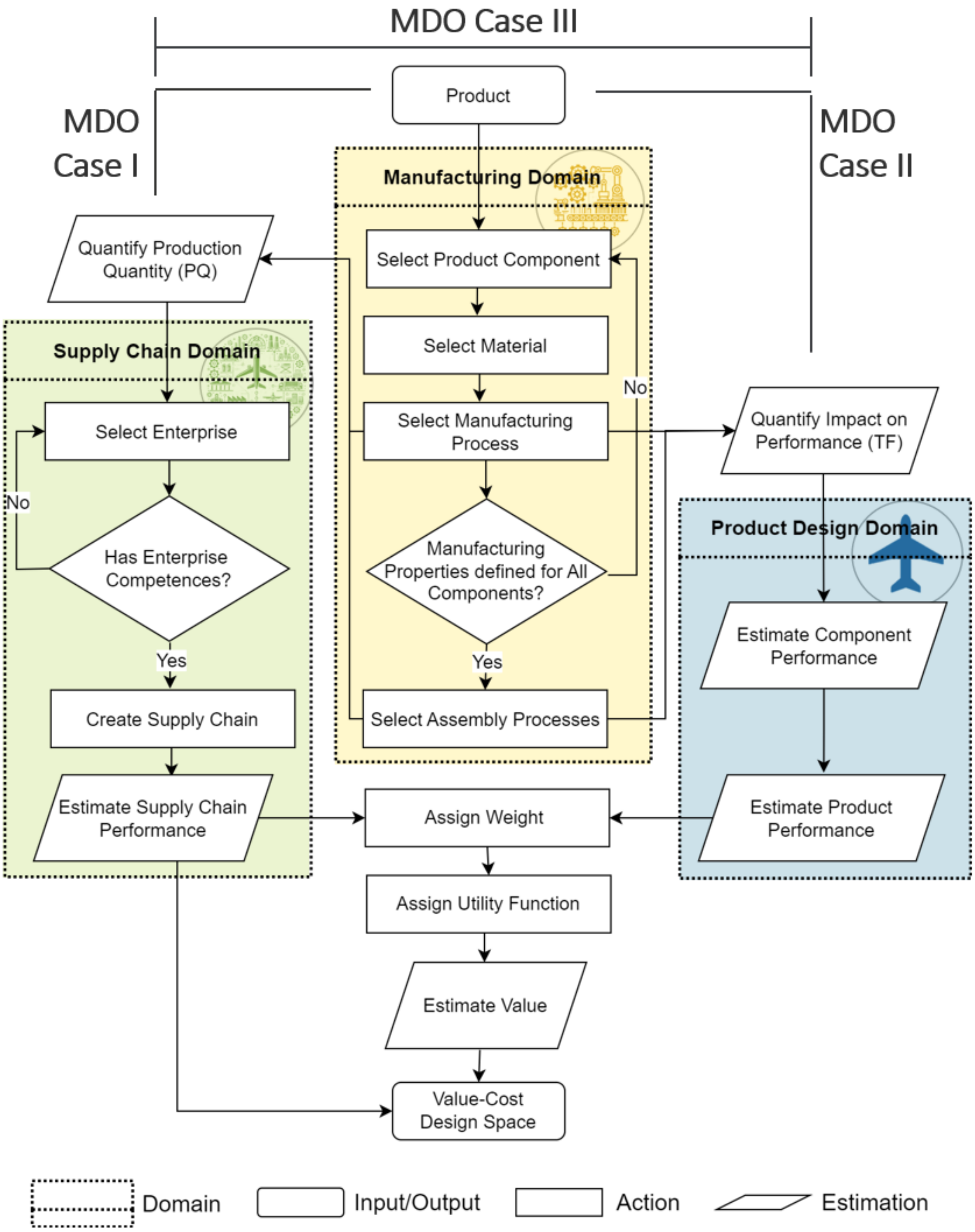


Figure 3.14: Value-driven methodology for the concurrent optimization of manufacturing and supply chain (MDO Case I); manufacturing and design (MDO Case II); manufacturing, supply chain and product design (MDO Case III).

functions of the MDO Case I; the product performance of the MDO Case II; the product and production performance of the MDO Case III. Depending on the number of selected product and production performance, mono-objective or multi-objective MDO problems characterize each MDO Case, leading to a single optimized solution or to a Pareto front, i.e. a set of non dominated solutions chosen as optimal for the multi-objective problems. The Pareto front visualization of a multi-objective MDO problems, however, is quite challenging, especially if the number of objective functions involved is high. In fact, its investigation requires the analysis of several plots depending on the number of the objectives involved in the optimization. The value model theory is adopted to simplify this investigation: the multi-objective Pareto front obtained from the MDO problems execution is converted in a 2D value-driven Pareto front. This requires the hypothesis of same weights and linear utility functions for all the attributes in the value model theory, as discussed in Section 3.5.1. These assumptions ensure that no order of priority is applied to attributes (same weights) and that no influence of decision-makers is taken into account (linear utility functions). In addition, they guarantee that the value-driven Pareto front is part of the multi-objective Pareto front. In this way, the trade-off analysis can be easily executed in the value-driven Pareto front by exploring one single 2D plot (Appendix A).

In the next sections, details on the design variables, constraints and objective functions characterizing each MDO Case are provided. However, a general overview of all the contrarians characterizing these MDO problems are already provided in Figure 3.15. These constraints represent the incompatibilities among materials and processes and the competences of the enterprises that might not have the right skills in performing the selected processes. In fact, not all the combinations of materials and processes selected for each component are feasible with the materials and processes characterizing other components (red lines). In addition, the selection of enterprises depends on their competences in performing the chosen materials and processes for the different components (0 as competence represents the constraint). These competences are expressed by numbers ranging from 0 to 9. When the competence is 0 means that the enterprise has no skills in performing the selected materials and processes.

Finally, the mathematical formulation of the problems related to these MDO Cases and details on the optimizer used are instead provided in the Appendix B.

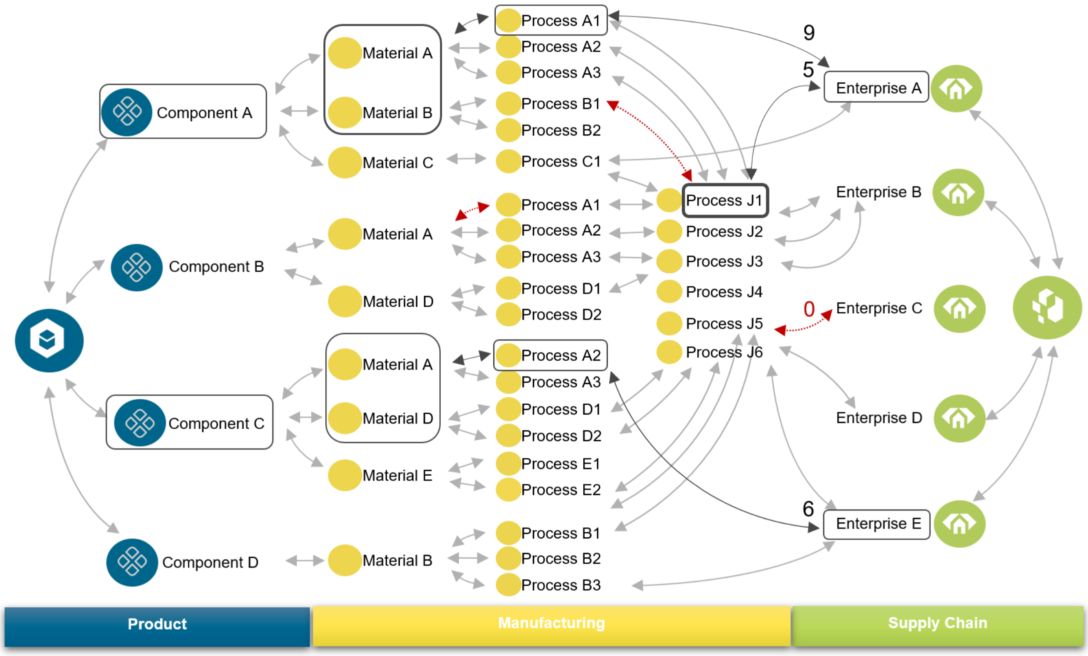


Figure 3.15: Example of design, manufacturing and supply chain constraints: feasible (dark gray line) and incompatible (red line) choices of materials and processes among components; competences (gray numbers) or lack of skills (red null) in executing processes selected for each component.

MDO Problems Case I: Concurrent Manufacturing and Supply Chain Domains Optimization

The MDO Case I aims at optimizing the manufacturing and supply chain domains (MDO Case I in Figure 3.14). In this case, the aim is to identify the optimum supply chain producing a specific product configuration, whose materials and processes are fixed. In this MDO Case, the technical performance of the product under design are not changing and, for this reason, not considered. Instead, the enterprises that can be selected in the supply chain can vary. Depending on the competences they have in performing the selected processes and quantity to be manufactured and assembled, the production performance change. The Quantities of interest (QoIs) for this MDO Case are summarized in Table 3.2.

The production performance are the objective functions of this MDO Case. Depending on the selected performance (can be one or more among production cost, time, quality, risk) mono-objective or multi-objectives MDO problems can be executed in this MDO Case. The manufacturing and assembly site are instead the categorical variables used as flag. The value is 1 or 0, depending on whether or not the company is selected as a manufacturing or assembly site for a specific component. If the enterprise is selected as manufacturing site, then a manufacturing

Table 3.2: Concurrent manufacturing and supply chain optimization formulation: role of quantities of interest in the optimization problem.

QoI	Role
Production Performance	Objective Function
Manufacturing Site	Design Variable
Manufacturing Quantity	Design Variable
Assembly Site	Design Variable
Assembly Quantity	Design Variable
Enterprise Competences	Constraint

quantity is assigned to this enterprise. The manufacturing quantity, expressed as continuous variable, represents the percentage of components that the enterprise is responsible to produce. The manufacturing quantity is therefore assigned for each of the components under manufacturing. Similarly, the assembly quantity is assigned to the enterprise if selected as assembly site. In this case, the assembly quantity represents the type of assembly process to perform which in turn depends on the joint components. However, only the enterprises having the competences in performing the selected manufacturing and assembly processes can be selected. Competences of enterprise represent the constraint of this MDO Case. A summary of the design variables characterizing this MDO Case are reported in Table 3.3, an example of supply chain constraint in Figure 3.15.

Table 3.3: Concurrent manufacturing and supply chain optimization formulation: design variables.

Design Variables	Type	Value	Meaning
Manufacturing Site	Categorical - 2 levels	0 1	Not Selected Selected
Manufacturing Quantity	Continuous	]0,100]	Percentage of components
Assembly Site	Categorical - 2 levels	0 1	Not Selected Selected
Assembly Quantity	Categorical - 3 levels	1 2 3	Assembly type 1 Assembly type 2 Assembly type 3

Ideally, MDO problems having all the design variables reported in Table 3.3, can be executed. However, in the application case related to this MDO Case reported in Section 5.1.6, some of them are assumed fixed to reduce the complexity of the optimization problem.

MDO Problems Case II: Concurrent Manufacturing and Product Design Domains Optimization

The second MDO Case aims at optimizing the manufacturing and product design domains (MDO Case II in Figure 3.14). The ambition is to identify the optimum product configuration while changing the materials, manufacturing and assembly processes. The manufacturing choices in fact influence the technical performance of the product components and consequently of the product iself. The objective is therefore to identify which combination of materials and processes, characterizing the product components, minimizes or maximizes the product technical performance. In this case, the incompatibilities among the materials and processes selected for each component must be considered.

The supply chain performance are instead fixed in this MDO Case since it is assumed that the same supply chain, made of enterprises having the right competences, is performing the production and assembly of the entire product. The QoIs playing a key role in this MDO Case are summarized in Table 3.4.

Table 3.4: Concurrent Manufacturing and Aircraft Design Optimization Formulation: Role of Quantities of Interest in the Optimization Problem.

QoI	Role
Technical Performance	Objective Function
Materials & Processes	Design Variable
Materials & Processes Incompatibility	Constraint

Depending on the number of technical performance selected, a mono-objective or multi-objectives optimization problem can be performed. The choice of materials and processes combination is the design variable. As reported in Table 3.5, this is a categorical variable and therefore used as a flag: it is 1 when the specific combination of materials and processes for the specific component is selected, 0 otherwise.

Table 3.5: Concurrent manufacturing and aircraft design optimization formulation: design variables.

Design Variables	Type	Value	Meaning
Materials & Processes	Categorical - 2 levels	0 1	Selected Not selected

Finally, the incompatibilities among materials and processes of different components are the constraints of this MDO Case. An example of incompatibilities is shown in Figure 3.15 by the red dashed line. The results of an MDO problem of this MDO Case is reported in Section 5.1.6.

MDO Problems Case III: Concurrent Manufacturing, Supply Chain and Product Design Domains Optimization

The third MDO Case, finally, aims at optimizing the manufacturing, supply chain and product design domains at the same time (MDO Case III in Figure 3.14). The challenge is to identify the solution optimizing, at the same time, the aircraft and production performance while changing the manufacturing processes and the enterprises performing such processes. In fact, the product performance is impacted by the choice of materials and processes selected for each of the product components. At the same, the production performance changes depending on the enterprise competences selected to perform the defined manufacturing or assembly processes. This MDO Case is therefore a combination of the previous two. As consequence, all the already mentioned quantities of interest, play here a key role in this MDO Case as reported in Table 3.6.

Table 3.6: Concurrent manufacturing, supply chain and product design optimization formulation: role of quantities of interest in the Optimization problem.

QoI	Role
Product Performance	Objective Function
Production Performance	Objective Function
Manufacturing Site	Design Variable
Manufacturing Quantity	Design Variable
Assembly Site	Design Variable
Assembly Quantity	Design Variable
Materials & Processes	Design Variable
Enterprise Competences	Constraint
Materials & Processes Incompatibility	Constraint

A multi-objective MDO problem characterizes this MDO Case involving at least one product and production performance. The design variables are the production and assembly quantity and site as well as the choice of materials and processes characterizing each product component. However, also in the application case of this MDO Case reported in Section 3.5.3, some of them are assumed fixed to reduce the complexity of the MDO problem. Ideally, all of them can be considered while executing MDO problems. The constraints are both the enterprise competences and the materials and processes incompatibilities, as shown in the example of Figure 3.15.

3.5.3 Value-driven Decision-making and Uncertainty Propagation

The last part of the methodology introduced in Section 3.5.1 leverages the value model theory to aggregate production and product performance in a single dimensionless measure, that is the value, with the assumptions of same weights and linear utility functions for all the criteria. With the same assumptions, the value theory is also applied in Section 3.5.2 to simplify the visualization of a multi-objectives Pareto front.

In this section, it is explained how to leverage value model theory to include decision-makers expectations in the design space and simplify the tradespace exploration for the identification of the best solution when considering multiple criteria. The equations are the same reported in Section 3.5.1, while the way they are applied is different. In addition, how to propagate uncertainty to value through weights and utility functions is explained. This is useful to increase decision-makers´awareness when taking decisions since the behaviour of the value solutions is analysed.

Decision-making

To streamline the multi-criteria decision-making process and create a value-driven tradespace, four key steps are needed. The first step relates with the definition of the criteria (also called attributes). An attribute is a decision-maker perceived metric that measures how well a decision maker-defined objective is met and define decision-makers´qualitative preferences. Decision-makers can decide what are the most important criteria when taking decisions and express the qualitative preference with respect to this criteria. Attributes might be defined, for instance, among the production and design performance. To these attributes, a weight is assigned. Through weights, decision-makers defines the relative importance of each attribute giving them the opportunity to prioritize one criteria with respect to another one. The sum of the weights bust be one (see Section 3.6). The third step is the elicitation of the utility functions. These functions are used to quantify the qualitative decision-makers´preferences. Finally, once the weights and utility functions are defined for all the attributes, the value is estimated following the equation 3.5.

The most challenging part in the value estimation regards the elicitation of the Single Attributes Utility Functions. Decision-makers have to quantify their preferences by considering each attribute per time, independently from each other. This simplifies the decision-making process: although there are multiple criteria that the decision-makers consider important, the analysis of preference quantification for these criteria is done individually. This quantification passes through the assignment of utility to the attributes contents. Therefore, the SAU functions transform the numerical contents of individual attributes into utilities. Utility is a dimensionless parameter ranging from 0 to 1. Higher utility means desirable solutions for decision-makers. Therefore, higher utility lead to higher decision-makers´satisfactions with respect to the specific numerical content of the attribute.

To define utility functions, it is important to fix the least acceptable (LA) and the max desirable (MD) numerical contents of the attribute and assign to them respectively utility 0 and 1. Solutions with contents outside these boundaries are excluded from the tradespace, unless an alternative arrangement has been made with the decision-makers. The behavior of the function (increasing or decreasing) depends on the specific attribute and the qualitative preference of the decision-maker regarding it. For instance, a decreasing trend defines the utility function for production time, as longer production times result in lower decision-maker satisfaction and, consequently, lower utility assigned to the solutions. The shape of the functions represents the attitude of the decision-makers in taking decisions and it is completely defined by decision-makers. For example, considering the utility functions shown in Figure3.16, the blue line refers to a decision-makers which is more conservative if compared with the decision-maker of the green line. In fact, for the same solution (blue point), a higher utility (blue star) is assigned to it.In addition, the difference in the utilities for two solutions (yellow and blue) is higher than the green line case. Therefore, the elicitation of the utility functions strictly on how decision-makers make decisions regarding each attribute, and it may vary between different decision-makers. To define utility functions, several methods are available. However, interactive tools in which decision-makers can directly design utility functions support decision-makers in well representing their qualitative preferences [75].

Once defined the utility functions and the weights to all the attributes, the value-driven tradespace is generated. The solution with highest value on the tradespace represents the **best** solution, meaning the solution that most matches decision-makers´expectations with respect to all the aggregated attributes. This value-driven tradepsace therefore includes decision-makers´preferences. Then, several explorations can be made changing, for instance, the boundaries of the attribute contents, the weights and/or the utility functions.

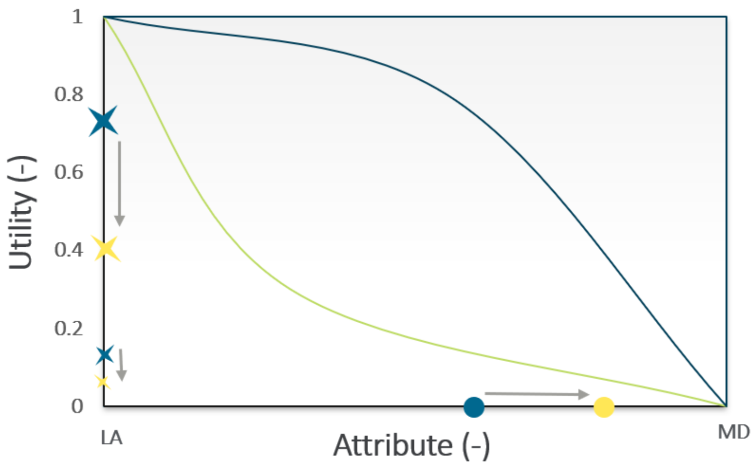


Figure 3.16: Example of decreasing utility functions trend used to quantify decision-makers qualitative preferences.

Uncertainty Propagation

To analyse the behavior of the alternatives populating the value-driven tradespace, uncertainty is propagated to value through weights and utility functions. Therefore, once obtained a value-driven Reference Pareto front, generated for instance by assuming same weights and linear utility functions for all the attributes, a uniform distribution is used to propagate uncertainty on the value through the weights and/or utility functions. It means that hundreds of weights combinations and utility functions trends are analyzed to understand how the value of the solutions change. The objective is to identify the robust and flexible solutions. The robust solution is the alternative minimizing the value oscillation. To identify the robust solution, the maximum and minimum value of each solution is estimated when changing the weights and/or utility functions. The alternative with the lowest difference between is the robust solution. The flexible solution, instead, is proposed as the alternative having the highest probability to be on the Pareto front when varying weights and/or utility functions. To identify the flexible solution, the Pareto front is estimated anytime weights and/or utility functions change. Then, a check is made to verify if the solutions of the Reference Pareto front are on the new estimated one. The number of positive cases (solution is on the Pareto front) with respect to the total cases provides the probability that this is solution is optimal. The flexible solution is then the alternative having the highest probability to stay on the Pareto front.

In this research activity, the robust and flexible solutions are identified in three case studies, summarized in Figure 3.17 and described here-after. Instead, an application case of these case studies is described in Section 5.1.8

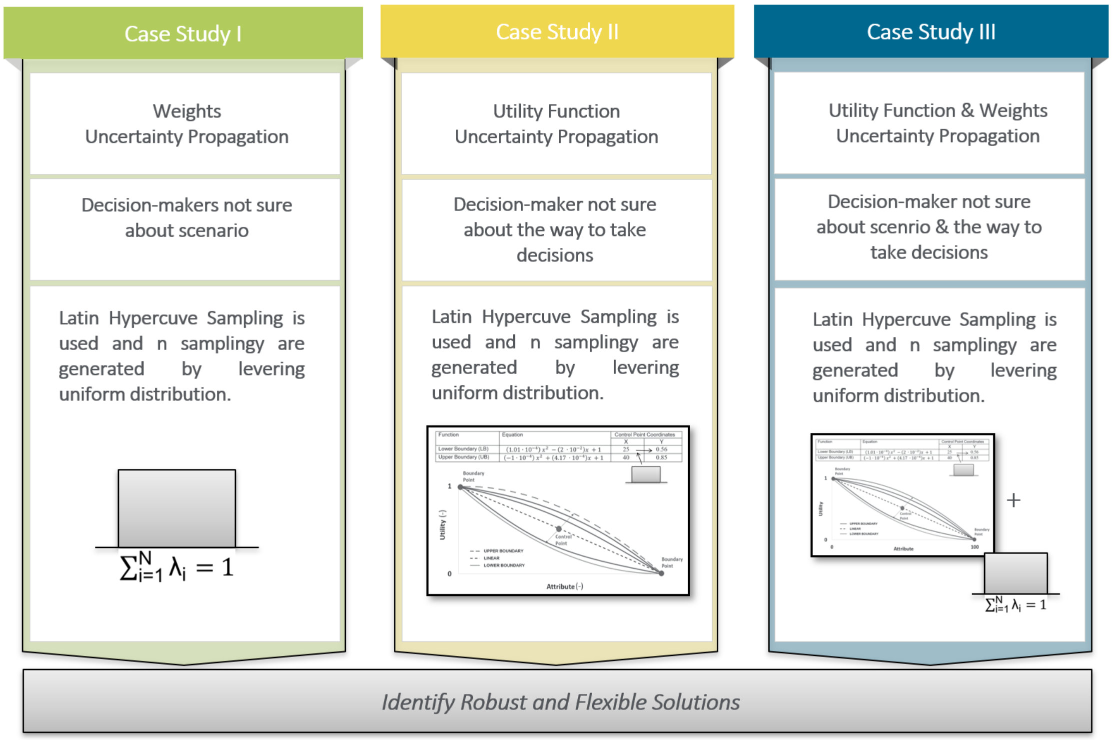


Figure 3.17: Uncertainty Propagation Case Studies.

Case Study I - Weights Uncertainty Propagation

Weights are used to prioritize attributes. Adding uncertainty in the weights is useful when decision-makers is not sure about the scenario to analyse. To propagate uncertainty through the weights, the Latin Hypercube Sampling (LHS) method is used and the samplings are generated by levering a uniform distribution. The choice of such distribution for the samplings allows decision-makers to analyze all the possible combinations that can be generated. Each weight changes from 0 to 1, but a constraint is set to assure that their sum is 1.

Case Study II - Utility Functions Uncertainty Propagation

Utility functions are used in the value model to quantify the qualitative decision-makers 'expectations with respect to each attribute. Adding uncertainty in the utility functions is useful when decision-makers is not sure about the way they would take decisions. Introducing uncertainty in the utility functions is more challenging than the previous case study. In fact, the trend of each function (increasing/decreasing) must be preserved while changing the slope of the function. To assure this condition, boundaries have to be set and a control point defined. To add uncertainty in the functions, a uniform distribution can be defined for the samplings of the control point. An example of uncertainty propagation in the utility functions is reported in Figure 3.18.

Function	Equation	Control Point Coordinates	
		X	Y
Lower Boundary (LB)	$(1.01 \cdot 10^{-4})\,x^2 - (2 \cdot 10^{-2})x + 1$	25	0.56
Upper Boundary (UB)	$(-1 \cdot 10^{-4})\,x^2 + (4.17 \cdot 10^{-4})x + 1$	40	0.85

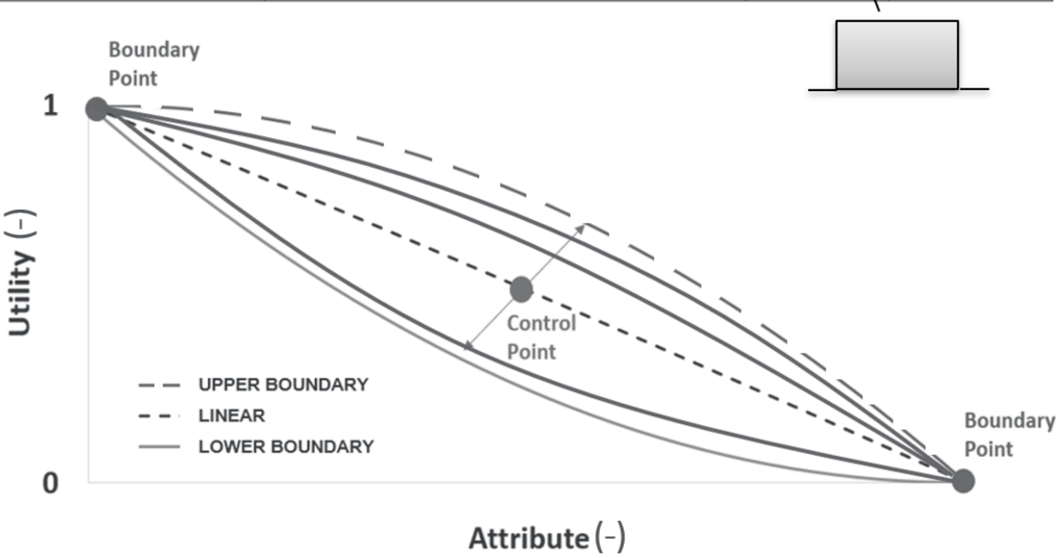


Figure 3.18: Control Point and Boundary Functions to perform utility functions uncertainty propagation analysis.

In this example, uncertainty is propagated through a utility function of one attribute assumed to have a decreasing trend (for instance time). Two boundary Points are defined to assure the constraints on the utility (y axis ranging from 0 to 1) and the trend of the functions (decreasing). Instead, a control point is used to add uncertainty in the function, meaning to change the slope of the function between the lower boundary and the upper boundary. These boundary functions are defined by the utility or trend function constraints. For instance, functions out of the upper function boundary might provide points with utility higher than 1, which is not feasible according to utility definition. The equations of the boundary functions (lower and upper) and the coordinates of the control points are also included in Figure 3.18). To generate all the functions between the upper boundary and lower boundary functions, the Latin Hypercube Sampling (LHS) method is used and the samplings of each coordinate of the control point are generated by levering a uniform distribution.

Case Study III - Weights & Utility Functions Uncertainty Propagation

Weights are used to prioritize attributes while utility functions to quantify the qualitative decision-makers' expectations with respect to each attribute. Adding uncertainty in weights and utility functions is useful when decision-makers are not sure about the scenarios to analysed (weights) and way they would take decisions (utility functions). This case study is a combination of the previous two. Therefore, for the weights a uniform distribution between 0 and 1 is defined while for functions a uniform distribution for the samplings of the control point are used to assure the consistency of the trend functions.

Author Contribution & Reference

- **Donelli, G.**, Ciampa, P. D., Nagel, B., Lemos, G., Mello, J., Cuco, A. P. C., van der Laan, T. (2021). A model-based approach to trade-space evaluation coupling design-manufacturing–supply chain in the early stages of aircraft development. In AIAA aviation 2021 forum (p. 3057)

  This paper introduces the model-based systems engineering approach for defining stakeholders, needs and requirements of the aircraft, manufacturing and supply chain systems. In addition, the value-driven methodology for the concurrent coupling of the aircraft, manufacturing and supply chain domains is presented.
- **Donelli, G.**, Ciampa, P. D., Lefebvre, T., Bartoli, N., Mello, J. M., Odaguil, F. I., van der Laan, T. (2022). Value-driven Model-Based Optimization coupling Design-Manufacturing-Supply Chain in the Early Stages of Aircraft Development: Strategy and Preliminary Results. In AIAA Aviation 2022 Forum (p. 3723).

  This paper focuses on the formalization of the aircraft, manufacturing and supply chain systems architectures and on the MDO strategies to adopt to perform the optimization problems including aircraft, manufacturing and supply chain domains.
- **Donelli, G.**, Mello, J. MGD.Odaguil, F. IK.van der Laan, T..Lefebvre, T., Bartoli, N., Boggero, L., Nagel, B. (2023).Value-driven Systems Engineering Approach addressing Manufacturing, Supply-chain and Aircraft Design in the Decision-Making Process. In INCOSE 2023 Conference.

  This paper explains how to leverage the Multi Attributes Utility (MAU) theory to perform decision-making activities when considering the aircraft design and production criteria. The key criteria to consider when taking decisions related to the supply chain are introduced and explained.
- Merola, U., **Donelli, G.**, Lefebvre, T., Bartoli, N., Mello, J. M., Odaguil, F. I., van der Laan, T., Björn, N. (2023, July). Value-driven Optimization Campaign Addressing Manufacturing, Supply Chain and Overall Aircraft Design Domains in the Early Development Stage. In INCOSE International Symposium (Vol. 33, No. 1, pp. 1357-1376).

  This paper supports the MDO activities in exploring multiple optimization strategies and alternatives to formalize and execute the MDO problems of the three MDO Cases analysed in this PhD study.

Author Contribution & Reference

- Merola, U., **Donelli, G.**, Pezzella, G. (2022). Value-driven Optimization Campaign addressing manufacturing, supply chain and overall aircraft design domains in the early development stage. Master Thesis dissertation, Vanvitelli University.

  In this master thesis dissertation, supply chain domains models are explored and finalized. For instance, an investigation is done to identify how to estimate manufacturing cost depending on the enterprises competences. Furthermore, additional studies on the MDO problems are performed to also identify the best way to exchange information among domains and later through technologies.
- **Donelli, G.**, Ciampa, P. D., Mello, J. M., Odaguil, F. I., Cuco, A. P., van der Laan, T. (2023). A value-driven concurrent approach for aircraft design-manufacturing-supply chain. Production Manufacturing Research, 11(1), 2279709.

  This paper describes in the details the flowchart characterizing the value-driven methodology proposed for the concurrent design evaluation of the manufacturing, supply chain and aircraft domains.
- Ascione, G., **Donelli, G.**, Boggero, L., Björn, N. (2024). Uncertainty Propagation in Value-driven Decision-making for the Aircraft, Manufacturing and Supply Chain Design. In ICAS Conference.

  This paper explains how to introduce uncertainty propagation in the value-driven decision-making processes when leveraging the Multi Attribute Utility theory considering aircraft design and production criteria.

4

Methodology Implementation

Contents

4.1 A Model-based Systems Engineering Approach

The formalization of the Framework Processes, and thus the methods presented in Chapter 3 for achieving the concurrent conceptual design of the aircraft, manufacturing, and supply chain systems, can be executed using either a model-based or document-based approach.

The document-based approach is a traditional method of managing information and requirements in various industries, including engineering, project management, and software development. It relies on the use of documents, such as text files, spreadsheets, and reports, to capture, store, and communicate information. Documents are shared among stakeholders to communicate project progress, changes, and updates. This sharing can be done via email, file-sharing platforms, or other communication methods. As projects grow, the volume of documents increases, making it challenging to manage and maintain consistency. Any change requires manual updates in multiple places, increasing the risk of inconsistencies. Collaboration is often asynchronous, with delays in sharing updates and feedback. Maintaining and establishing traceability between various documents can be challenging.

The model-based approach, often referred to as Model-Based Systems Engineering (MBSE) approach in the engineering fields, is a modern way of managing information and requirements that uses digital models instead of traditional documents. This approach provides a structured, integrated, and dynamic way of modelling, representing and analyzing complex systems throughout their lifecycle. Information is captured in centralized digital models that are continuously updated. These models provide a unified, consistent view of the systems and their components. Models are dynamic, meaning changes to one part of the system automatically propagate to other connected parts, ensuring that information remains consistent and up-to-date. They can integrate various aspects of the system, facilitating a holistic understanding. Visual representations, such as diagrams, simulations, and dashboards, make it easier to communicate complex information in a clear and concise manner. For the upstream processes, the model-based approach enhances traceability by linking requirements directly to a specific component, process, or function within the model, allowing for clear tracking of where and how requirements are implemented. For the downstream processes, digital models instead allow for automation of simulations, analyses, and optimizations, which can be performed rapidly and iteratively to test and validate system performance. Tools within the model-based environment can perform tasks such as performance assessment, optimization and sensitivity analysis enhancing the accuracy and efficiency of the design process. When changes occur, the model is automatically updated, maintaining consistency and traceability without the need for manual cross-referencing accelerating the design iterations. In addition, models can handle complex, large-scale projects in a unified environment, making it easier to align different teams and disciplines. In a nutshell, a model-based approach improves accuracy and consistency, enhance collaboration, scalability and flexibility leading to faster iteration and innovation. For the outlined reasons, a model-based approach is adopted to execute the processes of the S4S Framework. While various models and tools are available for implementing these processes, this section focuses specifically on those used in the application cases presented in Chapter 5. Figure 4.3 provides a comprehensive overview of all the tools. Most of these tools have been developed internally by DLR. For completeness, however, also available commercial tools are mentioned. Recently, in fact, activities related with the implementation of the S4S Framework processes by leveraging commercial tools have been initialized, especially for the upstream phase processes.

For some processes, multiple technologies have been explored in the application cases and therefore here discussed. The focus, however, is first on technologies that integrate all the tools utilized for the different processes of the Framework within a shared work environment, specifically Ke-Chain and MBSE-Env.

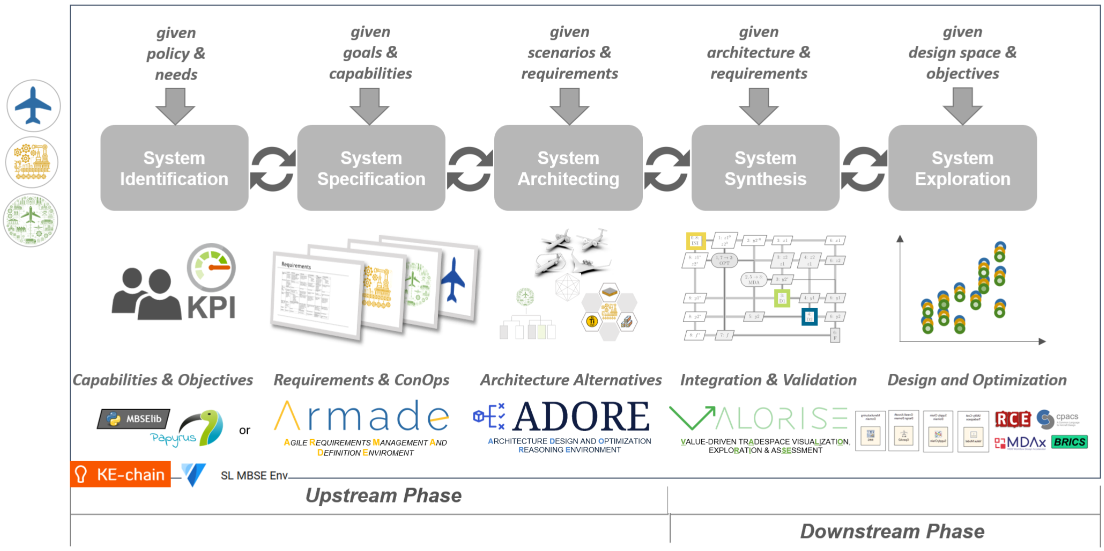


Figure 4.1: S4S Framework Technologies Overview.

Ke-Chain is a web-based collaborative platform, developed by KE-Work, connecting all the technologies together into a single development process [90]. Multiple users can access the platform and specify through tables and interfaces, all the data of the system under development, as stakeholders,needs, requirement elements and requirement attributes. Moreover, Ke-chain can be exploited to define all the connections between the different elements, therefore addressing the functionality of supporting the traceability of the model. All the collected data can be then verified to assure completeness and correctness qualities.

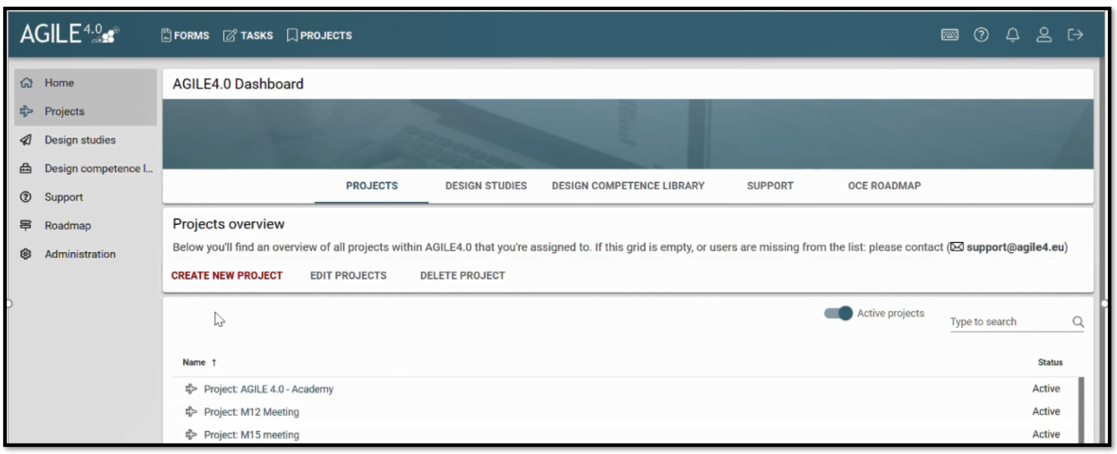


Figure 4.2: Ke-Chain to facilitate through tables or similar methods data exchange between S4S Framework Technologies [90].

MBSE-Env is a web-based collaborative platform, developed by DLR, connecting all the technologies into a single environment. Multiple users can access the platform and the different technologies of the framework. All the technologies are connected through a common data repository and different format are used to automatize the exchange of information among them.

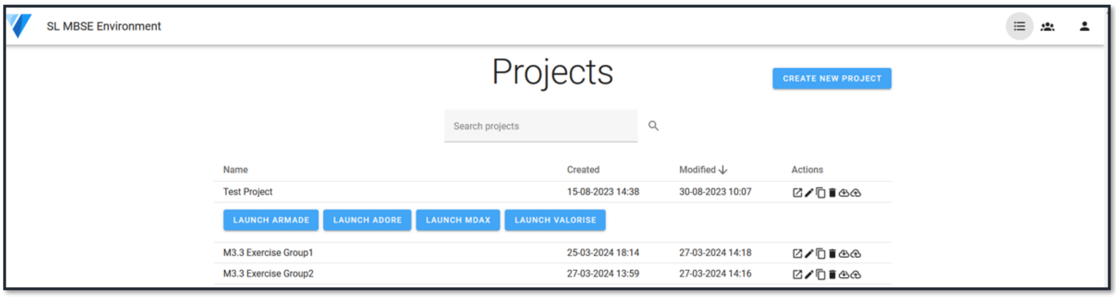


Figure 4.3: MBSE-Env supporting information exchange between S4S Framework technologies through a shared repository.

Among available commercial tools, there is IBM Workspace Environment [91] which is under investigation and Dassault Systemes 3D Experience environment [92] that act as single version of the truth to anchor outcome-based processes and capture all activities in one place while connecting individuals, teams, departments and external collaborators on the same innovative products, projects and services.

The following sections instead provide descriptions of the technologies used for implementing the upstream and downstream processes. For the downstream processes, new tools have been developed to implement the new methodology proposed in this study (Section 3.5), enabling the concurrent design, optimization, and decision-making for the manufacturing, supply chain and aircraft systems evaluation. The main difference between the two platforms is that Ke-Chain uses tables or similar methods to gather input variables or facilitate data exchange between the various technologies within the Framework. The MBSE-Env enables instead direct information exchange between tools through a shared repository.

4.2 S4S Framework Upstream Phase Technologies

The technologies related to the upstream phase support the first three processes of the Framework, as shown in Figure 4.4. These technologies support the modelling of stakeholders and their needs, along with systems requirements and architectures.

For the modelling of stakeholders, their needs and the derived requirements two options are investigated: Ke-Chain combined with Papyrus and ARMADE integrated in the MBSE-Env.

Ke-Chain and Papyrus. Data related to the stakeholders, needs and requirements are first collected through a tabular format in Ke-Chain. Once the model is

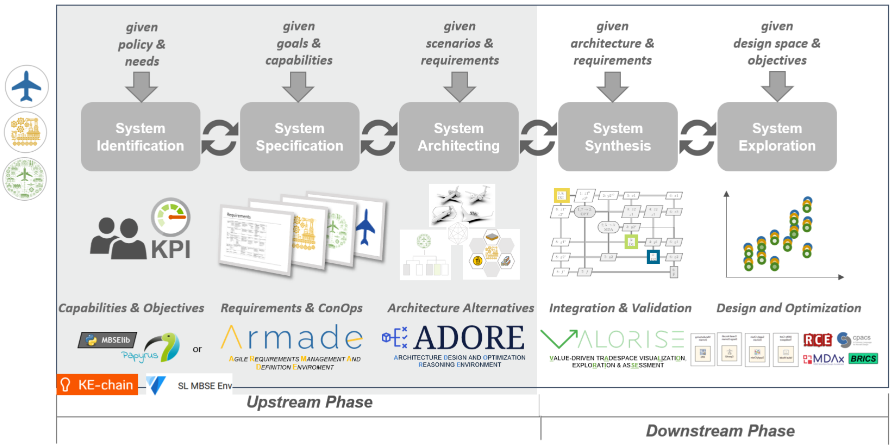


Figure 4.4: S4S Framework Upstream Technologies.

created, it can be exported and visualized in the form of SysML diagrams. This is automatically allowed by DLR's tool MBSElib, which has been conceived to generate all the system views and save them as a Papyrus project file [21]. This automatically created file includes the models of stakeholders, needs and requirements and it can be opened in the Papyrus environment for inspection and verification [93].

ARMADE, integrated in MBSE-Env, stands for Agile Requirements Management And Definition Environment. It is a software too developed by DLR and used for the collaborative definition and management of system requirements. It supports MBSE methodology by enabling model-based requirement verification and validation, and linking requirements to system architecting and design activities [94].

The architectural design space, thus all the instances that can be generated from the logical architecture, is instead modeled using a DLR tool called ADORE.

ADORE is a web-based user interface, Java and Python based, implementing the Architecture Design and Optimization Graph (ADSG). It is used to model the logical architectures of the systems, defining numerical optimization problems and interfacing with optimization frameworks for driving the design space exploration [29].

For the modelling of the systems requirements and architectures, several commercial tools are also available. Among others, the most used once are No Magic CAMEO Systems Modeler [95], IBM Doors Next Generation (DNG) [96], IBM Engineering Systems Design Rhapsody [97] and the open-source software CAPELLA [98]. In details, IBM DNG is a software used purely for requirements management, CAPELLA for systems architecture design. Instead, in CAMEO and Rhapsody designers can either handle requirements and architectures modelling.

4.3 S4S Framework Downstream Phase Technologies

Technologies supporting the modelling of the downstream phase, shown in Figure 4.5, support the modelling of the concurrent design, optimization and decision-making methodologies. In addition, through these technologies, such methodologies can also be executed collaboratively meaning that multiple partners can share their own expertise when needed without providing details on the codes. This is extremely useful when the design and optimization of complex systems have to be analysed. More details on the technologies used to execute the application cases are provided in the next sections. Nevertheless, commercial tools and platforms are also available for executing such processes. For instance, modeFRONTIER is a software solution for simulation process automation and design exploration developed by ESTECO [99], an italian engineering software house, to reduce complexity, improve efficiency and cut development time.

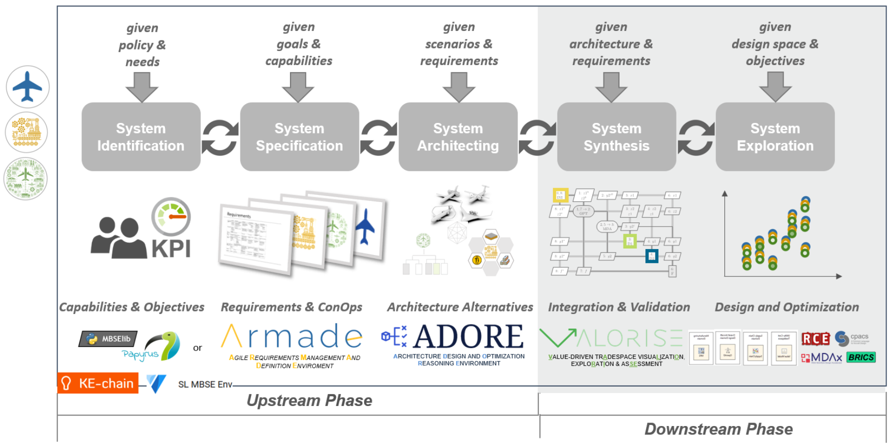


Figure 4.5: S4S Framework Downstream Technologies.

4.3.1 Concurrent Design Evaluation Methodology Implementation

Technologies enabling the concurrent design of the supply chain, manufacturing and aircraft design domains are those leveraged to implement the methodology described in Figure 3.11, Section 3.5.1. In details, Python-based codes, shown in Figure 4.6, implement the models and equations behind the domains of manufacturing, supply chain, aircraft design and value model theory. All the tools, except the one related to aircraft design, have been implemented from scratch. The overall aircraft design tool called OPENAD, developed by the DLR Institute of System Architectures in Aeronautics, is instead used to estimate the aircraft performance [100]. In this section, the tool related to the product design domain refers to the aircraft since it represents the product under design in both the application cases reported in Chapter 5.

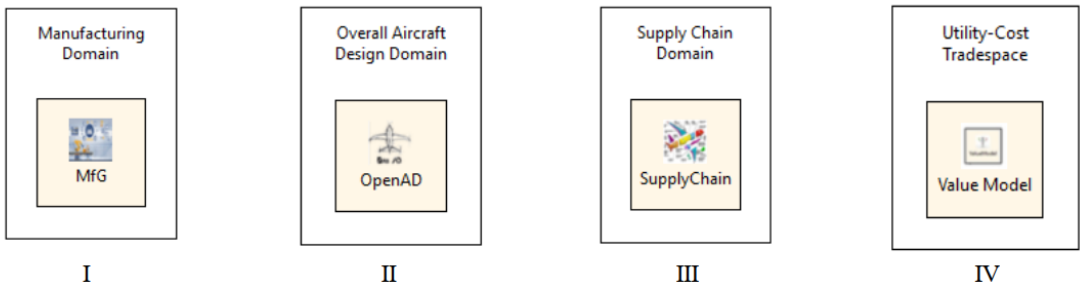


Figure 4.6: Disciplinary codes implementing, respectively, the Manufacturing Domain (I), the Aircraft Design Domain (II), the Supply Chain Domain (III) and the Value-model Theory (IV).

The python-based disciplinary tools need to exchange information to achieve the value-driven tradespace, as shown in Figure 3.12, Section 3.5.1. For example, the Technology Factor provided as output from the manufacturing domain code is needed from the OAD discipline to run and estimate the aircraft performance. To allow the automatic execution of these methodology, the following technologies are leveraged.

CPACS as common language. CPACS, which stands for Common Parametric Aircraft Configuration Schema, is used to automate the exchange of information between disciplinary codes [101]. CPACS has been developed by the German Aerospace Center (DLR) located in Hamburg, to support the collaboration among different experts. It is an xml file serving as a central description of the aircraft, for instance in terms of properties and geometry. Information not yet modeled in CPACS, can be stored in CPACS tool specifics branches. A disciplinary code is CPACS-compliant when it is able to extract the inputs needed for the analysis from the CPACS file and, after the run, upload the outputs in the same file. The CPACS-ized tools can be connected together in a simple design process, since able to communicate in the same language.

MDAx to set-up the MDO problems. The MDO process coupling the disciplinary codes in a single workflow, is automatically generated by the MDAO Workflow Design Accelerator, short MDAx [102]. MDAx, developed by the DLR in Hamburg, enables workflow integrator and disciplinary experts to model, inspect, and explore workflow components and their relationships. It provides an intuitive workflow modeling environment using an expansion of the XDSM format with additional design rules.

RCE to execute the MDO problems. The MDAO workflow, set-up with MDAx, is executed within the Remote Component Environment (RCE). RCE is an engineering framework software, developed by DLR for the management and execution of the development process and optimization [103].

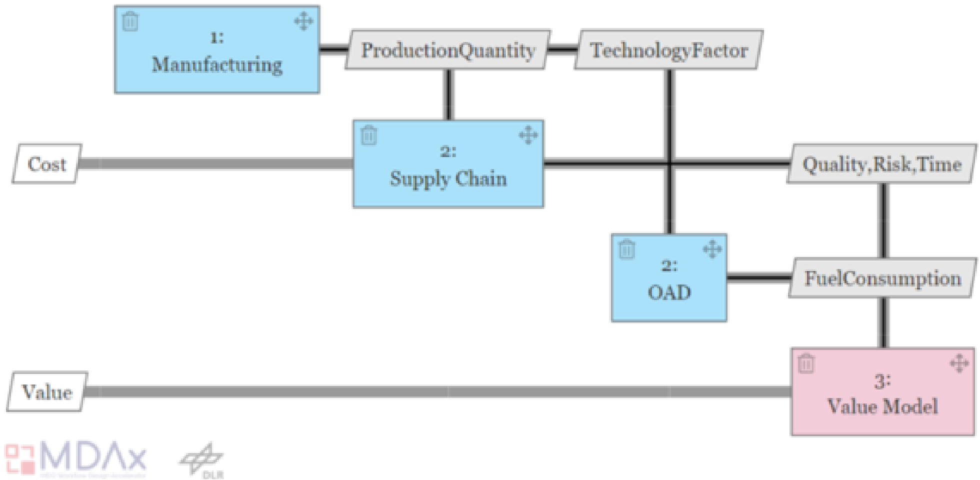
Therefore, in this study, CPACS is used as the common language to allow the exchange of information between the disciplinary implemented modules.In particular, specific branches are implement to include information on manufacturing and supply chain. MDAx is then used to automatically generate the MDAO problem, which is exported and executed within the PIDO (Process Integration Design Optimization) environment RCE. The XDSM representing the methodology and the relative executable workflow are reported in Figure 4.7.

The XDSM, in Figure 4.7a, includes the main disciplinary competences on the diagonal, the coupling variables thus the exchanged variables among competences in the gray boxes while the outputs of the methodology in the white boxes. This workflows can be exported and executed to run the methodology and get the results. Figure 4.7b shows the disciplinary tools integrated in the RCE environment. This workflow can also be adjusted and executed with a selection of these tools if different analyses have to be performed. For instance, in case of aircraft and manufacturing concurrent design, only tools relevant to these domains are used. All of these technologies can be integrated and used in Ke-Chain or in the MBSE-Env.

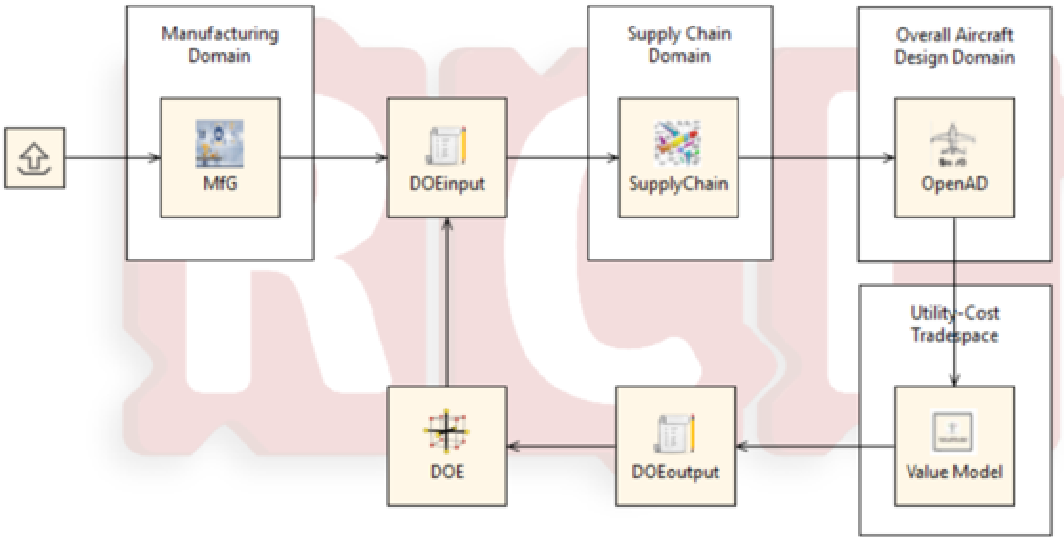
4.3.2 Concurrent Optimization Implementation

Optimization algorithms are included in methodology to allow the concurrent optimization of the three domains, as described in Section 3.5.2. In this case, a collaborative execution involving different partners is needed. In fact, the expertise related to the optimization algorithms is provided by ONERA, the French aerospace center. In addition to the previous technologies that allow the execution of the methodology, also the following once are adopted to enable the collaborative execution of the optimization problems.

BRICS or UPLINK to collaborative execute the MDO problems. BRICS is based on a simple protocol that supports single or repetitive remote execution of tools within a local workflow [104]. It facilitates the definition and implementation of cross-organisation workflows by interconnecting local workflows through links. While executing the linked workflows, BRICS takes care of the notifications and data-file exchange involved [105].



(a) XDSM of the Concurrent Design Methodology, built in MDAx.



(b) Executable Workflow of the Concurrent Design Methodology, done in RCE.

Figure 4.7: Concurrent Design Methodology XDSM Workflow modelled with MDAx [102] and Executable Workflow run in RCE [103].

UPLINK is used to run collaborative workflows, meaning workflow including tools belonging to different partners. Conceptually, this is realized using RCE's standard approach of providing access to local tools as distributed services, while keeping the tool's files and execution on the local machine. The main difference with BRICS is that tools are now shared among partners in specific group and organizations can include these tools in the own workflow with owners permission [106].

SEGOMOE to run optimization algorithms. SEGOMOE stands for Super

Efficient Global Optimization using Mixture Of Experts [107], combining efficient global optimization proposed by Jones [108] and constraint management introduced by Sasena [109]. This algorithm has been successfully applied to various test cases in a mono [110–112] or multi-objective [113, 114] context.

An example of collaborative workflow used to run the concurrent optimization is reported in Figure 4.8. First, ONERA executes the workflow including the optimization tool. Information related to the optimization, like the design variables are included in the CPACS file. This CPACS file is sent to DLR through BRICS for the estimation of the objective and constraint functions. DLR gets the CPACS as input and executes the methodology. The supply chain and aircraft performance are estimated and stored, with the value, in the CPACS file. This CPACS file, collecting all the information, is sent again to ONERA through BRICS. ONERA proposes a new input and the process starts again. At the end of the optimization process, both the database and the predicted Pareto front are obtained. The points of the predicted Pareto front are then sent to DLR, which runs again the methodology for the evaluation of the true Pareto front. If there is no much difference between the predicted and true Pareto fronts, post-processing of the results begins. If not, the optimization process starts again, including the points of the true Pareto front in the database (step 3 in the algorithm description reported in Figure 1 in the Appendix B).

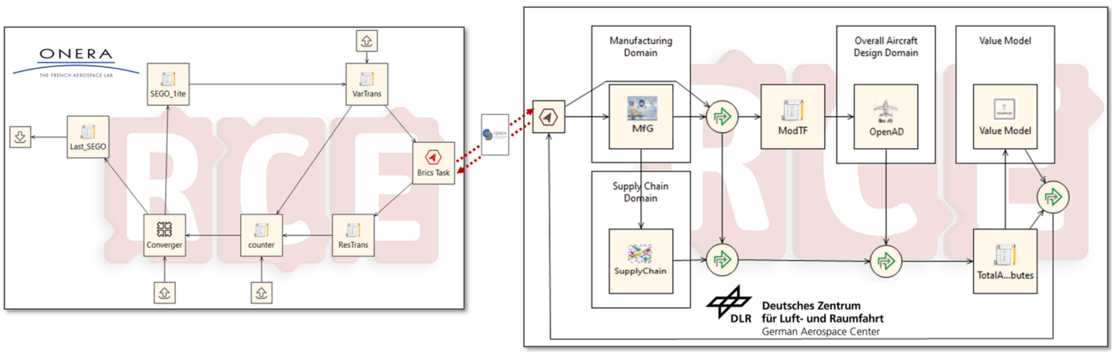


Figure 4.8: Collaborative Workflows to execute concurrent manufacturing, aircraft and supply chain optimization problems using BRICS technology.

An example of collaborative workflow using UPLINK technology is instead reported in Figure 4.9. In this case, DLR and ONERA shared the dedicated RCE group in which DLR provides access to the all the tools in its own workflow. The same steps previously described are therefore executed without exchanging the CPACS files between ONERA and DLR.

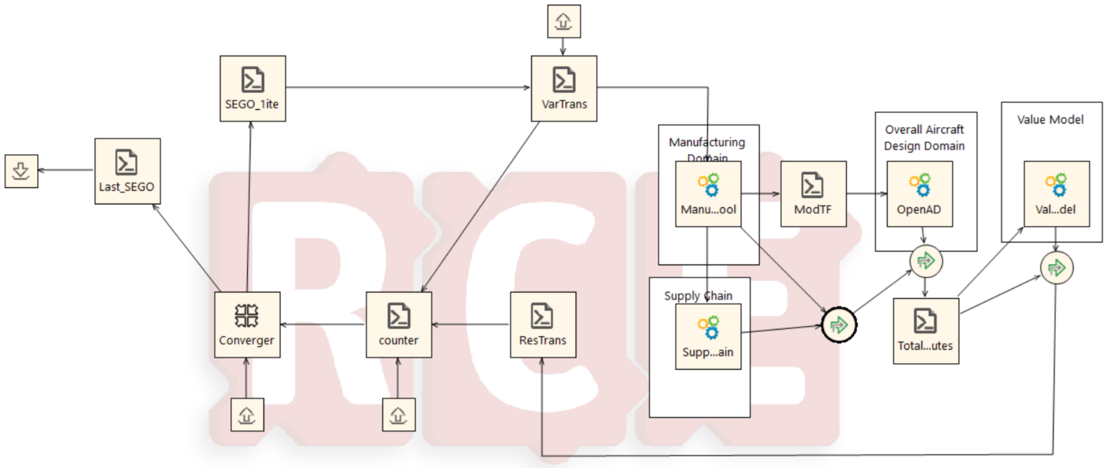


Figure 4.9: Collaborative Workflows to execute concurrent manufacturing, aircraft and supply chain optimization problems using UPLINK technology.

4.3.3 Decision-making and Uncertainty Propagation Implementation

To streamline the multi-criteria decision-making process and create a value-driven tradespace for the identification of the best alternative trading stakeholders´expectations with respect design and production criteria, the MAU theory (Section 3.5.3) has been implemented in a more sophisticated tool with respect to the one shown in Figure 4.6. In particular. VALORISE, which stands for Value-driven trAdespace visuaLizatiOn, exploRatIon and aSsEssment is an interactive dashboard that has been developed by DLR to support the modelling of the value-driven decision-making process, facilitate the analysis of real-time strategic scenarios and allow the exploration of the value-driven tradespaces for the best and robust solutions identification. VALORISE can be used as interactive dashboard directly by decision-makers for the identification of the best solution or as an executable tool integrated in a tool-chain to explore many weights combinations and/or utility functions and perform the uncertainty propagation case studies described in Section 3.5.3. More details on how VALORISE can be exploited to perform these activities are provided in this Section. In both cases, however, VALORISE needs as inputs the specifications of the criteria defined by decision-makers, e.g. the name and unit of measures, as well as the numerical estimation of such criteria for all the alternatives populating the design space. These inputs can be important by using different files format, among others CPACS file shown in Figure 4.10.

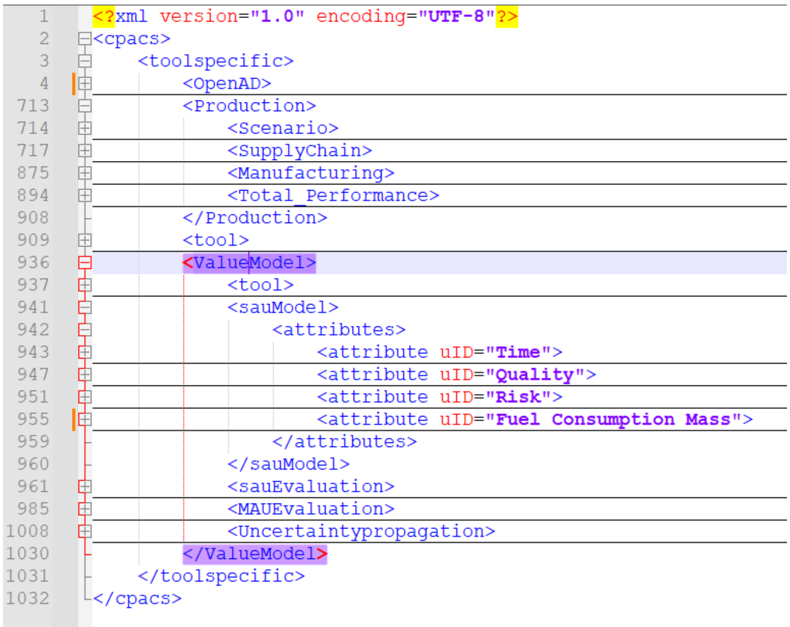


Figure 4.10: CPACS file including information to perform value-driven decision-making and uncertainty propagation analysis.

Tradespace Exploration: VALORISE as Dasboard

The settings of the value-model, thus the assignment of weights and utility functions (Section 3.5.3) can be defined by decision-makers directly in VALORISE as shown in Figure 4.11.

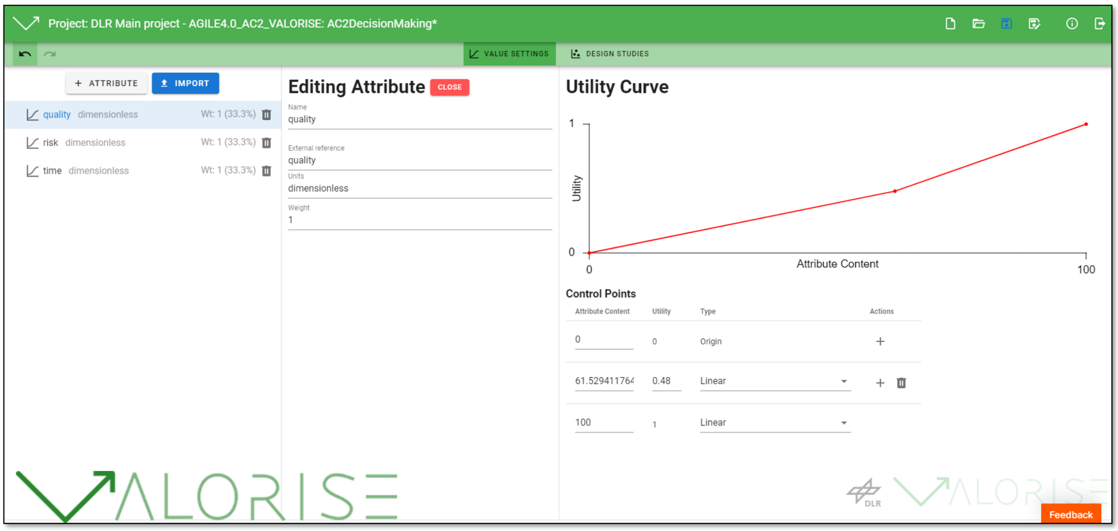


Figure 4.11: VALORISE Dashboard settings per each attribute - utility functions and weights.

Decision-makers can interactively draw utility functions to represent their expectations with respect to each selected attribute and set several weight combinations to analyze the scenario of interest. Many scenarios can be then investigated real-time in VALORISE. In fact, changes on the attributes weights and/or on utility functions (e.g. on the boundaries of contents) are directly visualized on the dashboard. For instance, in Figure 4.12 a comparison is shown among five different scenarios in which the weight combinations or the utility functions are changed. This allows decision-makers to investigate the behavior of the alternatives in different scenarios before taking strategic decisions.

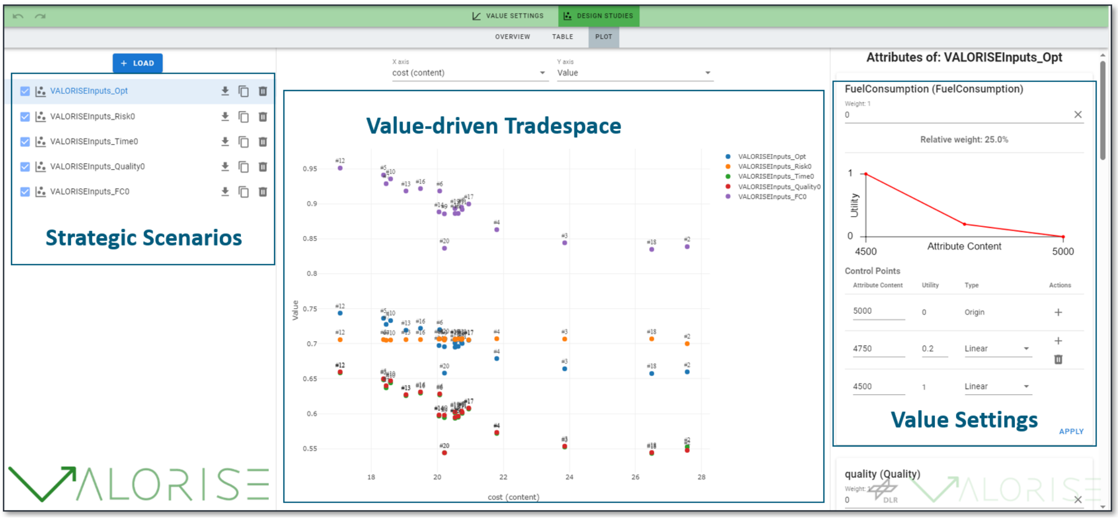


Figure 4.12: VALORISE Dashboard supporting the Multi-Attributes Decision-making Process.

The use of VALORISE as dashboard is worth when a limited number of cases in terms of weights combinations are of interest for the decision-makers. When the behaviour of the alternatives in value have to be investigated considering hundred of weights combinations or utility functions variation, then VALORISE can be used as executable tool and integrated in a toolchain, as explained in the next section. Finally, VALORISE also offers the possibility to export a table including the value and the attributes contents of each solution in different format if needed for further analysis.

Uncertainty Propagation: VALORISE as Executable Tool

Finally, to perform the uncertainty case studies described in Section 3.5.3 and analyse the behaviour of the solutions in terms of value, VALORISE is used as executable tool and integrated in a toolchain with other tools. In this case, using VALORISE not as a dashboard reduces the computation time. In fact, decision-makers don´t have to manually set all the possible combinations.

An example of VALORISE used as executable tool to support uncertainty propagation analysis is reported in Figure 4.13.

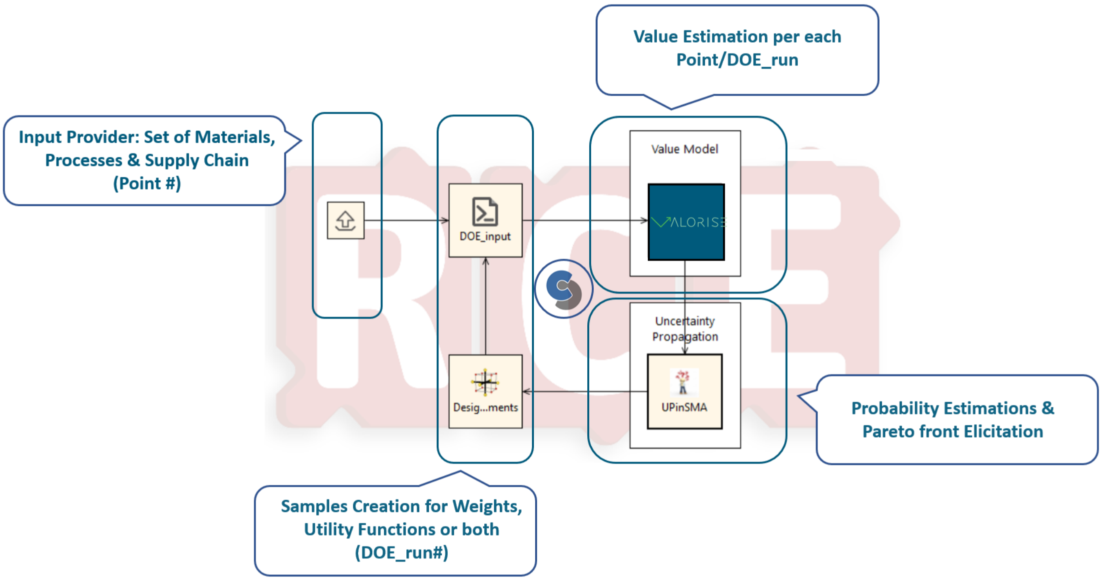


Figure 4.13: VALORISE tool supporting the Uncertainty Propagation in Value-driven Multi-Attributes Decision-making Process.

In this workflow, each solution (Point #) is analysed per each sample created to generate weights and/or utility functions variations (Section 3.5.3. Based on these settings, the value of the solution is anytime estimated with VALORISE. Then UPinSMA, a tool developed by DLR is used to evaluate the value oscillation of the solution and if the solution is on the Pareto front. The robust solution can be so identified. In addition, the probability of the solution to be on the Pareto front is also evaluated to define the flexible solution, as explained in Section 3.5.3.

Author Contribution & Reference

- **Donelli, G.**, Ciampa, P. D., Nagel, B., Lemos, G., Mello, J., Cuco, A. P. C., van der Laan, T. (2021). A model-based approach to trade-space evaluation coupling design-manufacturing–supply chain in the early stages of aircraft development. In AIAA aviation 2021 forum (p. 3057) [115]

  This paper presents the tools to perform the value-driven methodology for the concurrent coupling of the aircraft, manufacturing and supply chain domains.

Author Contribution & Reference

- **Donelli, G.**, Boggero, L., Nagel, B. (2023). Concurrent Value-Driven Decision-Making Process for the Aircraft, Supply Chain and Manufacturing Systems Design. Systems, 11(12), 578.

  This paper introduces VALORISE as the interactive dashboard to perform multi-criteria decision-making process and support decision-makers in elicitating the utility functions and perform tradespace exploration.
- Ascione, G., **Donelli, G.**, Boggero, L., Björn, N. (2024). Uncertainty Propagation in Value-driven Decision-making for the Aircraft, Manufacturing and Supply Chain Design. In ICAS Conference.

  This paper explains how to introduce uncertainty propagation in the value-driven decision-making processes and how to leverage VALORISE as executable tool.
- Boggero, L., Bussemaker, J., **Donelli, G.**, Torrigiani, F., Nagel, B. (2024). Processes, Methods and Tools supporting the development of aeronautical systems. In ICAS Conference.

  This paper introduces all the processes and technologies of the MBSE-Env: from stakeholders, needs, requirements to architectures, MDAO and decision-making activities.
- Allegra, G., **Donelli, G.**, Forlingieri, M. Rachna, H. (2025). Identify the Best Supply Chain, Manufacturing and Aircraft Architecture with an integrated PLE and MBSE (MBPLE) approach. SUBMITTED in INCOSE 2025.

  This paper introduces the main standards to formally write manufacturing and supply chain requirements together with the aircraft requirements by leveraging the IBM Doors Next Generation Tools. In addition, Rhapsody is leveraged to create an S4S architecture baseline while PTC pure::variants software to generate several alternatives of this architecture. The best architecture is identified by leveraging the concurrent value-driven methodology proposed in this PhD thesis.
- Aversano, P., **Donelli, G.**, Boggero, L. Nagel, B. (2025). Aircraft, Manufacturing and Supply Chain Architectures Formalization and Optimization: Methods and Tools. SUBMITTED in INCOSE 2025.

  This paper shows a process to perform the S4S architectures generation and optimization. In addition, the commercial tool CAMEO and the in-house tool ADORE also leveraged to highlight the benefits and limitations of using tools that implement such processes differently.

5
Methodology Application

Contents

5.1 Horizontal Tail Plane Concurrent Design, Manufacturing and Supply Chain

The first application case is framed within the European H2020 Project AGILE4.0 (G.A 815122, [116]). The ambition of this project is to bring significant reductions in aircraft development costs and time-to-market through the implementation of an integrated cyber-physical aeronautical supply chain, including design, production, certification and maintenance, leading to innovative and more sustainable aircraft products. To meet this challenge a Consortium of 18 industry, research and academia partners from Europe, Canada, Brazil, and Russia collaborate togheter. A representation of the domains addressed by the project and the Consortium are shown in Figure 5.1.

Figure 5.1: AGILE4.0 project: Over Concept (left), application cases (right) and consortium, [116].

Seven application cases are defined within these domains (see Figure 5.2). Each application case focuses on a specific aircraft component, it´s led by an industrial partner and aim to achieve a specif objective. The first two application cases (1,2) are framed in the production domain, the following three application cases to the certification domain while the last two to the upgrade domain. The application case of interest for this study is the application case 2, led by Embraer and run in collaboration with GKN/Fokker, DLR and ONERA.

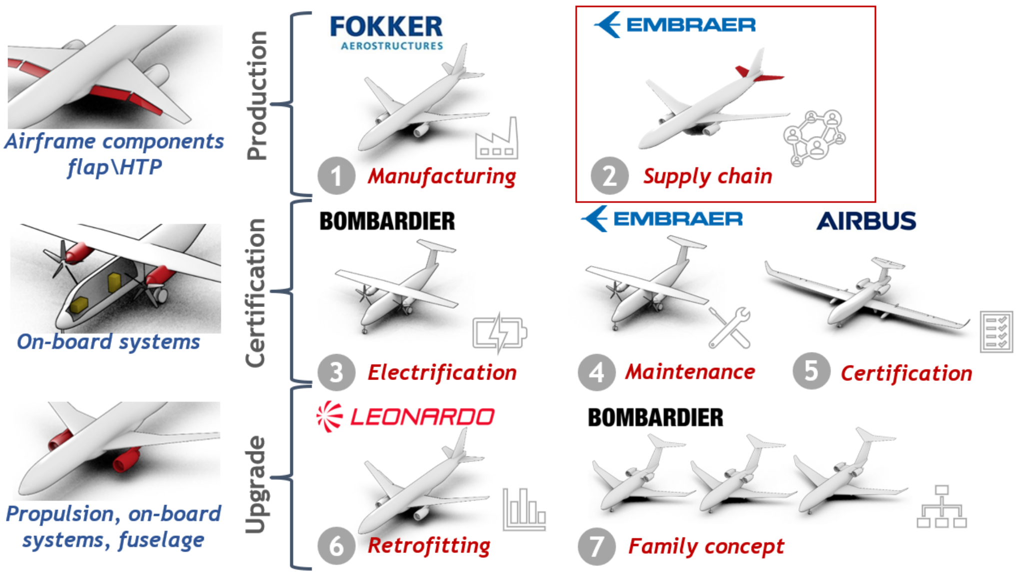


Figure 5.2: AGILE4.0 Industrial Application Cases, [116].

The ambition of this application case is to identify the most efficient but also competitive alternative matching stakeholders´expectations when considering design and production criteria. To achieve this objective, the S4S Framework is leveraged and the technologies showed in Figure 5.3 are adopted to model stakeholders´s needs, requirements and architectures. These architectures are then evaluated and the best and robust solutions on the design space are identified.

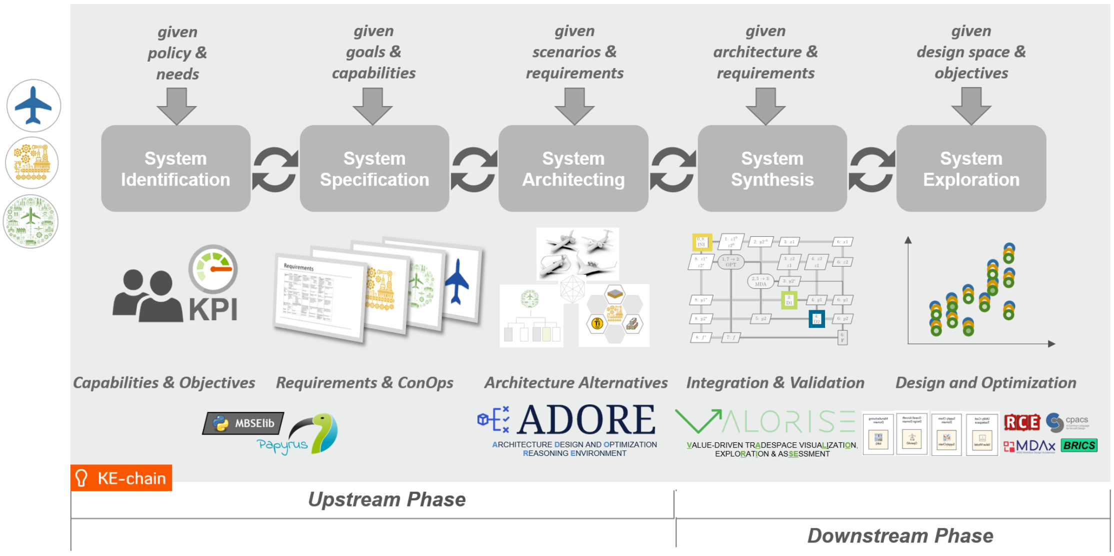


Figure 5.3: S4S Framework Tools applied for the Horizontal Tail Plane Concurrent Design, Manufacturing and Supply Chain.

Before showing the results of the application of such technologies to model all the processes of the framework, more details on the application case are provided in the next section.

5.1.1 Application Case Specifications

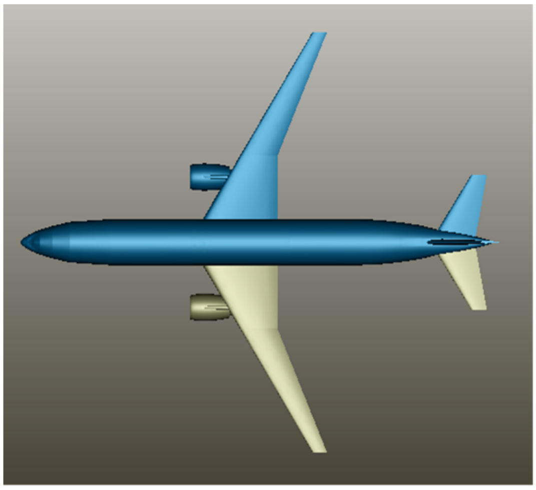
The baseline aircraft configuration characterizing this application case is a 90-passenger regional aircraft. The three view of this aircraft and its TLARs are shown in Figure 5.4.

The main characteristics, in terms of geometrical parameters and masses, are summarized in Table 5.1.

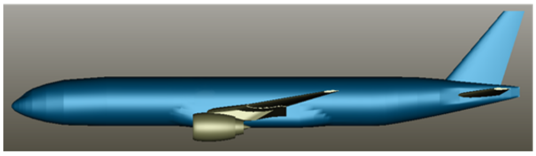
Table 5.1: Reference Aircraft Main Parameters.

Geometrical Parameters			Mass Breakdown		
Parameter	Unit	Value	Parameter	Unit	Value
S	m2	81.4	MTOW	kg	44898
b	m	27.186	MZFW	kg	37309
AR	-	9.09	MOEW	kg	28129
MAC	m	3.796	MEW	kg	24874
lf	m	34	MPAYLOAD	kg	9180

The focus of this application case, however, is on the horizontal tail plane (HTP) of this aircraft configuration. The manufacturing and structural properties of the main HTP components, identified in the skins, spars, stringers and ribs are reported



Parameter	Imperial	International
Long-range cruise Mach, ISA, WTO	0.78	0.78
Design payload	90 Pax	90 Pax
Design range	1890 [nm]	3500 [km]
Fuselage length	111.5 [ft]	34 [m]
Take-Off field length	4921 [ft]	1500 [m]
Landing field length	4593 [ft]	1400 [m]
Initial cruise altitude	36000 [ft]	10972 [m]



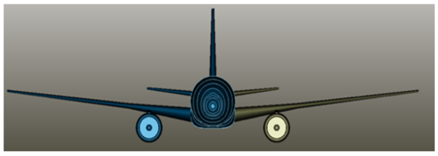


Figure 5.4: Baseline Aircraft Configuration Three-view and Top Level Aircraft Requirements.

in Table 5.2. For each of them, the materials and manufacturing processes are specified. The structural layout, that is the numbers of the main components of the HTP, is also included in the table and it is assumed fixed in the application case.

Table 5.2: Horizontal Tail Plane Manufacturing and Structural Properties.

Components	Materials & Processes	Numbers
Skins	Sheet Metal Stretch Formed	2
Stringers	Aluminum Z-extrusion	30
Spars	Aluminum Machined	2
Ribs	Aluminum Machined & Sheet Metal Stretch Formed	20

Instead, different materials, manufacturing and assembly processes can be selected for each of the main HTP components. At the same time, different enterprises can be selected to execute these processes. The number of materials, manufacturing processes and enterprises that can be selected to perform these processes are summarized in Table 5.3. In case of composite, thermoset and thermoplastic are accounted as two materials.

For the assembly processes, instead, three assembly phases are considered: the assembly 1 in which skins and stringers are joint; the main assembly in which the pre-assembled components are combined to build the HTP; the final assembly in which the HTP is aggregated in the aircraft. For each assembly phase, different

Table 5.3: Number (N°) of choices related to Materials, Manufacturing Processes and Enterprises.

Components	N°Materials	N°Manufacturing Processes	N°Enterprises
Skins	2	6	21
Stringers	3	5	21
Spars	3	5	21
Ribs	4	6	21

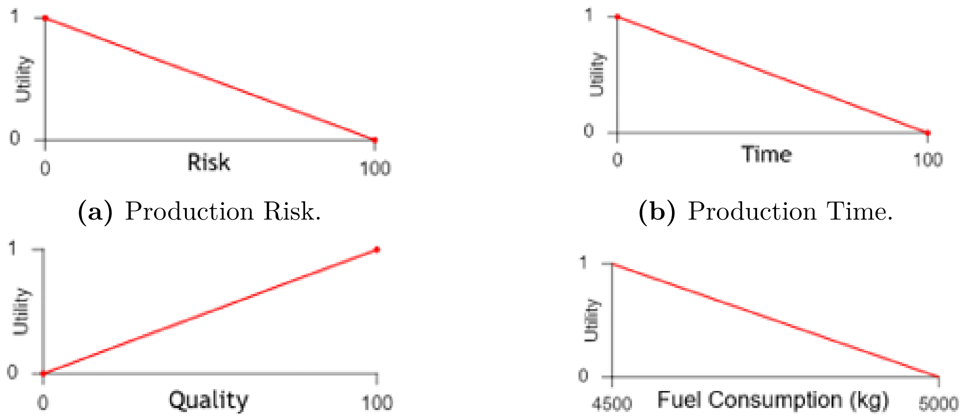
assembly processes and enterprises can be selected. The number of choices available is reported in Table 5.4.

Table 5.4: Number (N°) of choices related to Assembly Processes and Enterprises.

Assembly Phase	N°Processes	N°Enterprises
Assembly 1	8	21
Main Assembly	4	21
Final Assembly	-	1

The assembly processes needed to integrate the HTP in the aircraft are not considered in this application case and it´s assumed that one single enterprise is responsible for doing it. All the choices in terms of materials, processes and enterprises lead to multiple alternatives (architectures) characterized by different aircraft and supply chain performance. The supply chain performance have been already introduced in Section 3.5.1. As mentioned, the production cost, time, quality and risk are assumed as key performance for the supply chain because of the key role they have in the supply chain management. The product performance instead have been not specified in Section 3.5.1 since depending on the product under design. In this application case, the fuel consumption mass in cruise is assumed as main aircraft performance because it´s a key parameter for the selection of commercial regional aircraft - like the reference aircraft. These parameters, except cost, are then aggregated in a value with the assumption of same weights and linear utility functions. The linear utility functions adopted in this application case are shown in Figure 5.5. The supply chain performance are normalized because of intellectual properties of industrial partners collaborating in this application case. The production cost, instead, is used as other independent variable for the value-cost tradespace generation. For this reason the linear utility functions is not defined for the production cost.

For the same reasons mentioned before, all the identified supply chain and aircraft performance are also recognized by decision-makers as crucial when taking decisions. In this application case, the two decision-makers involved, indicated as



(a) Production Risk.

(b) Production Time.

(c) Production Quality.

(d) Fuel Consumption Mass.

Figure 5.5: Linear Utility Functions for a) Production Risk b) Production Time c) Production Quality and d) Fuel Consumption.

Decision-maker A and Decision-maker B, are the industrial partners collaborating in the application case. In Section 5.1.7, the utility functions they defined for each attribute are introduced and discussed. Criteria related to the manufacturing are not explicitly considered for the identification of the best solution since manufacturing results are including in the supply chain performance.

Concluding, based on all the mentioned assumptions, several case studies of different complexity are performed in the next sections to show the advantages of leveraging the S4S framework, validate the proposed concurrent design methodology and show all the possible trade-off studies that can be performed when executing the concurrent design, optimization or uncertainty analysis.

5.1.2 System Identification

The first step of the S4S Framework deals with the modelling of stakeholders, needs and requirements. Stakeholders involved in the design, manufacturing and supply chain of the HTP are collected in a tabular format, within Ke-Chain, as shown in Figure 5.6.

As shown in this figure, several stakeholders are involved in the design, manufacturing and production of an horizontal tail plane. In addition, since the horizontal tail plane is integrated in the aircraft, also stakeholders related to the aircraft design and production are accounted. Thus, stakeholders vary from the certification authorities, airlines, flight crew to the passengers, maintainers, manufacturers. The model realized in Ke-Chain is exported and then imported in Papyrus for visualization, as explained in Section 4.1. In Papyrus, the stakeholders' hierarchy is visualized in a diagram shown in Figure 5.7.

Stakeholder	ID	Linked to needs	Needs	Parent stakeholder
OEM-Quality	ST-0003	Yes	N30 | N53	OEM
OEM-Purchasing	ST-0002	Yes	N2 | N3 | N29 | N35 | N47 | N36 | N31	OEM
OEM-Controlling and Finance	ST-0001	Yes	N6 | N1 | N46	OEM
Passengers	ST-0008	Yes	N16 | N17 | N42 | N28	
Regulation Authority	ST-0009	Yes	N33 | N34 | N11	
OEM Production/Engineering	ST-0010	Yes	N8 | N37 | N38 | N52	OEM
OEM - Technological Development	ST-0011	Yes	N39 | N40	OEM
OEM - Planning	ST-0012	Yes	N5 | N18	OEM
Suppliers Tier II	ST-0004	Yes	N15 | N24 | N27	
Shareholders	ST-0005	Yes	N32	
Funding Agencies	ST-0006	Yes	N41 | N23	

Figure 5.6: Stakeholders collected in a Ke-Chain.

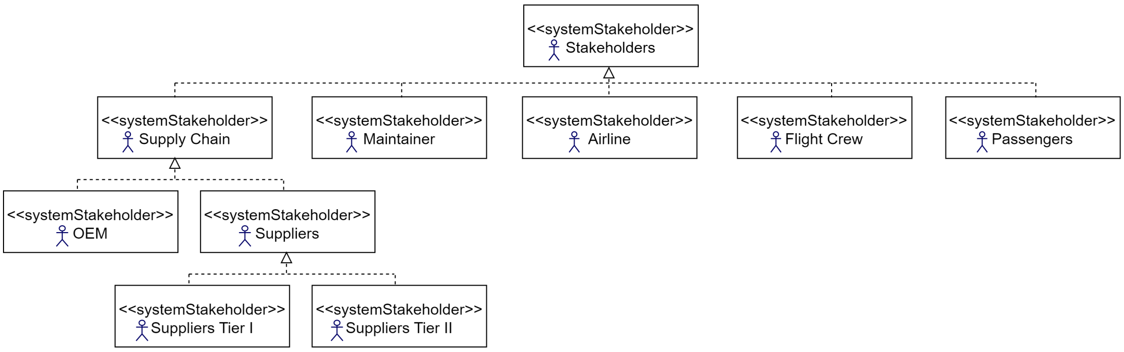


Figure 5.7: Model of Stakeholders involved in the design, manufacturing and production of the horizontal tail plane.

In this Figure 5.7, the focus is on the supply chain stakeholders, thus on the companies involved in the production of the HTP: the Original Equipment Manufacturer (OEM), the supplier tier I and the supplier tier II are supposed to be involved in the supply chain. The OEM is responsible for the production and assembly of the entire aircraft; the supplier tier I for the production and assembly of aircraft components (e.g. the horizontal tail plane); while minor parts are assigned to supplier tier II. For supplier Tier I and Tier II, supplier is assigned as parent stakeholders.

Each of this enterprise has different needs. For instance, the OEM, which provides the final product (aircraft) to the airlines, has interest in selling a large volume of aircraft but also in having a well-produced HTP, especially if outsourced to suppliers. An example concerning the needs of the OEM-Sales department is reported in Figure 5.8. Indeed, it´s an interest of the OEM Sales department to sell a large volume of aircraft, be competitive and increase the client databse as well as sell in dollars to avoid currency exchange issues.

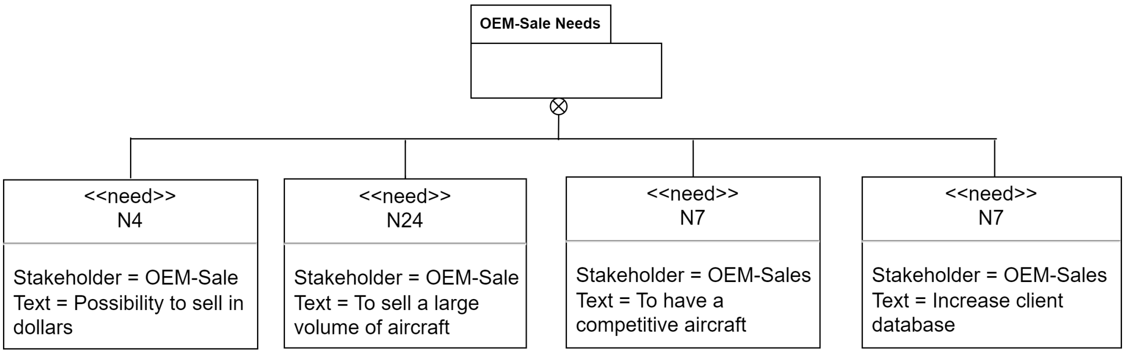


Figure 5.8: Example of OEM-Sales Department´Needs.

5.1.3 System Specification

The second process of the S4S Framework concerns the modelling of the systems requirements. Stakeholders´ needs are converted into requirements, which follow specific modelling rules and patterns to eliminate any ambiguity of interpretation (Section 2.1.1). An example of aircraft requirements modelled in Ke-Chain for this application case is shown in Figure 5.9.

Requirement	ID	Text	Priority	Type
R3	R-0001	The aircraft shall have technologies with maturity TRL 6	Low	Design constraint
R13	R-0002	The aircraft shall take off with the TOFL of maximum 1500 m during the take-off condition flight	Low	Performance
R14	R-0003	The aircraft shall have the design range of 3500 km	Low	Design constraint
R7	R-0004	The aircraft shall have the surface roughness of maximum XX ± XX μm during the entire aircraft life cycle	High	Design constraint

Figure 5.9: Aircraft Requirements collected in Ke-Chain.

Nevertheless, requirements collected for this application case concern also the enabling systems, thus the supply chain and manufacturing. Moreover, one subsystem level for each system is considered: the HTP for the aircraft; the OEM and the suppliers for the supply chain system; the machines for the manufacturing system. The complete model of requirements can be found here [117]. These requirements, collected in Ke-Chain are then visualized in Papyrus. An example of the HTP requirements visualized in a Papyrus diagram is reported in Figure 5.10. These requirements refer to the HTP performance as well as to its cost production.

Requirements, however, are derived from needs. An example showing traceability between needs and requirements, with respect to the example shown in Figure 5.8,

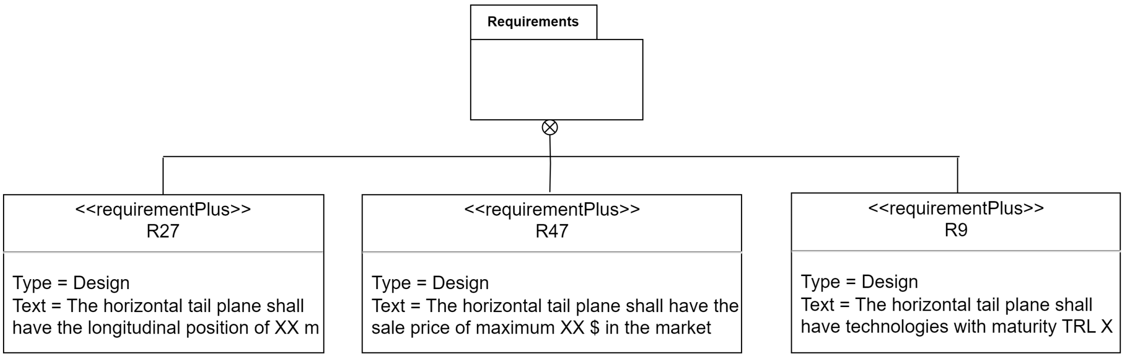


Figure 5.10: Example of Horizontal Tail Plane Requirements.

is reported in Figure 5.11.

The OEM´s need to sell a large volume of aircraft (N24) is translated into a requirement related to the sale price of the aircraft (R80). From this requirement, others can be derived. For instance, the requirement on the sale price of the aircraft impacts the sale price of the aircraft components, thus the sell price of the horizontal tail plane. A requirement on the sale price of the HTP (R47) is derived from the one related to the aircraft. On the other hand, the OEM´s need to have a well-designed HTP (N52) leads to technical HTP requirements related to the design and manufacturing variables, for instance to the quarter-chord sweep angle, HTP mass and reference area (respectively R11, R25, R43). The HTP must be therefore compliant with these requirements. In the example analysed, in which the HTP is outsourced, the supplier tier I is the "responsible stakeholder" in charge of the effective application of these requirements to the product. In case of non-compliance of the HTP with these requirements, several consequences occur. For instance, the HTP noncompliance with the requirements of design, manufacturing and production implies a loss of competitiveness in the market, due to lower aircraft performance or production issues. The consequences are also included in the Papyrus model, as shown in Figure 5.11. Requirements shown in this Figure, follow the rules and the patterns specified in Section 2.1.1. Once specified the main elements of the patterns, the requirement text is automatically generated in Ke-Chain. Then the model is exported and visualized in Papyrus. For instance, the requirement R80 of Figure 5.11 follows the design constraint pattern:

The SYSTEM shall (exhibit) DESIGN CONSTRAINTS (in accordance with PERFORMANCE while in CONDITION)

In this case, the system is the aircraft while the design constraint regards the aircraft sale price. This value must not exceed a prefixed value.

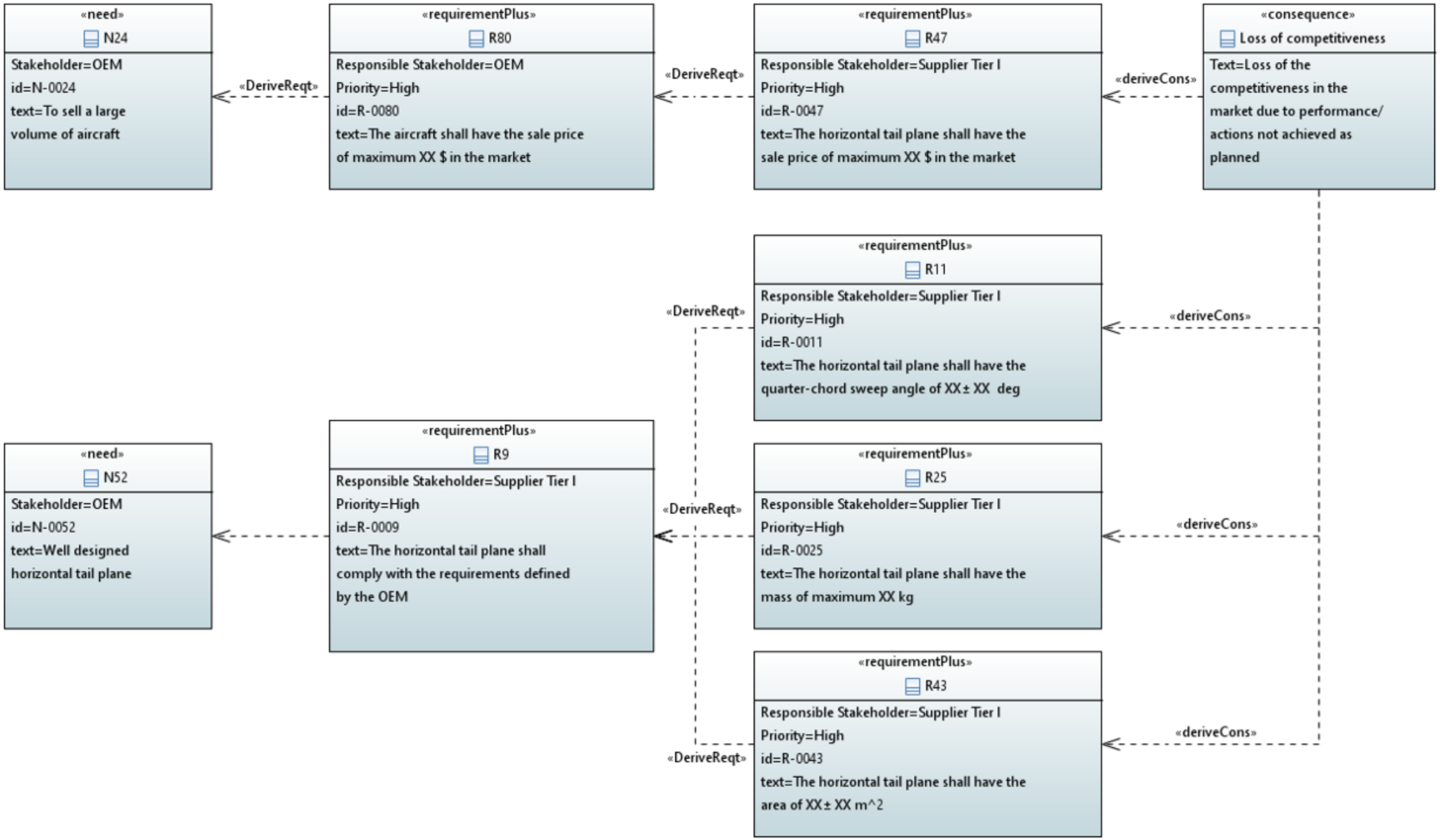


Figure 5.11: OEM´s needs and requirements concerning the supply chain domain (N24) and the manufacturing and design domains (N52).

This sale price is the one that the aircraft must have in the market. The latter is the condition in which the requirement occurs. The requirement pattern view which highlights the key elements of the design constraint requirement pattern is shown in Figure 5.12.

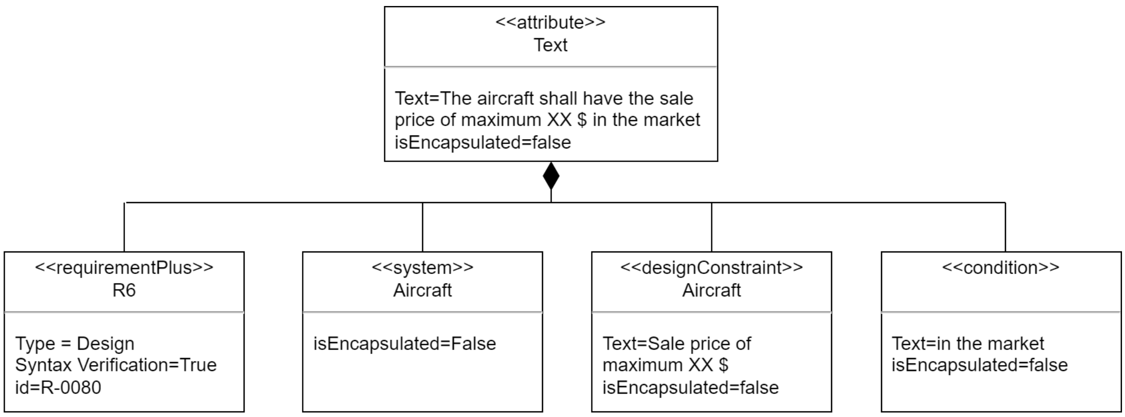


Figure 5.12: Design Constraint Pattern View: sale price as constraint.

In other requirements the system is the supply chain, manufacturing or their components. An example of performance requirement pattern view having the OEM as system is shown in Figure 5.13. The OEM shall sell (function) a certain number of aircraft (performance) in the market (condition).

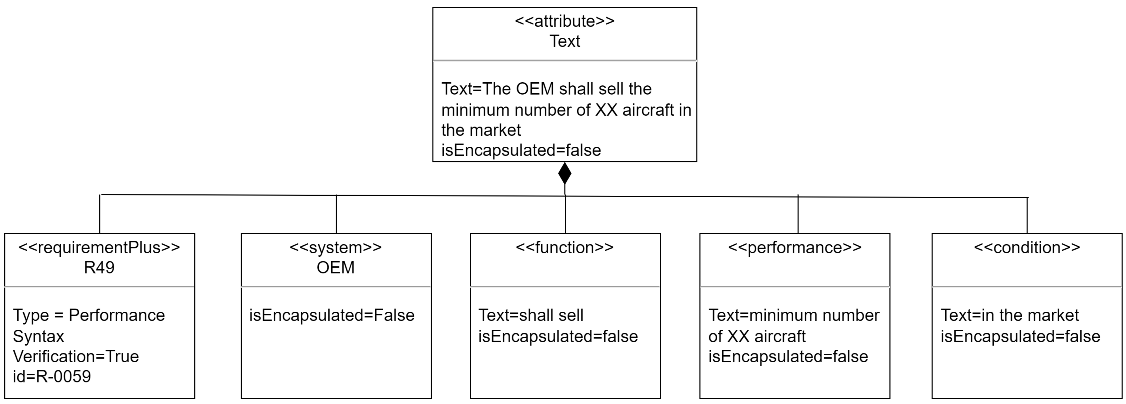


Figure 5.13: Performance Requirement Pattern View: OEM as System.

5.1.4 System Architecting

The third process of the S4S Framework relates with the modelling of the architectural design space and thus with the generation of the architectures. These architectures are modelled in ADORE. To improve readability of the model, a simplified but representative system architecture coupling the three systems of

HTP, manufacturing and supply chain is shown in Figure 5.14. However, the complete model can be found here [117].

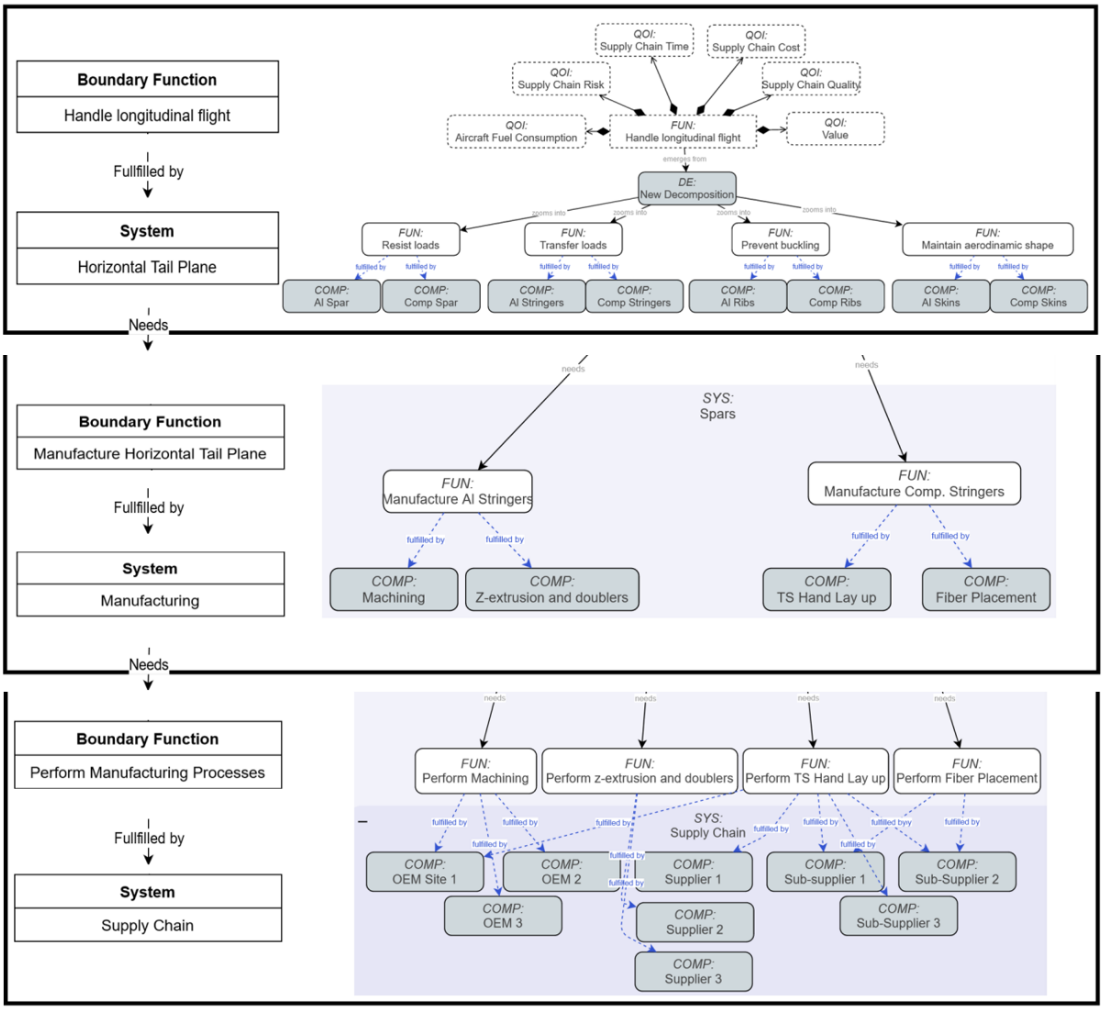


Figure 5.14: Representative architectural design space including Horizontal tail plane, manufacturing and supply chain systems, modelled in ADORE.

In this Figure, it is possible to recognize the boundary functions, defined from requirements, associated to each system. Thus, the horizontal tail plan system has to handle the longitudinal flight, the manufacturing system has to manufacture the horizontal tail plane, while the supply chain system has to perform manufacturing processes. The key aspect of this multi systems architecture modelling is the translation of an induced function of a system in the boundary function of the other one, as explained in Section 3.4.

The architecting process starts with the boundary function "Handle longitudinal flight" fulfilled by the HTP system and particularly by its components: spars, skins, stringers and ribs. In fact, to guarantee the longitudinal flight, the spars have to resist to loads, the stringers to transfer loads, the ribs to prevent the buckling and the skins to maintain the aerodynamic shape. All these functions and components characterize the HTP architecture. Moving down in the complete architecture, the manufacturing system architecture is defined. Each HTP component can be made of different materials, e.g. aluminum, composite, titanium. For each material several manufacturing processes can be selected. An example of manufacturing processes for aluminum is the pressed and stretch formed, for composite is the automatic fiber placement. At the same time, multiple assembly processes can be selected based on the already chosen materials and manufacturing assembly. The assembly processes to use also depends on the components that have to be put together. The manufacturing processes and the assembly processes are identified as the main components of the manufacturing system. Concluding, the manufacturing and assembly processes have to be performed by enterprises having the capability of doing it. These enterprises can be OEM or Suppliers Tier I/Tier II. The different combinations of these enterprises represent the different supply chain architectures. Therefore, the OEM and suppliers are proposed as the main components of the supply chain system.

A zoom on the spar component is reported in Figure 5.15 to better highlight the link between the three systems architecture (HTP, MfG, SC). In ADORE all the components identified for the HTP architecture (spars, stringers, ribs and stringers) are modelled as systems.

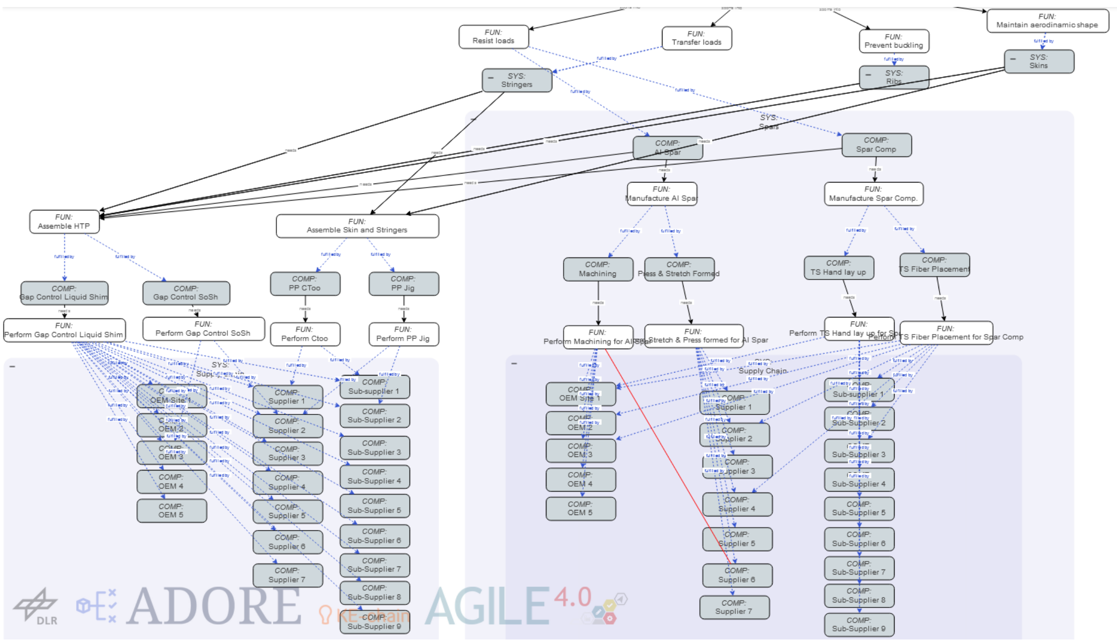


Figure 5.15: Architectural Design Space: Zoom on spars components to highlight the manufacturing and supply chain architectures.

First there is the definition of the components in terms of materials. In the system spars (SYS: spars) there are aluminum spars (Al Spar) and composite spars (Spar Comp). Then, to these components the function “Manufacture Component” is linked. In this specific case, the two functions “manufacture Al Spar” and “manufacture Spar Comp” are added. These functions represent the link between the HTP architecture and the MfG architecture. In fact, to manufacture HTP components are needed the manufacturing processes. Therefore each function “Manufacture component” is fulfilled by the manufacturing processes machining, press and stretch formed, TS Hand Layup, TS Fiber placement, modelled as components. The blue-dotted lines indicate the possibility to make a choice for each component with respect to the different manufacturing processes. The function “Perform manufacturing process” allows to move from the MfG architecture to the SC architecture. Then, for each manufacturing process, different OEM or suppliers can be selected (as shown from the blue-dotted lines). These enterprises, however, must have the capability to perform the selected manufacturing processes. The incompatibility constraint (red line in Figure) can be used to specify that a specific manufacturing process can not be performed by a specific OEM/supplier. The same model illustrated for spars is applied to the other HTP components, thus stringers, skins and ribs. The difference relays in the manufacturing processes that might differ from one component to another one. Modelling the HTP components as systems in ADORE gives the possibility to assign an instance to each system, that is the number of components (systems) characterizing the architecture. For instance, two spars characterize the HTP architecture. Therefore, an instance equal to 2 has been assigned to the spar system in ADORE. This means that all the choices modelled in the system will be taken twice, first for the spar 1 and then for the spar 2. Similarly, it applies to other HTP components, according to Table 5.3. For the assembly processes instead, decision is taken only once, i.e. in the moment that skin and stringers have to be assembled. For this reason, assembly processes are not modelled in ADORE as system (see Figure 5.15).

Once created the architectural design space, then multiple architectures can be generated choosing:

- materials for each HTP component;
- manufacturing and assembly processes for each material and HTP component;
- enterprise, OEM sites and supplier, performing manufacturing processes;
- enterprise, OEM sites and supplier, performing assembly processes.

These architectural choices, related to the aircraft, manufacturing and supply chain systems lead to different aircraft and supply chain performance. Quantities of Interest (QoI) are introduced in the architectural design space to correctly evaluate and formulate the MDO design problems in the later processes of the S4S Framework. These QoIs can be defined as design variables, objectives and constraints of the optimization problems (see Section 2.1.2). Some QoIs representative for this application case are reported in Figure 5.16. These QoIs are set as objective functions of the MDO problems, as explained in Section 5.1.6.

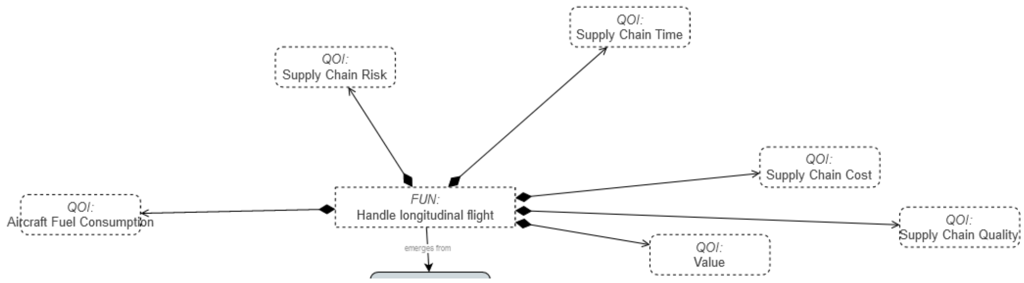


Figure 5.16: Quantities of Interest modelled in ADORE representing the Objective Functions of the MDO Problems.

5.1.5 System Synthesis & Exploration: Concurrent Design Evaluation

The last two processes of the S4S Framework deal with the evaluation, optimization and identification of the best alternative of the architectural design space, generated in the previous process. The focus here is on the application of the methodology introduced in Section 3.5.1 for the evaluation of the value of each architecture, and thus the evaluation of the supply chain and aircraft performance.

The possible choices that can characterize this application case are introduced in Section 5.1. In this case study, however the number of choices is limited to get a simple case to use for validating the methodology. In terms of manufacturing choices, two materials and different manufacturing and assembly processes are combined to achieve 3 HTP configurations, in addition to the reference one (Table 5.3). In Table 5.5, the reference HTP is indicated with the ID1. The other three HTP configurations differ for the choice of materials, manufacturing and assembly processes. In particular, the HTP configurations 1 and 3 are mainly made by aluminium while HTP configuration 2 and 4 mainly by composite. Each HTP configuration exhibits different manufacturing and assembly processes.

Table 5.5: Technology factors (TF) and their impact on the aircraft fuel consumption.

HTP ID	$TF_{Drag}[-]$	$TF_{Weight}[-]$	Fuel Consumption Mass [kg]
1	1	0.85	4837
2	0.70	0.76	4785
3	0.99	0.84	4832
4	0.89	0.78	4783

Once defined the manufacturing properties, a TF is used to quantify the impact that these choices have on the aircraft performance. In the table, two technology factors, indicated as TF_{Drag} and TF_{Weight}, are adopted to quantify the impact that materials, manufacturing and assembly process has on the HTP performance, respectively on drag and weight. The variation in fuel consumption due to these TFs is also reported in Table 5.5. In this way, the impact that manufacturing properties has on the aircraft performance is estimated. However, the manufacturing choices also influence the supply chain performance. As shown in Table 5.6, 21 enterprises are involved in the production of HTP configurations 1 and 2, while 16 for the HTP configurations 3 and 4.

Table 5.6: Supply chain assumptions for the production of the HTP configurations: produced in House (H), Produce in House and Outsources (H & O), Outsourced (O).

HTP ID	Number of Enterprises	Number of Supply Chains	Production Scenario			Means of Transportation
			H	H & O	O	
1,2	21	12	3	5	4	W, Ra, A, Ro
3,4	16	2	1	1	0	W, Ra, Ro

In this first case, enterprises are combined in 12 different ways, thus generating 12 supply chains per HTP configuration 1 and 2. In the second case, enterprises are only combined in 2 supply chains for each HTP configuration 3 and 4. In total 28 supply chains are analysed for the four HTP configurations. These supply chain options belong to different production scenarios depending in which enterprise the HTP components are manufactured and/or assembled. In fact, the same enterprise might have different production sites placed in different part of the world and each enterprise can decide whatever to produce in its own sites or supply to other enterprises. Three production scenarios can be identified:

- In-House (H): the HTP components manufacturing and assembly is performed in one or multiple production sites of the same enterprise;
- In-House and Outsourced (H & O): the HTP components manufacturing and assembly is performed in different sites of the same enterprise but also supplied to other enterprises;

- Outsourced (O): the HTP components manufacturing and assembly is completely supplied to other enterprises.

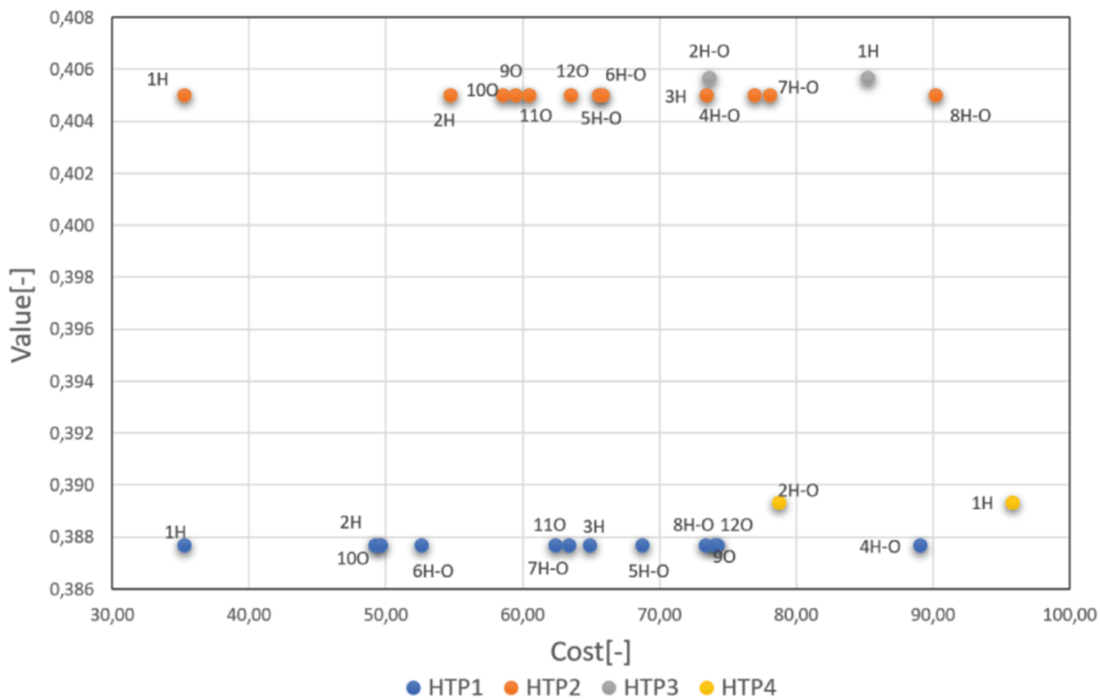
In each production scenario, multiple supply chains are involved, as reported in Table 5.6. For instance, the number of supply chains involved in the production scenario 'House' is three meaning that different production sites of the same enterprise are combined in the three different ways. Finally, the means of transportation are indicated in Table 5.6. As already mentioned, enterprises are spread over the world. Therefore, HTP components have to be moved from enterprises in which they are manufactured to enterprises in which they are assembled. Means of transportation are classified in water, railway, air and road. Depending on the geographic location of the enterprises involved in the supply chains, different means of transportation are used. As shown in Table 5.6, all the means of transportation are involved for the manufacturing and assembly of HTP configuration 1 and 2; air means of transportation are not used in the manufacturing and assembly of HTP configuration 3 and 4. With these assumptions, the supply chain production cost, time, quality and risk are estimated based on equations reported in Table 3.5.1. The supply chain performance and the aircraft performance are finally aggregated in the value with the assumptions of linear utility functions (see Section 5.1.1. Instead, four simple but representative weight combinations are analysed with the objective to also validate the proposed methodology:

- Weight Combination I: fuel consumption has a not-null weight;
- Weight Combination II: time has a not-null weight;
- Weight Combination III: risk has a not-null weigh;
- Weight Combination IV: all the attributes have the same weight.

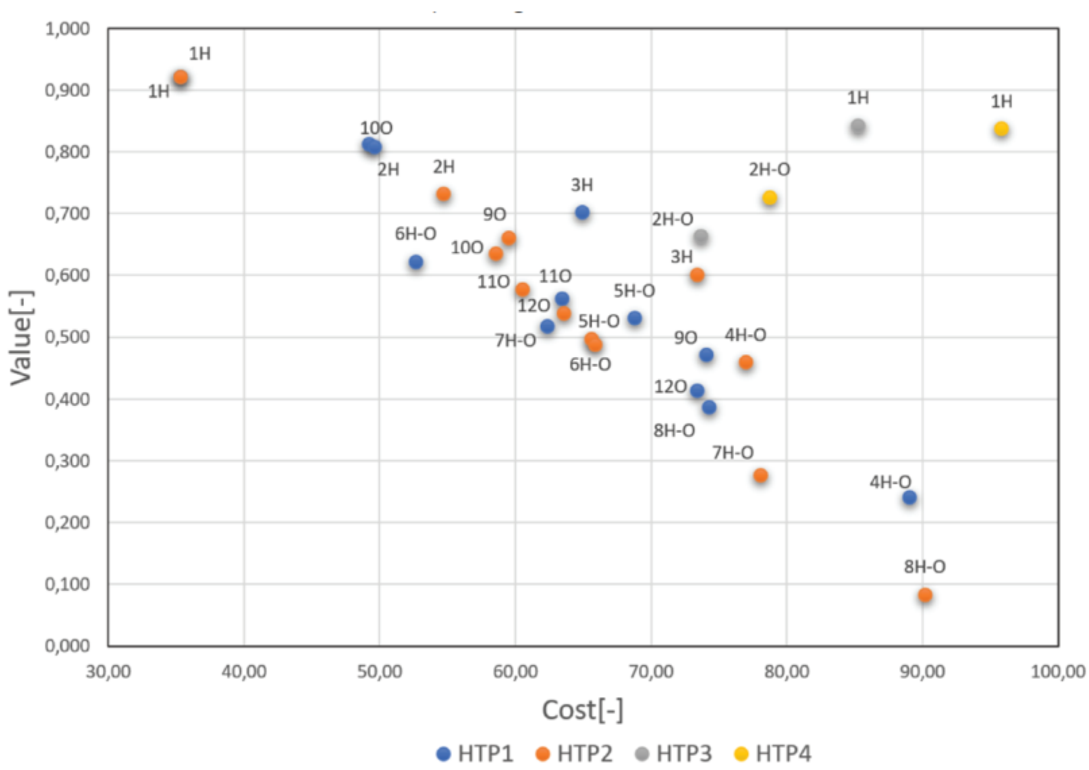
The first three cases address scenarios in which only one criteria have a not-null weight. In this case, the value can be identified with the specific attribute having a not-null weight, thus respectively with the fuel consumption, time and risk. These cases allow to easily verify and validate results since it is expected the value following the same trend as the represented variables. Instead, in the last weight combination, all attributes have the same weight, thus the same importance. Since no priority is applied to attributes, it is expected to achieve intuitively comprehensive results.

The value-cost solutions tradespaces based on these assumptions are shown in Figure 5.17. In each value-driven tradespace, colours refer to different HTP configurations, numbers to supply chains (different for each HTP configuration), letters to production scenarios (In-House: H, In-House and Outsourced: H-O, Outsourced: O).The first tradespace in Figure 5.17a, refers to the weights combination I in which only the fuel consumption has a not-null weight. As expected, the best solution (highest value) is related to HTP 3, which is the one with the lowest fuel consumption (see Table 5.5). In this case, the value follows the fuel consumption trend. In terms of production cost, instead, for both HTP1 and HTP2, the solution 1 H is the one with the lowest cost. The solution 1 H is related to a supply chain in which the production and assembly of all the HTP components are performed at the same enterprise, specifically at the same site. The enterprise involved in the supply chain 1 H of HTP1 is, however, different from the one involved in the supply chain 1 H of HTP2 because of the different competences needed to produce the specific HTP configuration. Nevertheless, in both cases solution 1 H minimizes the production cost, especially the transportation cost, as expected. No other information can be extracted from this tradespace in terms of quality, risk and time since a null weight has been assigned to these attributes.

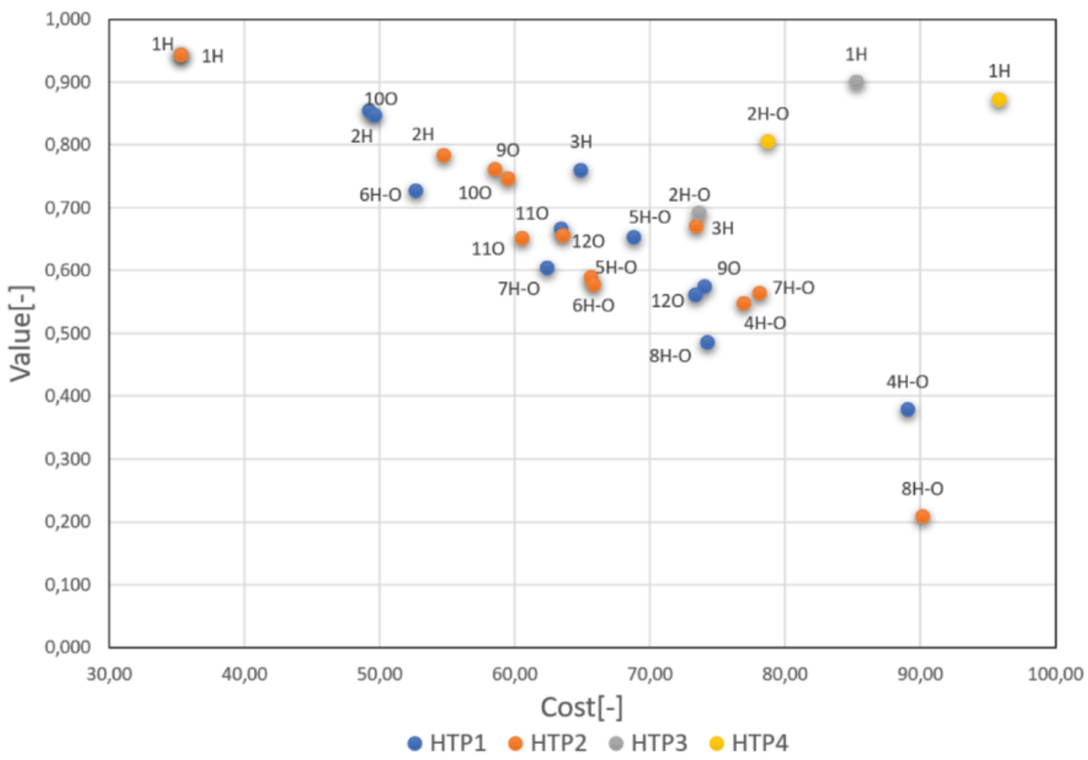
Figures 5.17b and 5.17c instead, represent value-driven design spaces in which solutions only account respectively for time and risk, having all the other criteria a null weights. Thus, in this case, considerations on the aircraft performance cannot be addressed. In both tradespaces, the best solution for each HTP configuration is the alternative 1 H. As mentioned, this solution is related to a supply chain in which the production and assembly of all the HTP components are performed at the same site.



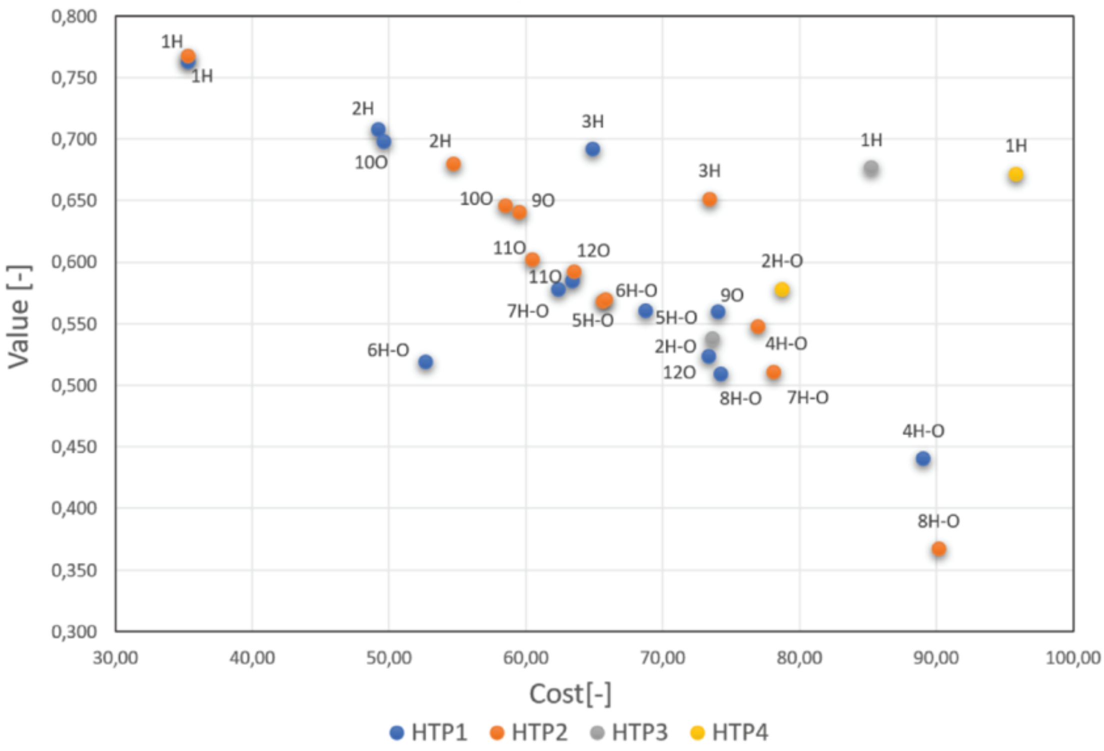
(a) Weight Combination I: fuel consumption has a not-null weigh.



(b) Weight Combination II: time has a not-null weight.



(c) Weight Combination III: risk has a not-null weigh.



(d) Weight Combination IV: all the attributes have the same weight.

Figure 5.17: Value-cost tradespace for different weight combinations: a) Weight Combination I, b) Weight Combination II, c) Weight Combination III, d) Weight Combination IV.

Therefore, this alternative also minimizes production time and risk. Instead, considering all the solutions of the tradespaces in Figures 5.17b and 5.17c, the alternative 1 H of HTP2 turns out to be the best one (highest value). The highest value in this case is related to the enterprises involved in the supply chain 1 H of HTP2 which are different, for instance, from the enterprises involved in the supply chain 1 H of HTP1 (very close in value). In fact, as already explained, enterprises are selected based on the competences, thus on the skills they have in producing the selected materials and processes for the HTP components. Enterprises involved in the supply chain 1 H of HTP2 have higher competences than enterprises selected for the production of other HTP configuration and consequently, lower production time and risk and thus higher value.

Finally, Figure 5.17d shows the valuecost tradespace when the same weight is assigned to all the attributes. In this case, multiple criteria are aggregated in the value, particularly the fuel consumption and the production risk, quality and time. As consequence, the best solution (highest value) is the one representing a good compromise in terms of low risk, time and fuel consumption but high quality, as required from stakeholder through utility functions. In this case, the solution with the best value turns to be again the alternative 1 H of HTP2. However, in this case both aircraft and supply chain performance are involved. As discussed, supply chain 1 H is the one minimizing production cost, risk and time. This could justify the highest value of this solution if fuel consumption was not considered. Instead, also the fuel consumption is aggregated in the value and the HTP2 configuration is not the one with lowest fuel consumption, which is instead the HTP3 (see Table 5.5). Despite that, without any priority in weights, being all the attributes aggregating in the value with the same weight, the best solution (highest value) is still the 1 H of HTP2 because the delta value due to the different fuel consumptions of HTP2 and HTP3 is lower with respect to the delta value generating by the production time, risk and quality. Thus, even if the HTP2 is not the one with lowest fuel consumption, the alternative 1 H-HTP2 is still the one with highest value because of better production time, risk and quality also aggregated in value. Similarly, in the value-cost tradespace of Figure 5.17d, the alternative 1 H of HTP1 has a slight difference in value with respect to the alternative 1 H of HTP2 due to the difference in fuel consumption between the two HTP configurations. In this way, the assessment of production performance is part of the results of the solutions tradespace exploration since the design phase.

5.1.6 System Synthesis & Exploration: Concurrent Optimization

The generated architectures can also be optimized by adding optimization algorithms in the methodology, as explained in Section 3.5.2. Particularly, for each of the described MDO Case, the results of an optimization problem are presented and discussed in this section. For a given MDO Case, in fact, several MDO problems can be investigated by increasing complexity. In the MDO Case I, the number of enterprises involved in the manufacturing and assembly processes can vary. In particular, a higher number of enterprises implies higher number of combinations to investigate and consequently a bigger size of the MDO problems. The size of the MDO problems in the MDO Case I can also increase when considering the production quantity of each HTP component (e.g. stringers) split among several enterprises. In the MDO Case II, instead, the number of materials, manufacturing and assembly processes determine the number of combinations to analyse and thus the size of the MDO problems. Finally, in the MDO Case III, the number of enterprises, materials and processes determine the size of the MDO problems.

In this optimization campaign, several MDO problems of increasing size, have been performed for each MDO Case to define the best optimization strategies, to test the technologies and validate the results. However, only the results of one MDO problem (highest investigated size) for each MDO Case are here discussed. In the next paragraphs, for each MDO Case, the assumptions of the MDO problems are first introduced to indicate the size of the MDO problems. Then, the Pareto front is presented to highlight some interesting trade-off studies that can be addressed. However, for all of the MDO problems, it is assumed that all the enterprises can always produce the amount of components (production quantity) assigned to them. It means that the capacity, i.e. the maximum amount of components that a specific enterprise can produce, is assumed to be not a constraint for all the MDO Cases. These assumptions have been set to limit the size of the investigated problems, which represent a viable proof of concept.

Concurrent Manufacturing and Supply Chain Optimization Problem Results

The aim of this MDO problem is to identify the optimum supply chain to produce a specific HTP configuration. It means that the materials and processes of each HTP component are fixed. These manufacturing properties are specified in Table 5.7. These processes can be performed by several enterprises.

Table 5.7: Manufacturing and supply chain domains: horizontal tail plane manufacturing properties.

HTP	Materials	Manufacturing Processes
Skins	Sheets Metal	Stretch Form
Stringers	Metal	Z-extrusion
Spars	Aluminum	Machining
Ribs	Aluminum and Sheet Metal	Machining and Stretch Form

The QoIs characterizing this MDO problem are reported in Table 3.2. As mentioned, the assembly quantity is fixed. The manufacturing quantity and site as well as the assembly site are the design variables. The number of enterprises that can be selected for the HTP manufacturing and assembly is reported in Table 5.8.

Table 5.8: Manufacturing and supply chain domains: number of enterprises involved in the manufacturing and assembly of the horizontal tail plane.

	Manufacturing Processes				Assembly Phases		
	Skins	Stringers	Spars	Ribs	1	Main	Final
Number of Enterprises	13	10	14	13	4	9	1

The full number of combinations of enterprises, thus of supply chains that can be selected to manufacture the HTP components, represents the size of this MDO problem. It is around 9×10^6 possibilities. This number of combinations is obtained also considering that the manufacturing quantity of the spars is split among enterprises with a percentage of 30% and 70%. Filling Table 3.2 with the information related to this MDO problem, it is possible to identify the total number of design variables and constraints, now summarized in Table 5.9.

The execution of this four-objective optimization problem leads to a multi-objective Pareto front, which is then converted in a 2D Value-driven Pareto front, as explained in Appendix A. The predicted Pareto front is obtained after several hours of optimization process, corresponding to more than 600 remote executions of the DLR workflow.

Table 5.9: Concurrent manufacturing and supply chain domains optimization: MDO problem definition.

	Function/variable	Nature	Quantity	Range
Minimize	Cost	cont	1	
Minimize	Risk	cont	1	
Minimize	Time	cont	1	
Maximize	Quality	cont	1	
	Total objectives		**4**	
with respect to	MfG Quantity - Skins	cat	13 levels	Sites
	MfG Quantity - Spars - 30%	cat	10 levels	Sites
	MfG Quantity - Spars - 70%	cat	10 levels	Sites
	MfG Quantity - Stringers	cat	14 levels	Sites
	MfG Quantity - Ribs	cat	13 levels	Sites
	Assembly Quantity - 1	cat	4 levels	Sites
	Assembly Quantity - Main	cat	9 levels	Sites
	Total categorical variables		6	
	Total relaxed variables		**73**	
subject to	Enterprise Competence		1	
	Total constraints		**1**	

The value-driven Pareto front of this MDO problem is shown in red in Figure 5.18. In this case, the value aggregates the supply chain performance thus the production time, risk and quality.

Three solutions of the Pareto front are analysed due to their importance for decision-makers:

- Solution 1 - Solution with highest value and cost
- Solution 10 - Solution with high value but lower cost
- Solution 3 - Solution with lowest value and cost

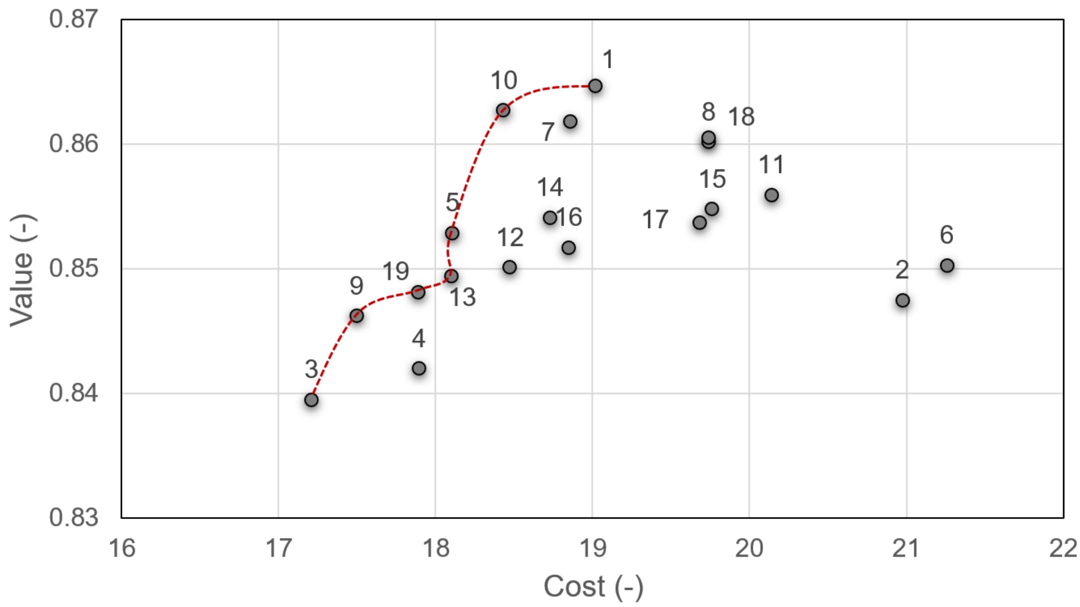


Figure 5.18: Manufacturing and supply chain MDO problem: value-driven Pareto front.

The solution with the highest value, Solution 1, is a supply chain in which the manufacturing and assembly processes of most of the HTP components are produced in house, as shown in Figure 5.19. The same supply chain characterizes Solution 10, meaning that the same enterprises are involved in both supply chains. However, these enterprises are not performing the same processes. Because of the lower competences that enterprises have in executing the assigned manufacturing and assembly processes in supply chain 10, the production time and risk increase while quality decreases. As consequence, the value of Solution 10 is lower than Solution 1. Nevertheless, supply chain 10 has a relatively lower cost than supply chain 1. The motivation still relays on the competences of the enterprises, which impact the manufacturing cost, as well as on the geographic location of these enterprises that lead to different fixed and transportation cost. Both solutions, however, present a higher cost if compared to other solutions like Solution 3. In this case, the manufacturing and assembly of HTP is also outsourced to suppliers. The lower competences and the geographic locations determine high production risk and time with low quality resulting in a low value. The transportation cost is, instead, not high because most of the HTP components are transported by water. This reduces the cost, but increases the risk and time.

Concluding, three different supply chains are analysed for the production of the same horizontal tail plane. Supply chain settings corresponding to Solution 1 is mostly produced in house. In this case, the production risk and time are minimized and the quality is maximized assuring high value. Nevertheless, this supply chain is

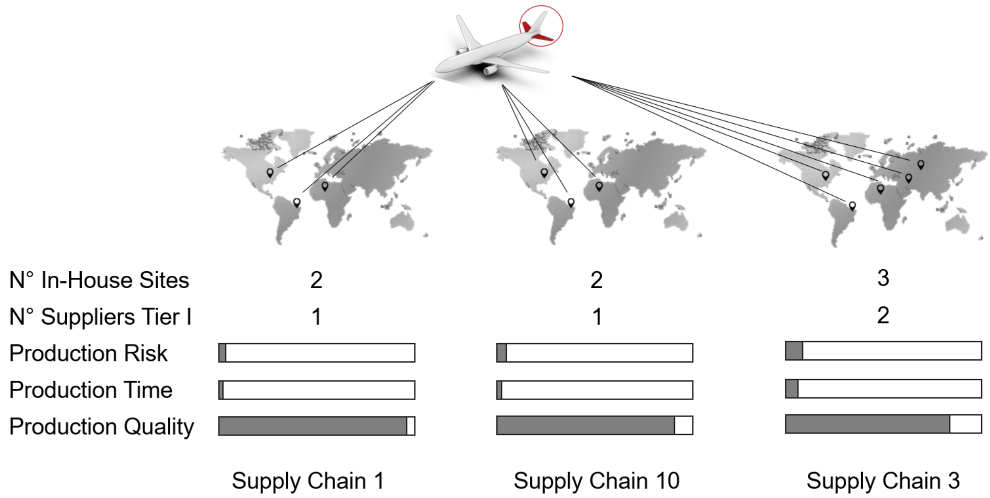


Figure 5.19: Manufacturing and supply chain MDO problem: supply chains details.

quite expensive due to the high fixed and transportation cost. Solution 10 might be a good alternative for decision-makers since the decrease in value is negligible compared to the reduction in cost. In this case, most of the manufacturing and assembly processes are still performed in house and this assures a reasonable level of production time, risk and quality (thus value). Finally, supply chain 3 guarantees the lowest value but the outsource brings some risks in the production which drastically reduces the value of this solution. Depending on the needs of an aeronautical company, decision-makers can take decisions considering all the proposed aspects. So, they can decide if to produce in house or outsource, be more risky or conservative or plan back-up solutions depending on the scenario analysed.

Concurrent Manufacturing and Overall Aircraft Design Optimization Problem Results

The main objective of this MDO problem is to identify the optimum aircraft configuration while changing the materials and processes of the HTP components. The QoIs are specified in Table 3.3. In this case, the enterprises responsible for the manufacturing and assembly of the HTP components are not changing. It is assumed that the same enterprise is performing all the processes. The number of materials and manufacturing processes that can be selected for each HTP component is instead reported in Table 5.10. The main challenge relays in the management of the constraints which are the incompatibilities among materials and processes selected for each component.

The full size of this MDO problem, thus the number of HTP configurations made by considering all the combinations of materials and processes for each HTP

Table 5.10: Manufacturing and overall aircraft design domains: number of materials and processes for each horizontal plane component.

	Horizontal Tail Plane Components			
	Skins	Stringers	Spars	Ribs
Number of Materials and Processes	5	4	4	4

component, is around 600 possibilities. Filling Table 3.3 with the information related to this MDO problem, it is possible to identify the total number of design variables and constraints given in Table 5.11.

Table 5.11: Concurrent manufacturing and aircraft design domains optimization: MDO problem definition.

	Function/variable	Nature	Quantity	Range
Minimize	Fuel Consumption	cont	1	
	Total objectives		**1**	
with respect to	Materials & Processes - Skins	cat	5 levels	Al-Mach., ..
	Materials & Processes - Ribs	cat	4 levels	Al-Mach., ..
	Materials & Processes - Spars	cat	4 levels	Al-Mach., ..
	Materials & Processes - Stringers	cat	4 levels	Al-Mach., ..
	Total categorical variables		6	
	Total relaxed variables		**17**	
subject to	Materials & Processes Incompatibility		1	
	Total constraints		**1**	

The objective is to identify the combination of materials and processes that minimizes the fuel consumption mass. As this problem is a single-objective optimization with a rather limited design space, less than one hour is required to reach the optimum. Nevertheless, it helped formalizing the incompatibility constraints that are also part of the last MDO Case. As expected, the optimum solution, those the combination of materials and processes of the HTP components that minimizes the aircraft fuel consumption mass, is a HTP configuration made by composite, as shown in Figure 5.20.

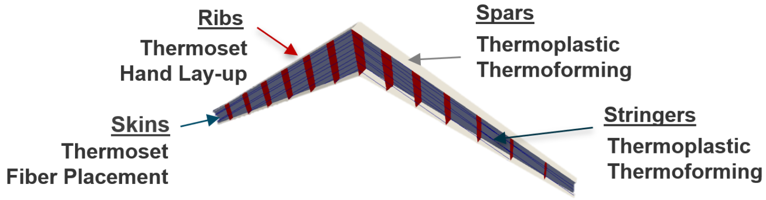


Figure 5.20: Manufacturing and overall aircraft design domains: optimum horizontal tail plane configuration.

Concurrent Manufacturing, Supply Chain and Overall Aircraft Design Optimization Problem Results

In the last MDO Case, the three domains of supply chain, manufacturing and aircraft design are optimized at the same time. The aim is to identify the optimum solution in terms of aircraft design, manufacturing and supply chain. The QoIs of this MDO problem are reported in Table 3.4.

In this case, the number of materials and processes for each HTP component can be selected as well as the enterprises to perform the chosen manufacturing processes. Nevertheless the enterprises performing the assembly processes are fixed. Therefore, for the supply chain domain, the manufacturing quantity and site are the design variables of this MDO problem. The assumptions related to this MDO problem are reported in Table 5.12: 21 enterprises are involved in the manufacturing of the HTP components, while several materials and processes can be selected for each HTP component. The assembly processes, instead, are fixed and, for this reason, not included in the table.

Table 5.12: Manufacturing, aircraft design and supply chain domains: number of enterprises, materials and processes involved in the horizontal tail plane design, manufacturing and supply chain.

	Horizontal Tail Plane Components			
	Skins	Stringers	Spars	Ribs
Number of Materials and Processes	6	4	5	5
Number of Enterprises	21	21	21	21

The full combination of HTP configurations and supply chains, made considering all the choices of materials, processes and enterprises reaches 11×10^6. Filling Table 3.6 with the information related to this MDO problem, it is possible to identify the total number of design variables and constraints reported in Table 5.13.

The execution of this five-objective optimization problem leads to a multi-objective Pareto front, which is then converted in a value-driven Pareto front to simplify the visualization of the results, as explained in Appenidx A.In this case, the value aggregates either the supply chain performance thus the production time, risk and quality and the aircraft performance, thus the fuel consumption mass of the aircraft in cruise. In order to obtain the predicted Pareto-front, the optimization problem required more than 700 evaluations leading to a computational time higher than half-day. In this case, a single optimal solution exists on the tradespace, as shown in Figure 5.21.

Table 5.13: Concurrent manufacturing, supply chain and aircraft design domains optimization: MDO problem definition.

	Function/variable	Nature	Quantity	Range
Minimize	Cost	cont	1	
Minimize	Risk	cont	1	
Minimize	Time	cont	1	
Maximize	Quality	cont	1	
Minimize	Fuel Consumption Mass	cont	1	
	Total objectives		**5**	
with respect to	MfG Quantity - Skins	cat	21 levels	Sites
	MfG Quantity - Spars	cat	21 levels	Sites
	MfG Quantity - Stringers	cat	21 levels	Sites
	MfG Quantity - Ribs	cat	21 levels	Sites
	Materials & Processes - Skins	cat	6 levels	Alu-Mach., ..
	Materials & Processes - Ribs	cat	5 levels	Alu-Mach., ..
	Materials & Processes - Spars	cat	5 levels	Alu-Mach., ..
	Materials & Processes - Stringers	cat	4 levels	Alu-Mach., ..
	Total categorical variables		8	
	Total relaxed variables		**104**	
subject to	Materials & Processes Incompatibility		1	
	Enterprise Competences		1	
	Total constraints		**2**	

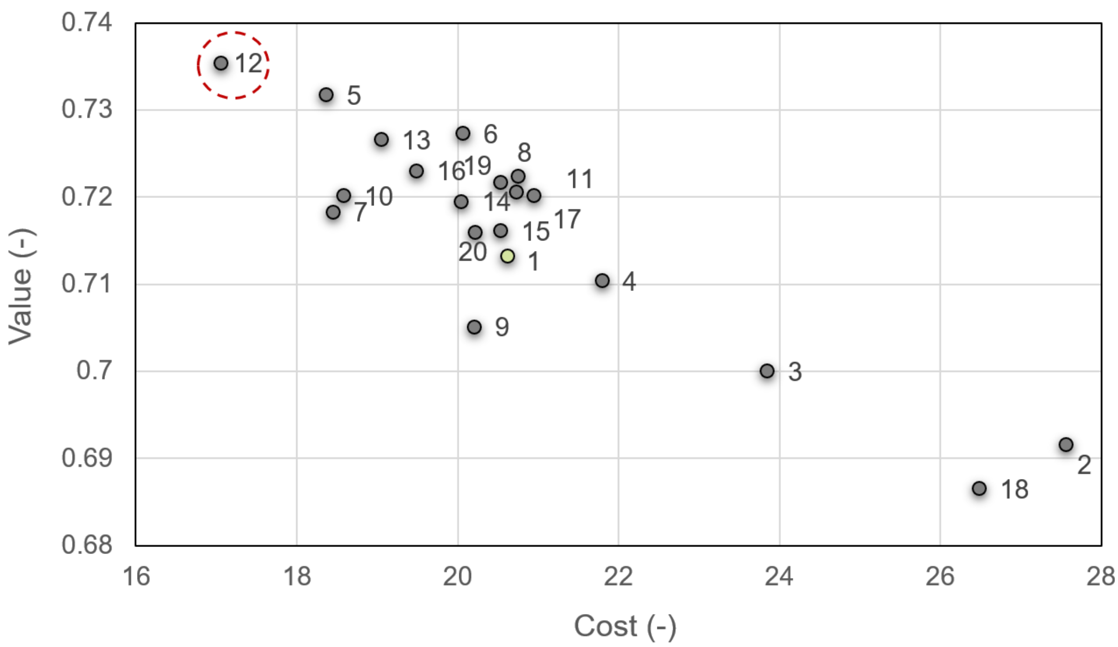


Figure 5.21: Manufacturing, supply chain and aircraft design MDO problem: global optimum (red circle) and solution minimizing the fuel consumption mass (green point).

The optimal solution, i.e. the alternative 12, represents the optimal compromise between the production and aircraft performance. The HTP configuration characterizing this alternative, in fact, is not the one minimizing the fuel consumption mass (see Figure 5.20). However, the high competences of the enterprise responsible for the production of this HTP configuration make this solution the global optimum (highest value). In addition, the HTP of the alternative 12 is completely made in house. This reduces the production risk and time and guarantees a high level of quality. The optimal solution in terms of aircraft performance minimizing the fuel consumption mass is instead the alternative 1 (green point in Figure 5.21). The HTP configuration behind this alternative is the one identified in the previous MDO Case, as expected (see Figure 5.20). However, the value of this solution is not so high because of the production performance. In this case, the supply chain involves OEM and suppliers. The outsource of some HTP components increases the risk and the time despite the high competences of the suppliers involved. As consequence, in this application case, the most efficient aircraft configuration (solution 1 - minimum fuel consumption) does not match with the optimal solution (solution 12). This also demonstrates the importance of considering at the same time aircraft and supply chain performance. Furthermore, the methodology might be leveraged to investigate on the improvements needed to make solution 1 more competitive (improve supply chain performance) or solution 12 more efficient (improve aircraft performance).

Concluding, in this specific application case, only one solution is optimal and a value-driven Pareto front does not exist. It means that, in this case, it is not possible to perform trade-off studies with the production cost. However, this also depends on the settings defined to estimated the value. As explained in Section 3.5.1, linear functions and same weights are assigned to the aircraft and supply chain performance to guarantee the robustness of the analytical solutions. However, the value-model theory is traditionally used to also include decision-makers´ expectations in the design space while changing the weights and utility functions. With different value settings, the value of the alternatives on the design space change and a value-driven Pareto front might be identified, as explained in the next section.

5.1.7 System Synthesis & Exploration: Decision-making

In the previous sections, the solution with the highest value is identified and several trade-off studies are performed in terms of value and cost. The solution with highest value, however, might be not the best solution for decision-makers since their expectations have been not implemented so far. The aim of this section is to identify the best solution, meant as the architecture well matching decision-makers´preferences with respect to the identified criteria of production time, risk, quality and fuel consumption. Production cost, as already mentioned, is used as other independent variable for the value-cost tradepsace exploration.

For each of these criteria, decision-makers have different expectations. For instance, they might prefer alternatives with low production risk but high quality. The qualitative decision-makers' expectations with respect to these criteria are summarized in Table 5.14. As expected, the best solution is supposed to be the alternative with lowest production risk, time and fuel consumption but highest production quality.

Table 5.14: Decision-maker´expectations.

Attribute	Decision-makers´Expecations
Production Risk	Lower the better
Production Time	Lower the better
Production Quality	Higher the better
Fuel Consumption Mass	Lower the better

These qualitative expectations are translated into utility functions. As mentioned, several ways can be used to define the utility functions. However interactive tools in which decision-makers can directly draw the utility functions guarantee a better accuracy in the representation of the qualitative preferences. For this reason, VALORISE has been used to support decision-makers in easily represent their own utility functions.

The case study analysed in this section is the same addressed in Section 5.1.6, meaning that the same assumptions are assumed. The valu-driven Pareto front shown in Figure 5.21 is therefore assumed as Reference Case since based on the assumptions of same weights for all the attributes and linear utility functions. The objective of this application case is to identify, among these optimal solutions, the best solution for decision-makers by trading, at the same time, their expectations with respect to the supply chain and aircraft performance. To consider these decision-makers´expectations, utility functions provided by the industrial partners involved in this application are considered. These utility functions, identified as Decision-maker A and Decision-maker B, are reported in Figure 5.22.

As shown in Table 5.14, the qualitative expectations are the same for both decision-makers. Instead, looking at Figure 5.22, the quantitative representation of such expectations (utility functions, red curves) differ for each decision-maker being different the way they would take decisions. For instance, referring to the time utility functions, the willingness of Decision-Maker A to accept a solution with low production time is lower than the one of Decision-Maker B. In fact,

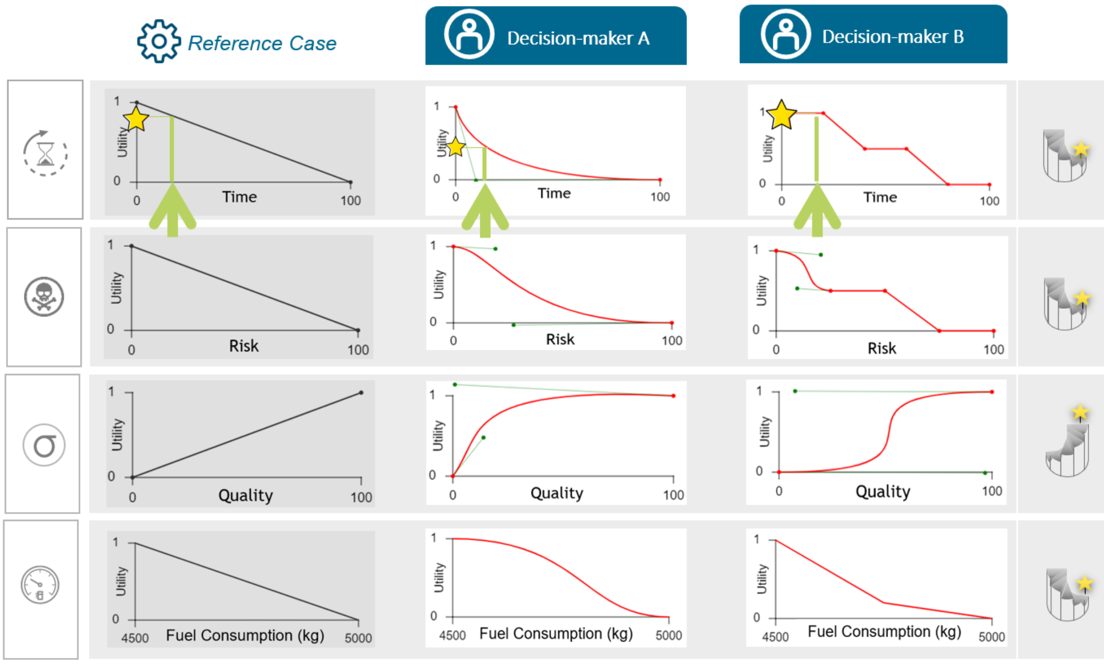


Figure 5.22: Single Attribute Utility Functions quantifying Decision-makers´expectations, made in VALORISE.

the utility associated to this alternative is different for each decision-maker, as shown by the yellow star in Figure 2. Utility functions therefore represent the way decision-makers would take decisions while considering each attribute. The use of the utility functions simplifies the multi-criteria decision-making process since decision-makers can model their expectations for each attribute without considering all of them at the same time. The aggregation is then done in the value estimation when also a weight is assigned to each attribute. Indeed, once defined the utility functions, decision-makers can investigate several scenarios in which attributes are prioritized in different ways by changing the weight combinations. In particular, three cases studies are investigated. In the first case study, the same weight is assigned to all the attributes (0.25) since the aim is to identify the best solution for decision-makers without prioritizing any of the attributes. Then, for completeness, also two case studies related to two different weight combinations are introduced while considering the Decision-maker A and Decision-maker B utility functions. For the Decision-maker A, the weight combination in which time has a weight null is investigated. Instead, for Decision-maker B, the weight combination in which risk has a weight null is presented. In both cases, many other scenarios of interest for decision-makers can be investigated and other trade-off studies performed, e.g. robust vs. best solution as explained in Section 5.1.8. The aim of these three case studies is to show how the value-driven tradespace can change according to decision-makers´priorities and needs.

Case Study I

The value-driven tradespaces generated by implementing the utility functions reported in Figure 5.22 and the same weights for all the attributes are reported in Figure 5.23.

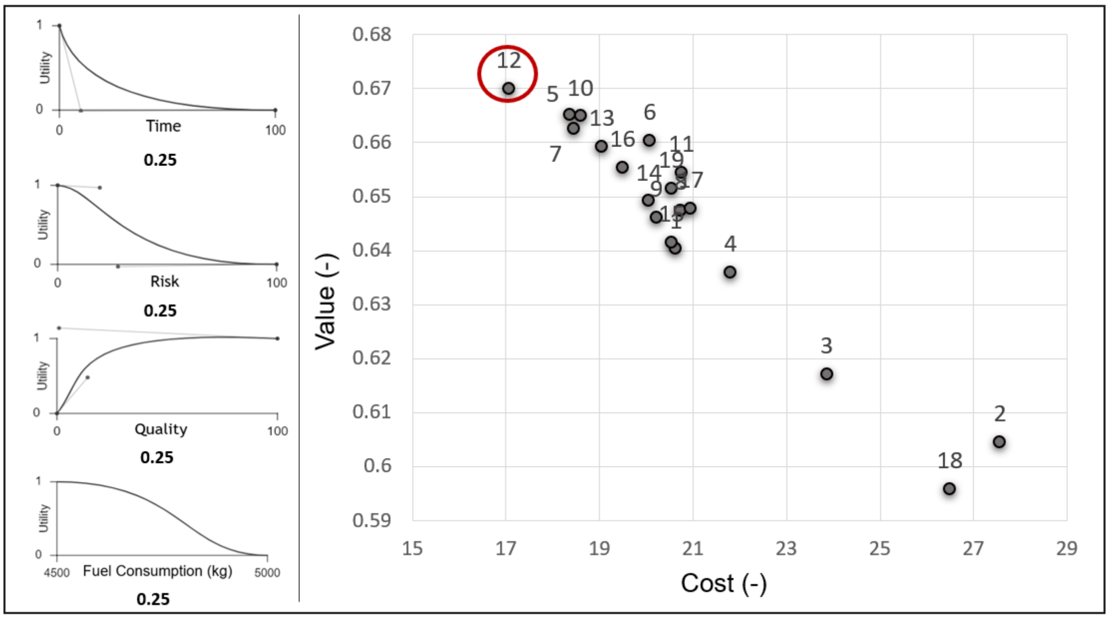
These figures respectively represent the value-driven tradespace influenced by Decision-maker A and the value-driven tradespace influenced by Decision-maker B. Each solution of these value-driven tradespaces correspond to a specific HTP configuration (specific materials and processes) and production scenarios (components made in house or outsourced). The best solution, that is the one with the highest value, is the alternative 12 for all the three cases. Therefore, despite the different way of taking decisions with respect to the single attribute (different utility functions), the best solution remains the same. As explained in Section 5.1.6, this solution is not the one minimizing the fuel consumption. However, all the manufacturing and assembly processes are performed in house, at one site, making this solution extremely competitive when considering the supply chain performance, thus the production risk, time and quality. These details can be also seen in Figure 5.25 and Figure 5.27, in which a comparison with other solutions is provided due to the analysis related to the weight combinations.

Thus, solution 12, which represents a quite efficient but extremely competitive aircraft, is the best one when considering both production and aircraft performance at the same without prioritizing any of these attributes.

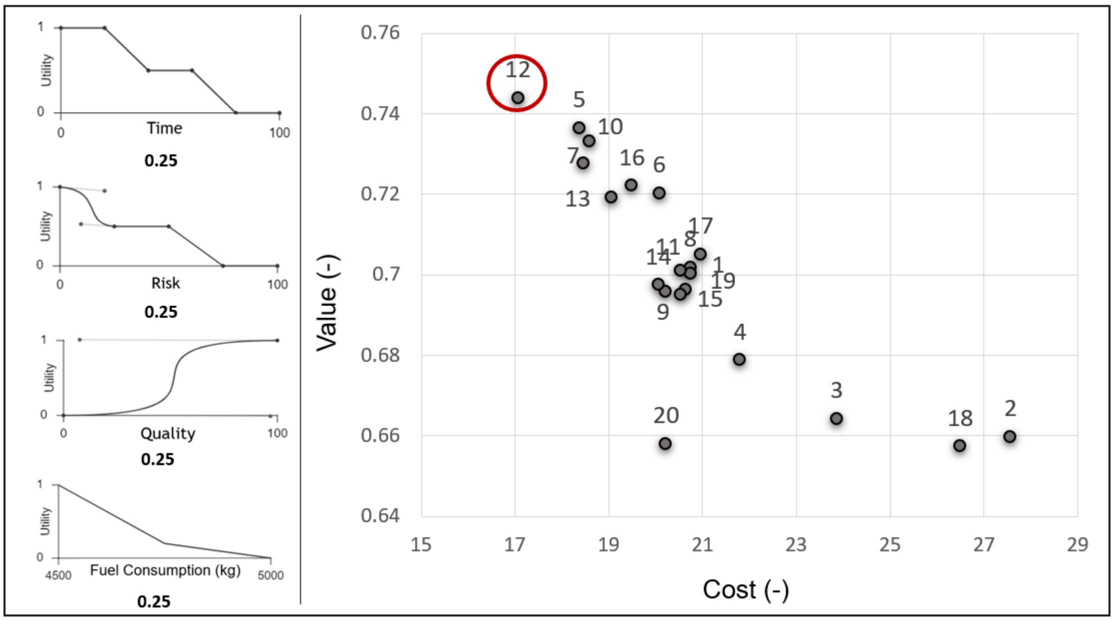
Case Study II

The Case Study II is the one implementing Decision-maker A utility functions and a weight combination in which time has a weight null. This scenario corresponds to a case study in which the decision-maker decides to not consider time as attribute. In other words, the decision-maker decides to investigate which is the best solution if time is not considered anymore as criteria influencing decisions. Figure 5.24 shows the value-driven tradespace representative of this case study. The red line, that is the value-cost Pareto Front, highlights as best alternative the solution 10 and not the solution 12 as in the previous case.

A detailed comparison between the two solutions is reported in 5.25. The location of the enterprises is qualitative and not reflecting reality due to industrial intellectual properties. The colors of the materials, manufacturing and world icons are instead



(a) Decision-maker A.



(b) Decision-maker B.

Figure 5.23: Value-cost tradespace implementing Decision-makers´utility functions: a) Decision-maker A, b) Decision-maker B.

gray since there are not similarities among these two solutions. In the other cases, same colors would have been applied. Solution 10 is characterized by an HTP configuration mainly made by composite. As consequence, the fuel consumption characterizing this aircraft configuration is lower than the one related to solution 10.

Therefore, from the aircraft design perspective, this solution is more efficient than solution 10. However, the aircraft configuration provided by solution 10 is less

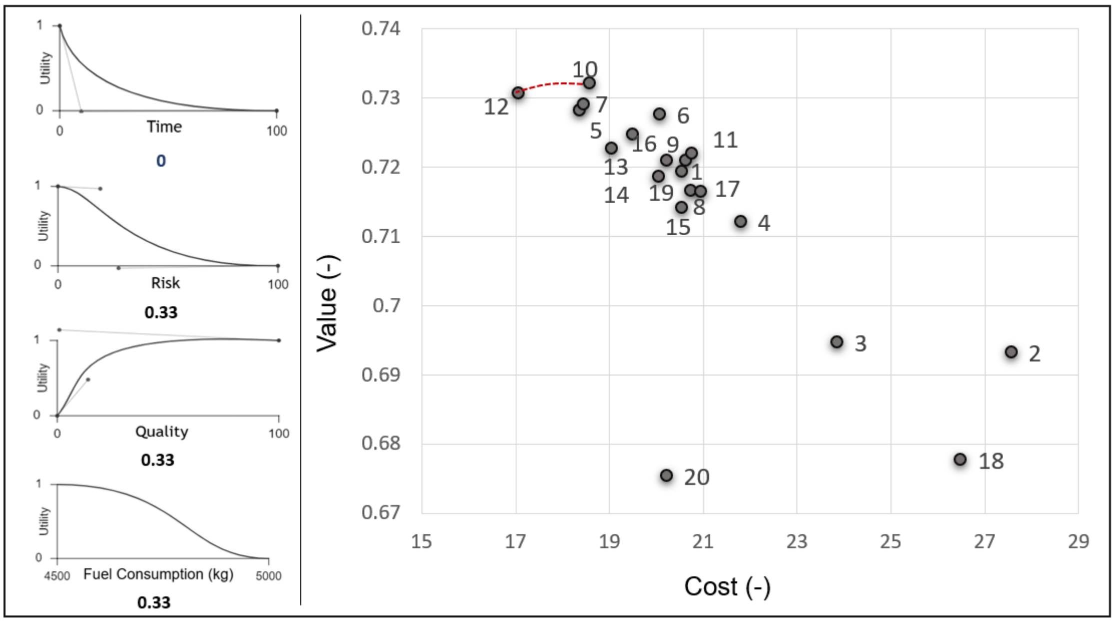


Figure 5.24: Decision-maker A Value-driven Tradespace Exploration when Time Weight is Null.

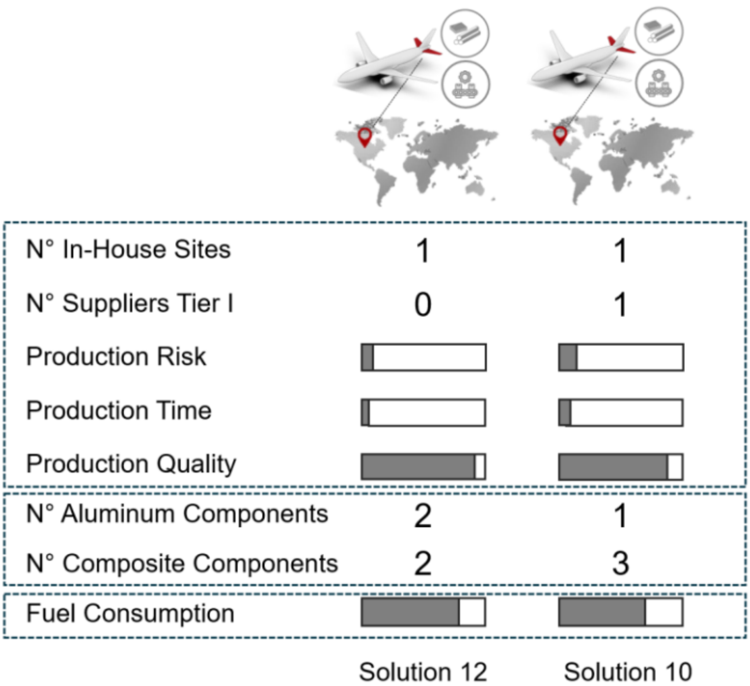


Figure 5.25: Decision-maker A Value-driven Tradespace Exploration when Time Weight is Null: Comparison between the Pareto Front Solutions. Location of enterprises is qualitative due to industrial intellectual properties.

competitive than the one guaranteed by solution 12. For solution 10, in fact, some of the HTP components are produced in house while others are outsourced to suppliers.

This has an impact of the production performance. In particular, the production risk, time and cost increases while the production quality decreases. In the previous case (same weights to attributes), solution 10 does not appear as best solution because the worse supply chain performance wins against the better aircraft performance. But, when time is not anymore considered as attribute, then the positive impact of the lower fuel consumption on the value is greater than the worse supply chain performance. In this case study, however, the decision-maker can perform a trade-off study among solution 10 and 12 and decide if to pay more for a more valuable solution or penalize a bit the performance for a more competitive aircraft.

Case Study III

The last case study is the one implementing Decision-maker B utility functions and a weight combination in which risk has a weight null. This scenario corresponds to a case study in which the decision-maker decides to not consider risk as attribute. In other words, the decision-maker decides to investigate which is the best solution if risk is not considered anymore as criteria influencing decisions. Figure 5.26 shows the value-driven tradespace representative of this case study.

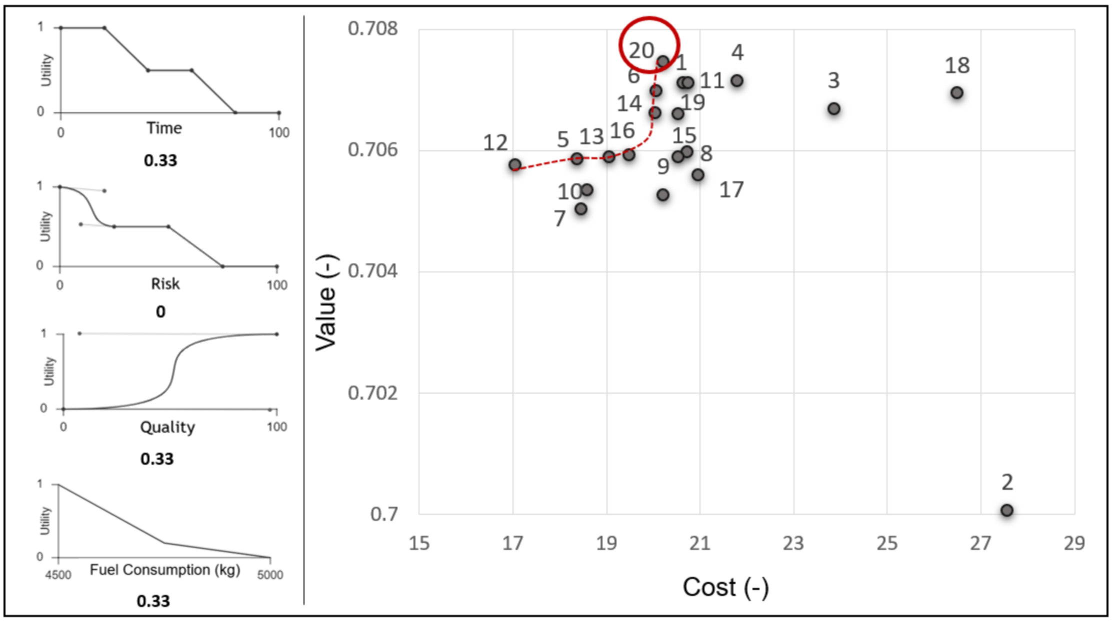


Figure 5.26: Decision-maker B Value-driven Tradespace Exploration when Risk Weight is Null.

The red line, that is the value-cost Pareto Front, highlights as best alterative the solution 20 and not the solution 12 as in the first case. A detailed comparison among the solutions of the value-cost Pareto Front is reported in Figure 5.27. The location of the enterprises is qualitative and not reflecting reality due to industrial intellectual properties. The same colors of the materials, manufacturing and world icons highlight the similarities among solutions. For instance, solutions 12 and 5 have the same supply chains while solutions 12 and 16 share the same materials but not manufacturing processes for the main HTP components.

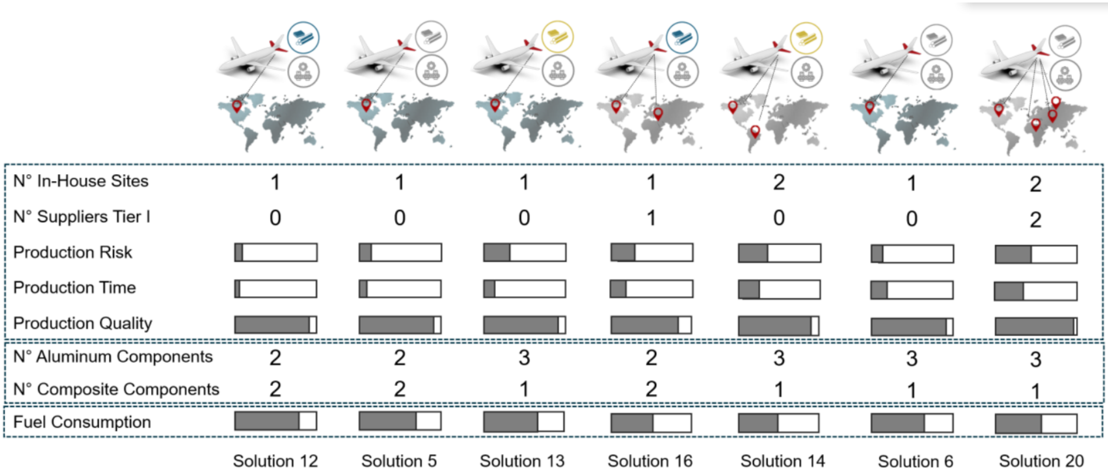


Figure 5.27: Decision-maker B Value-driven Tradespace Exploration when Risk Weight is Null: Comparison between the Pareto Front Solutions. Location of enterprises is qualitative due to industrial intellectual properties. Same colors of materials, manufacturing and world icons highlight the similarities among solution.

As shown in Figure 5.26, solution 12 is the one with the lowest risk and highest fuel consumption. When assigning a null weight to risk, the value of this solution drastically decreases while the value of all the other ones increases. For this reason, the value-cost Pareto Front is now composed by many alternatives. In particular, the best alternative, i.e. the one with the highest value, is solution 20. This solution is characterized by an HTP configuration made mainly in composite. The aircraft configuration characterizing this solution is therefore more performant than the one characterizing solution 12. Because of lower fuel consumption and the highest quality, solution 20 has a value higher than solution 12. However, the most performant aircraft configuration among all the solutions of the Pareto Front is solution 6. This solution has a lower value than solution 20 because of the lower production quality. Nevertheless, the HTP of solution 6 is made in house at one site while the HTP of solution 20 is partially made in house and partially outsourced with a consequent increase in time and risk. In this case, decision-makers can perform make or buy trade-off studies and decide if to risk more supplying some components to get higher quality or produce everything in house for a lower cost. The final decision will be always on decision-makers.

5.1.8 System Synthesis & Exploration: Uncertainty Propagation

The best solution on the value-driven Pareto front is identified in the previous section. The case study also showed that the value of solutions vary when changing the weights and/or utility functions. In this section, the aim is to analyse the behaviour of solutions in terms of value to increase decision-makers´awareness when taking decisions. The ambition is to introduce uncertainty in the weights and single attribute utility functions to give decision-makers insights on the behavior of the alternatives populating the value-driven tradespace, as explained in Section 3.5.3. For each of the case study, the robust and flexible solutions are identified. The possible choices of materials, manufacturing and enterprises are shown in Table 5.15. The assembly processes are instead fixed.

Table 5.15: Uncertainty Propagation Case Study Assumptions.

Components	Materials	Manufacturing Processes	Enterprises
Skins	2	3	3
Stringers	3	3	3
Spars	2	3	3
Ribs	3	3	2

Among the enterprises, there is one OEM site and two suppliers. Combining all the choices, 6765 alternatives can be generated. However, only 1891 are feasible solutions because of some manufacturing and production constraints. Before introducing uncertainty, however, the value-driven Reference Pareto front, shown in Figure 5.28 is obtained with the assumptions of same weights and linear utility functions.

Among the six alternatives populating the value-driven Reference Pareto-front, the best solution that is the solution with highest value, is solution 23. Details in terms of supply chain and HTP configurations characterizing the solutions of the Reference Pareto-front are shown in Figure 5.29. The same colors of icons mean that solutions share the same information in terms of materials and/or processes and/or supply chains.

The alternatives 9,12 and 15 are characterized by the same HTP configuration. For this reason, these solutions have the same fuel consumption mass. However, the value associated to them is different because of the supply chain performance. In particular, solutions 9 and 12 have a lower value since some of the HTP components are outsourced to suppliers and not produced in house. This leads to higher risk and lower quality with a consequent decrease of value. The alternative 23, 24 and 26

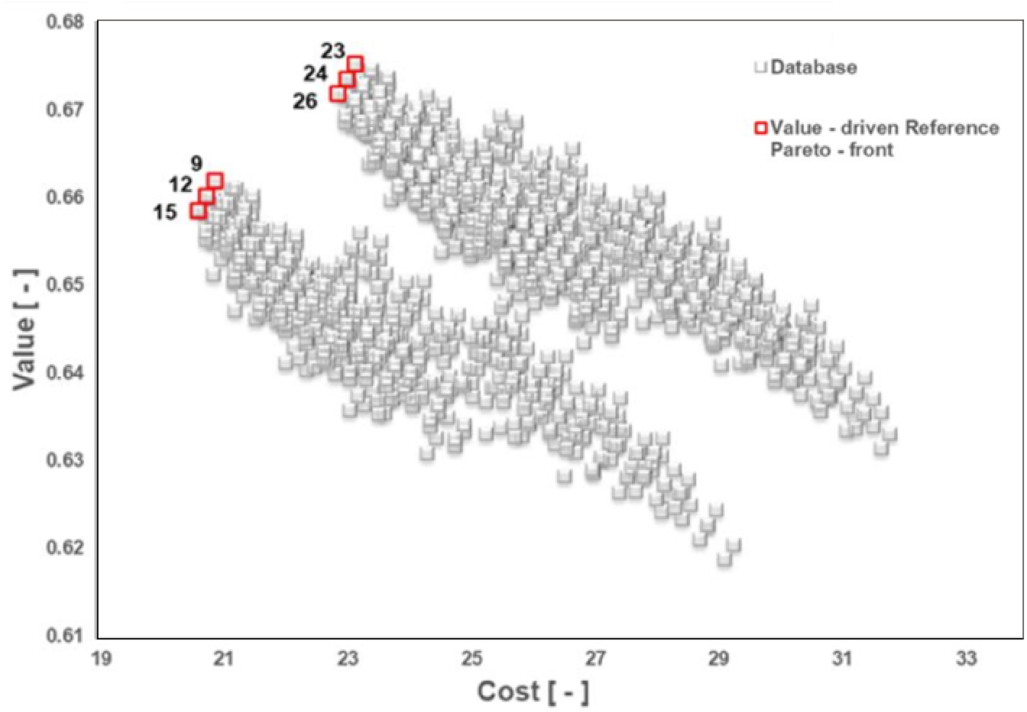


Figure 5.28: Value-driven Reference Pareto front for uncertainty propagation analysis.

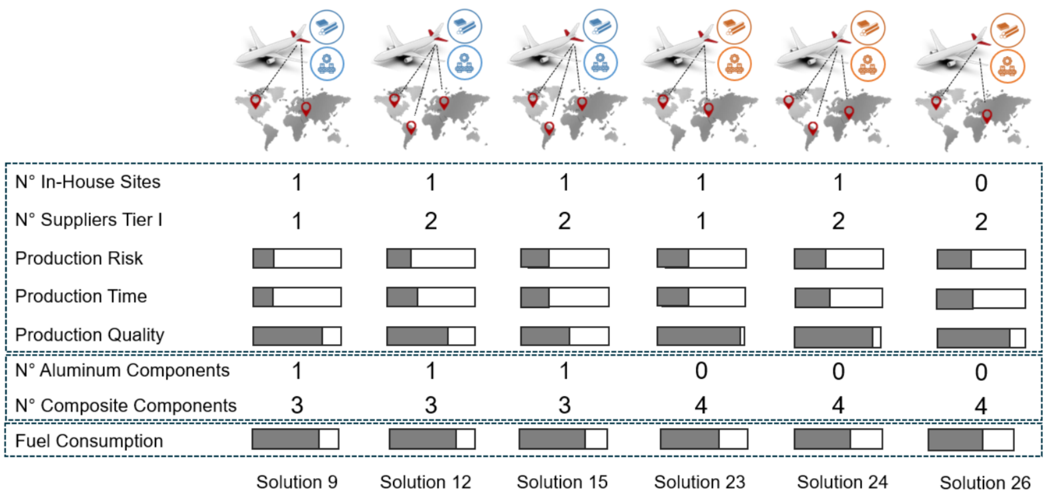
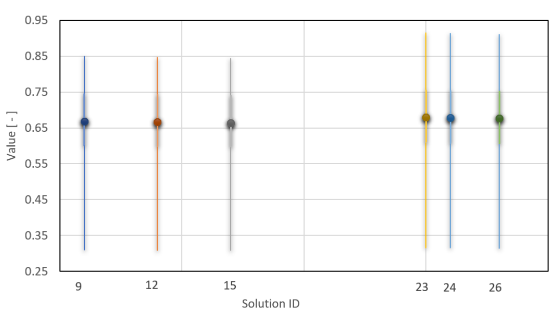


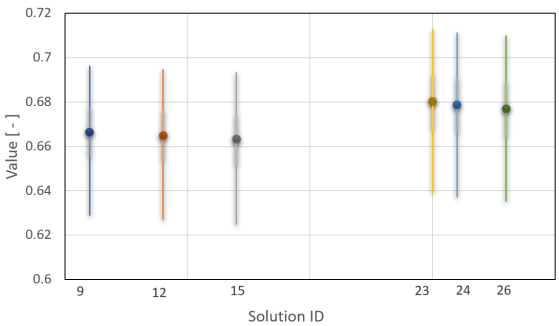
Figure 5.29: Details of the Alternatives populating the Value-driven Reference Pareto-front, Uncertainty Case Study.

instead are characterized by the same HTP configuration which differ from the one related to the other three solutions for the materials and processes used for the ribs. This HTP is made only by composite. This difference implies a lower fuel mass and therefore a higher value. In addition, the competences of the enterprises involved in the manufacturing of these HTP configurations are high. As consequence, the value of these solutions is higher than the value of others. Finally, among them, solution 23 has the highest value since mostly produced in house.

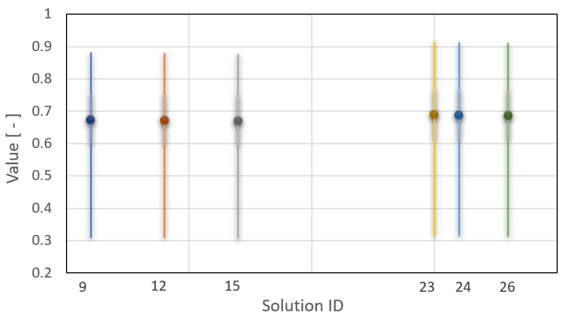
Uncertainty is then propagated to the value through weights or/and utility functions to analyse the behaviour of the Reference Pareto front solutions and identify which of them is robust and flexible. The results The results of the three case studies discussed in Section 3.5.3 are reported in Figure 5.30. In particular, in this Figure, the value oscillation of the solutions populating the Reference Pareto-front is shown. The value oscillation represents the range in which the value of the specific solution can vary. Lower is the oscillation, better is the solution for decision-makers since its variability with the scenario is low. As consequence, the robustness of this solution increases.



(a) Alternative 12 as Robust Solution.



(b) Alternative 9 as Robust Solution.



(c) Alternative 15 as Robust Solution.

Figure 5.30: Value Oscillations: Robust Solutions Identification: a) Case Study I, b) Case Study II, c) Case Study III.

The results in Figure 5.30 highlight that in the Case Study I, in which a uniform distribution is used to propagate uncertainty on the value through the weights, the alternative minimizing the value oscillation is solution 12. Instead, in the Case Study II, in which a uniform distribution is used to propagate uncertainty on the value through utility functions, the alternative 9 is the robust solution. Finally, in the Case Study III, in which a uniform distribution is used to propagate uncertainty on the value through the weights and utility functions, the alternative 15 is identified as robust solution. In addition, the gray boxes in Figure 5.30 highlights the 0.25 and 0.75 percentiles for each alternative. They show where most of solutions are located in terms of value when considering all the combinations per each case study. Indeed, the variation in value for the alternatives 12, 9 and 15 are the smallest in each case study. The same results, more in details, are reported in Table 5.16. Indeed, the minimum variation in terms of value is provided by the solutions 12, 9 and 15 respectively in the Case Study I, II and III.

Table 5.16: Numerical Value Oscillation of the Refence Pareto-front solutions for the three Cases Studies.

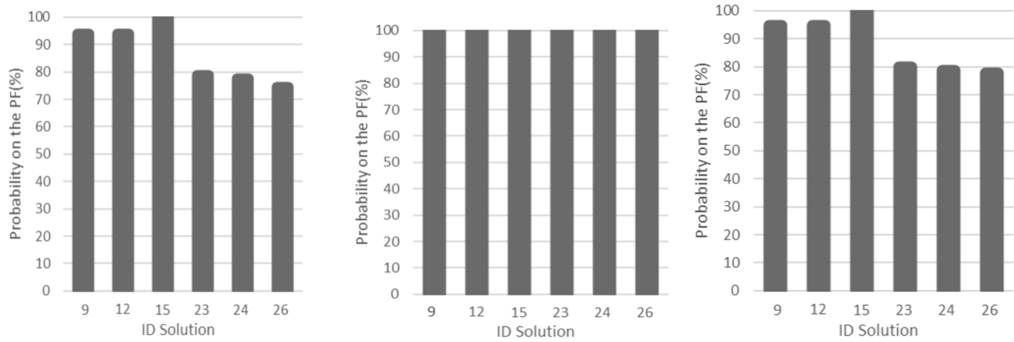
	Case Study	Solution ID					
		9	12	15	23	24	26
Δ Value	I	0.563	**0.562**	0.567	0.630	0.628	0.626
	II	**0.067**	0.067	0.068	0.073	0.074	0.074
	III	0.570	0.569	**0.568**	0.598	0.596	0.594

The Table also highlights how the solutions with highest value in the Reference Pareto-front, thus the alternatives 23, 24 and 26 have the highest value oscillation in the case studies. As previously explained, these solutions refer to HTP configuration mainly made by composite. Then, depending on the solution, this HTP is more or less produced in house or outsourced to suppliers. Instead, the solutions 9,12,15 also have some components in aluminum and again, depending on the specific solution, this HTP is mainly made in house or outsourced. In any case, considering these two groups of solutions (9,12,15 and 23,24,25), one of the trade-off study that decision-makers can perform is for example the following one:

- Invest for a quite expensive HTP configuration, produced in house or outsourced, that provides the highest value in a specific scenario (the reference case – no prioritization of attributes) but whose value change a lot depending on the scenario analyzed (solutions 23,24,26);
- Invest for a less expensive HTP configuration, produced in house or outsourced, that provides not the highest value in a specific scenario (the reference case – no prioritization of attributes) but whose value does not change a lot in relation with the analyzed scenario (solutions 9,12,15).

In addition, as explained in Section 3.5.3, the probability of the Reference Pareto front solutions to stay on the Pareto front is also estimated for each case study to identify the flexible solution. The results of this investigations are reported in Figure 5.31. In the Case Study I, Solution 15 is always on the Pareto front. In the Case Study II, all the alternatives are flexible solutions. In the Case

Study III, solution 15 is again the flexible solution. The same results are also reported in Table 5.17.



(a) Alternative 15 as Flexible Solution. **(b)** All Alternatives as Flexible Solution. **(c)** Alternative 15 as Flexible Solution.

Figure 5.31: Probability of Solutions to be on the Pareto-front: Flexible Solutions Identification: a) Case Study I, b) Case Study II, c) Case Study III.

Table 5.17: Probability of the Reference Pareto-front solutions to be on the Pareto-front for the three Cases Studies.

	Case Study	Solution ID					
		9	12	15	23	24	26
%	I	92	92	**100**	80	78	73
	II	**100**	**100**	**100**	**100**	**100**	**100**
	III	96	96	**100**	81	80	79

The alternative 15 is therefore an optimal solution in all the case studies analyzed. This solution has the lowest value in the value-driven Reference Pareto-front (Figure 5.28). However, as previously discussed, it is robust when changing both the utility functions and weights (Figure 5.30). It means that this solution doesn´t change drastically the value when changing the scenario of interest (weight) for decision-makers, neither their expectations (utility function). In addition, this alternative is always on the Pareto-front in all the case studies analyzed, meaning that this solution is always among the solutions optimizing the fuel consumption, production risk, time and quality. From the decision-makers perspective, new trade-off studies can be performed to increase the awareness in taking decisions. For instance, they might invest in a solution which has the highest value in a specific scenario (solution 23 in the Reference Pareto-front) but whose probability to remain optimal strongly depends on the analyzed case. On the other side, instead, they might invest in a solution which has a lower value but also cost and remains on the Pareto-front in any scenario. Concluding, the three case studies of this aeronautical application case highlights the importance of including uncertainty in the value-driven decision-making. It increases the decision-makers 'awareness when performing trade-off studies related to uncertain scenarios and/or expectations showing, for instance, that the best solution in a specific scenario might not be the robust solution.

5.2 Seaplane Fuselage Concurrent Design and Manufacturing

The second application case is framed within the European Horizon Project Colossus which aims at developing a methodology to enable the concurrent optimization of multiple layers: business models, system of systems, constituent system and subsystem (system component), as shown in Figure 5.32 (G.A 101097120, [118]). A Consortium of 14 partners including industries, universities and research centers is collaborating to achieve this objective.

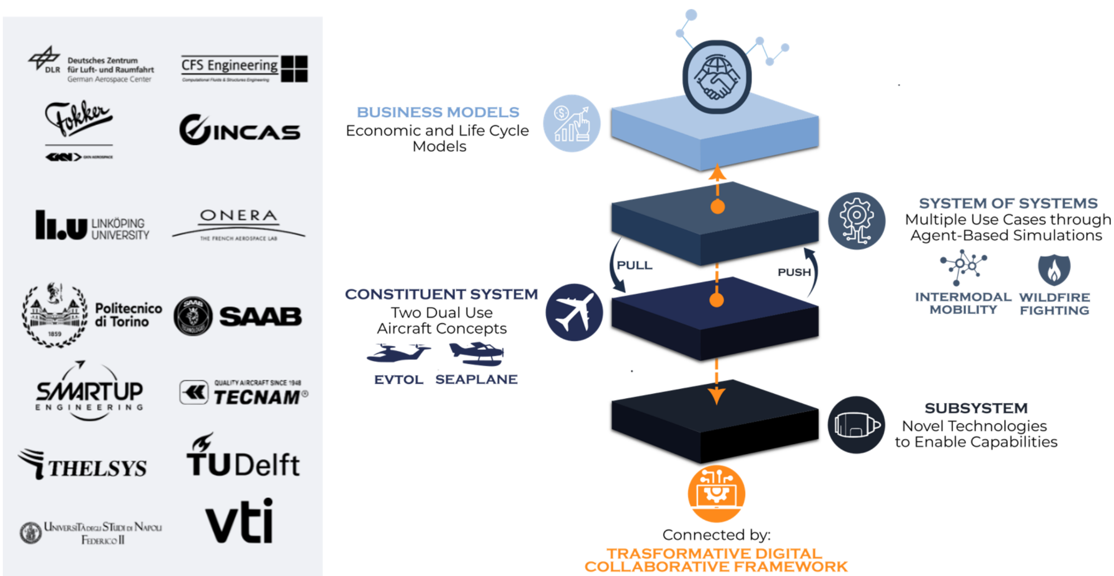


Figure 5.32: European Colossus Project Objective and Consortium, [118].

In particular, to develop a robust methodology two uses cases are analysed while following the Product Push and Product Pull paradigms:

- Sustainable Intermodal Mobility, named ADAM (advanced air mobility), with the objective to create a business model for sustainable 4D-intermodal mobility and evaluating the concept for performance, competitiveness, environmental impact and life cycle footprint;

- Aerial Wildfire-Fighting, named EVE (eco-friendly air vehicles for multiple operating environments), with the ambition to develop 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.

A Multi-Role seaplane with hybrid propulsion and a Multi-Role eVTOL based advanced air mobility are the constituent systems analysed in these use cases for passengers and goods transportation. Once designed, these constituent systems are combined in fleets and their behaviour is analysed in a simulation-embedded system of systems approach for the identification of the optimal performance [119]. A Transformative Digital Collaborative Framework (TDCF) is under development in the Colossus project to support the modelling, analysis and optimization of such a complex multi-levels systems approach [120]. In this context, the S4S Framework will be integrated in the TDCF and applied to enable the concurrent design and manufacturing of the fuselage of the seaplane configuration. In this application case, the supply chain system is not considered. However, as discussed in Section 3.1, the S4S are integrated in the broader SoS context. In this study, the focus is on the S4S and thus on the identification of the best constituent system configuration while considering manufacturing and aircraft performance simultaneously. The technologies used to perform the S4S Framework processes while considering only manufacturing and supply chain systems are shown in Figure 5.33.

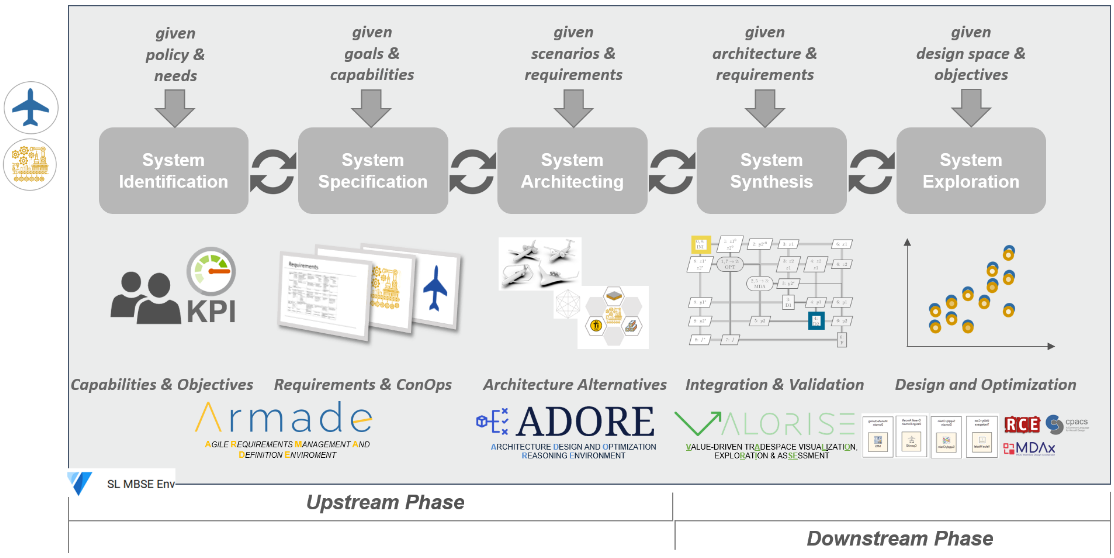


Figure 5.33: S4S Framework technologies applied in Colossus Project, focus on manufacturing and aircraft systems.

All the processes explained in Section 3.3 are still valid for this application case, even do the supply chain system is not considered proving also the flexibility of the S4S Framework applicability. This is true for both the upstream and downstream processes. In the following sections, results already available are described. More will come since Colossus is on going Project. Before showing the results, more details on the application are provided in Section 5.2.1.

5.2.1 Application Case Specification

The reference aircraft is a 9-12 seaplane passengers complaint with the CS23 requirements, designed from scratch with the objective to allow mobility of both cargo and passengers, wildfire fighting and additional special operations. The entry into services is assumed to be 2035. This seaplane should have hybrid propulsion architectures to reduce fuel burn and emissions by 30% if compared to a baseline seaplane in operation before 2020. To start the design of this aircraft configuration, a feasible set of TLARs is identified considering vehicle's operating scenarios, market analysis and performance evaluation of aircraft in the same category that represent competitors of the new product. The TLARs identified for this aircraft configuration are reported in Table 5.18 with the estimated masses.

Table 5.18: Reference Seaplane Top Level Aircraft Requirements and estimated masses, [121].

Parameter	Unit	Value
MTOM	lbm	$\leq$ 19000.0
N Passengers	-	15
Design Cruise Range	nmi	$\geq$ 500.0
Typical Cruise Range	nmi	300.0
Cruise Altitude	ft	10000.0
Cruise Mach Number	-	0.30
Take-off Distance	ft	$\leq$ 3280.0
Landing Distance	ft	$\leq$ 3280.0
Mass	**Unit**	**Value**
Operating Empty Mass	kg	4597.58
Maximum Take-Off Mass	kg	6548.87

The focus in on the fuselage of this configuration. In particular, the skin, stringers and frames are selected as main components. These components are shown in Figure 5.34. For each of them, several materials and manufacturing processes can be selected.

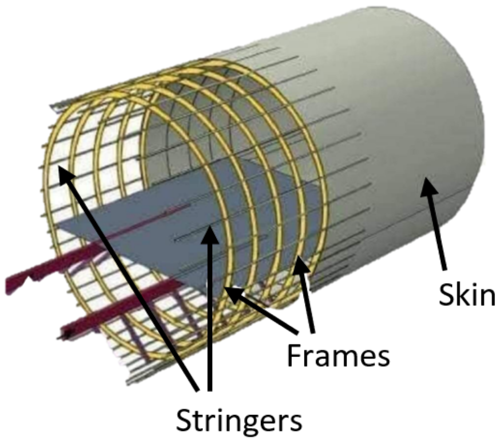


Figure 5.34: Fuselage main components analysed within the European Colossus Project, modified from [122].

The number of possible choices in terms of materials and processes for the main fuselage components are reported in Table 5.19. For composite, the use of different materials for fibers, for instance carbon or glass, account as other material choice.

Table 5.19: Number (N°) of choices related to Materials and Manufacturing Processes.

Components	N°Materials	N°Manufacturing Processes
Frame	3	4
Stringers	2	3
Panels	4	7

These choices has an impact on the seaplane performance, as explained in Section 3.5.1. The mass and the emission of the seaplane during mission are considered as main aircraft performance. Instead, other manufacturing parameters are assumed as main performance of the manufacturing system like quality, automation and cost, as explained in details in Section 5.2.3. The manufacturing cost are however used as other independent variable to create the value-cost tradespace.

5.2.2 Upstream Phase Processes

The upstream phase of the S4S Framework deals with the modelling of stakeholders, needs, requirements and architectures generation. For the modelling of stakeholders, needs and requirements, ARMADE is used.

An example of stakeholders modelled in ARMADE is shown in Figure 5.35. Among others, also the manufacturer is included.

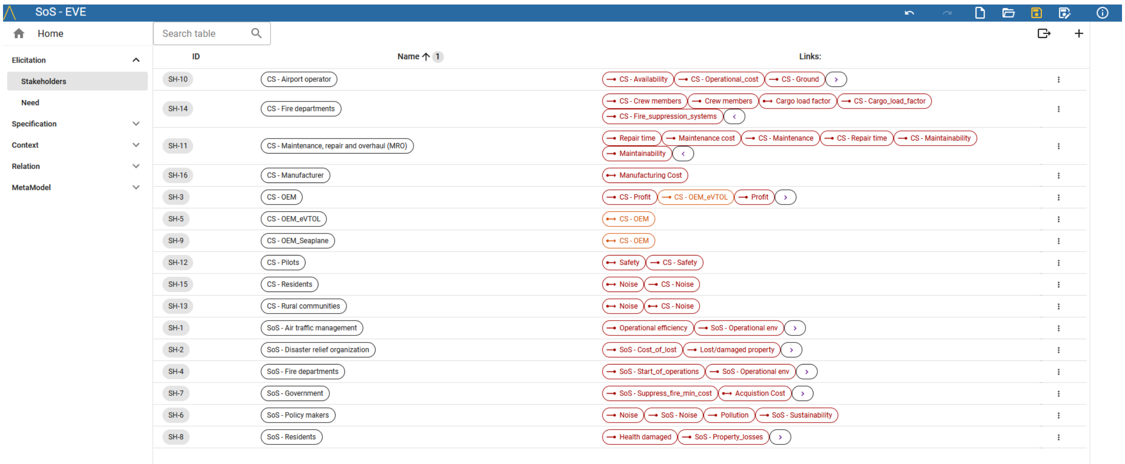


Figure 5.35: Seaplane stakeholders, ARMADE model.

Each stakeholder express needs. These needs are also implemented in ARMADE and an example is shown in Figure 5.36. For example, the manufacturer wishes to reduce the manufacturing cost or increase easiness of manufacturing processes.

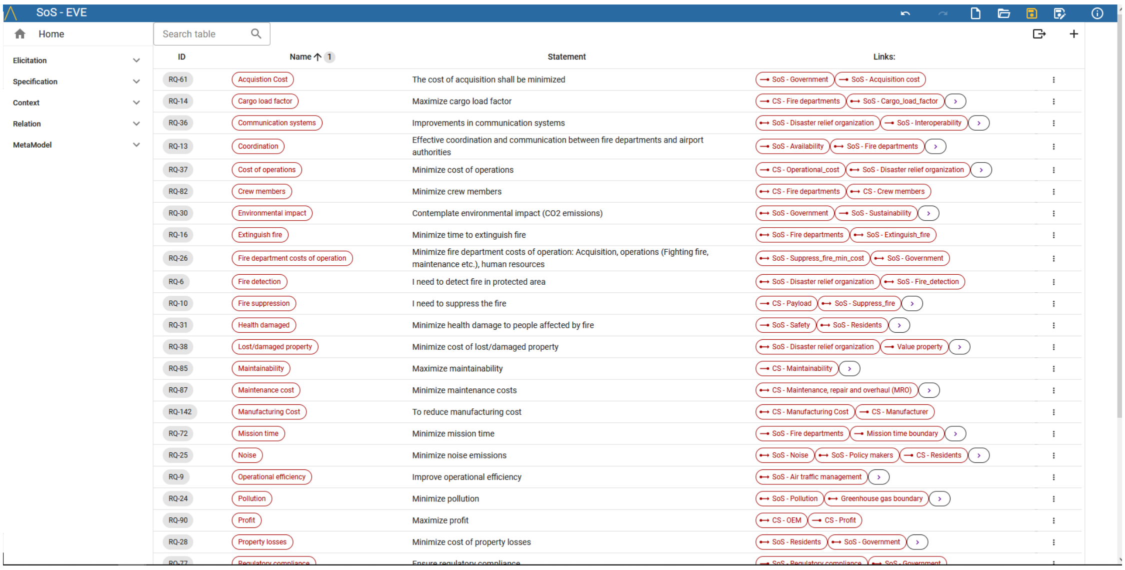
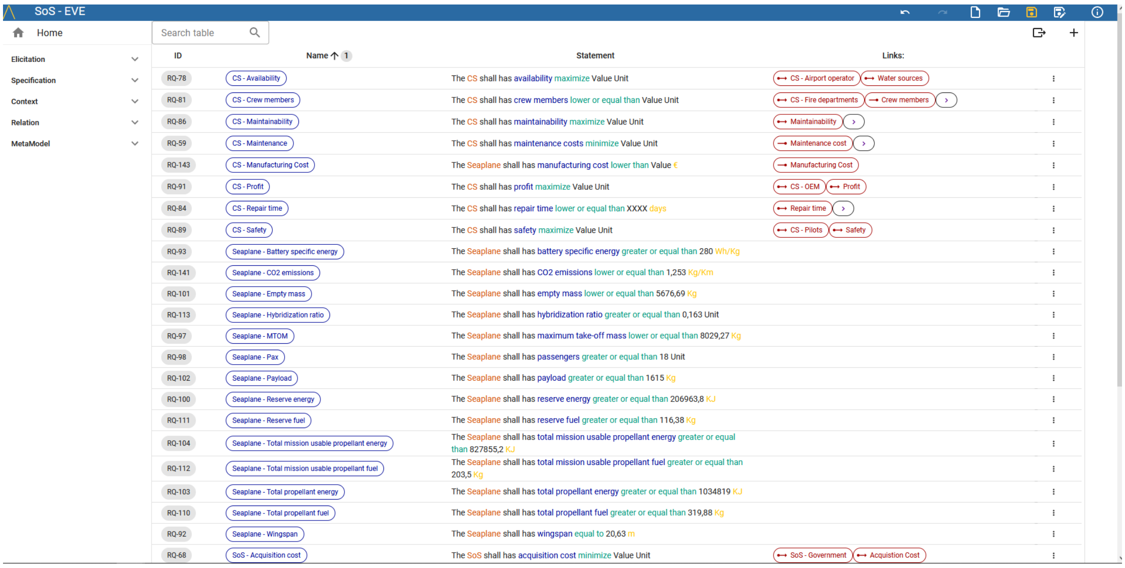


Figure 5.36: Seaplane stakeholders´needs, ARMADE model.

Finally, requirements are derived from needs. These are also modelled in ARMADE and shown in Figure 5.37. The need of manufacturers is converted in a requirement for the seaplane.



ID	Name	Statement	Links:
RQ-78	CS - Availability	The CS shall has availability maximize Value Unit	CS - Airport operator; Water sources
RQ-81	CS - Crew members	The CS shall has crew members lower or equal than Value Unit	CS - Fire departments; Crew members
RQ-86	CS - Maintainability	The CS shall has maintainability maximize Value Unit	Maintainability
RQ-59	CS - Maintenance	The CS shall has maintenance costs minimize Value Unit	Maintenance cost
RQ-143	CS - Manufacturing Cost	The Seaplane shall has manufacturing cost lower than Value €	Manufacturing Cost
RQ-91	CS - Profit	The CS shall has profit maximize Value Unit	CS - OEM; Profit
RQ-84	CS - Repair time	The CS shall has repair time lower or equal than XXXX days	Repair time
RQ-89	CS - Safety	The CS shall has safety maximize Value Unit	CS - Pilots; Safety
RQ-93	Seaplane - Battery specific energy	The Seaplane shall has battery specific energy greater or equal than 280 Wh/Kg	
RQ-141	Seaplane - CO2 emissions	The Seaplane shall has CO2 emissions lower or equal than 1,253 Kg/Km	
RQ-101	Seaplane - Empty mass	The Seaplane shall has empty mass lower or equal than 5676,69 Kg	
RQ-113	Seaplane - Hybridization ratio	The Seaplane shall has hybridization ratio greater or equal than 0,163 Unit	
RQ-97	Seaplane - MTOM	The Seaplane shall has maximum take-off mass lower or equal than 8029,27 Kg	
RQ-98	Seaplane - Pax	The Seaplane shall has passengers greater or equal than 18 Unit	
RQ-102	Seaplane - Payload	The Seaplane shall has payload greater or equal than 1615 Kg	
RQ-100	Seaplane - Reserve energy	The Seaplane shall has reserve energy greater or equal than 206963,8 KJ	
RQ-111	Seaplane - Reserve fuel	The Seaplane shall has reserve fuel greater or equal than 116,38 Kg	
RQ-104	Seaplane - Total mission usable propellant energy	The Seaplane shall has total mission usable propellant energy greater or equal than 827855,2 KJ	
RQ-112	Seaplane - Total mission usable propellant fuel	The Seaplane shall has total mission usable propellant fuel greater or equal than 203,5 Kg	
RQ-103	Seaplane - Total propellant energy	The Seaplane shall has total propellant energy greater or equal than 1034819 KJ	
RQ-110	Seaplane - Total propellant fuel	The Seaplane shall has total propellant fuel greater or equal than 319,88 Kg	
RQ-92	Seaplane - Wingspan	The Seaplane shall has wingspan equal to 20,63 m	
RQ-68	SoS - Acquisition cost	The SoS shall has acquisition cost minimize Value Unit	SoS - Government; Acquistion Cost

Figure 5.37: Seaplane requirements, ARMADE model,modified from [94].

From requirements, an architectural design space is generated. The ADORE tool is used. A very simple draft of the architectural design space is shown in Figure 5.38.

The guidelines provided in Section 3.4 still applies in this application case. In details, several architectures can be generated depending on the materials and processes selected at the sub-component level, specifically for the main components of the fuselage of each constituent system. Therefore, some materials and processes can be selected for frames, stringers and skins.

These choices will have an impact on the performance of the constituent system and thus on the general performance of the SoS. Other architectural choices can be made at the system of systems level. Among others, thus related with the behaviour of the constituent system, for instance on which tactic follow to fight the fire.

Activities on the upstream phase processes are still in progress within the Colossus Project and more detailed models will be obtained during the Project.

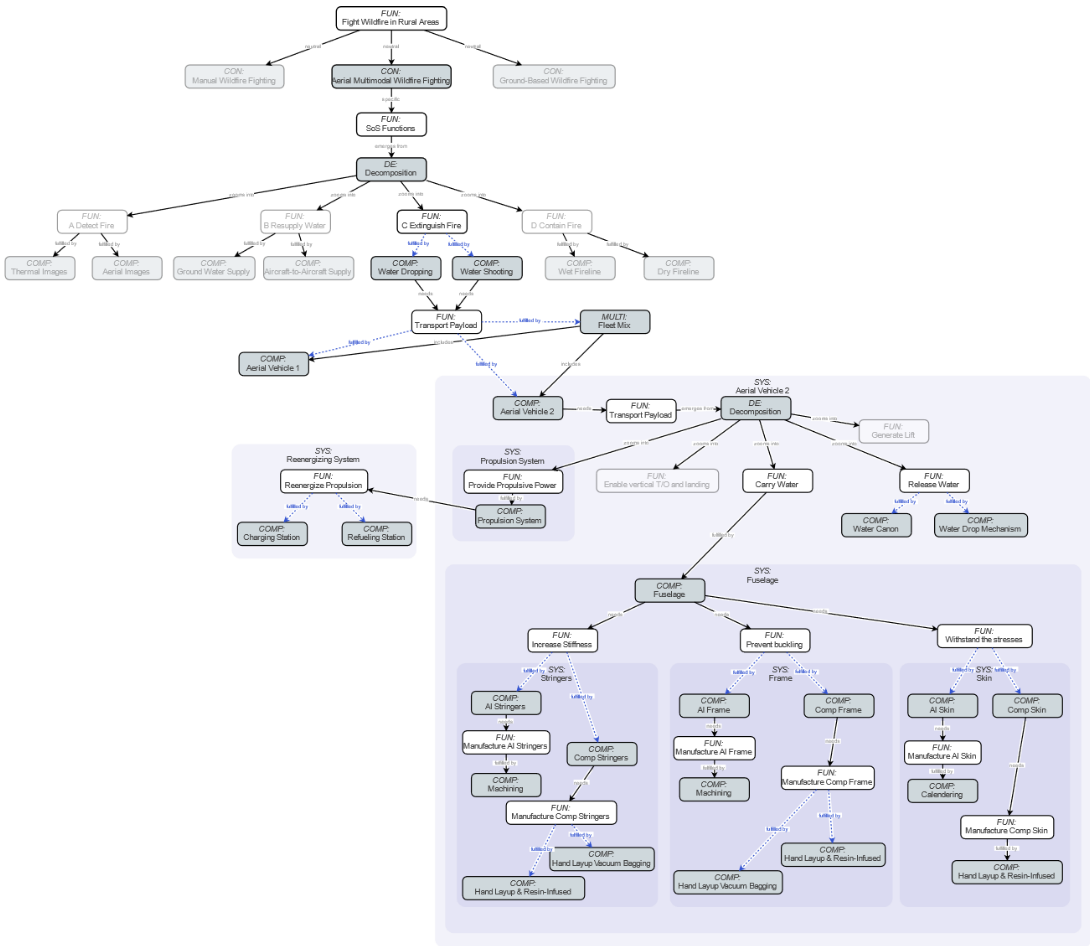


Figure 5.38: System of Systems architectural design space draft including manufacturing and design choices at the constituent system level, ADORE model, modified from [123].

5.2.3 Downstream Phase Processes

The downstream processes of the S4S Framework are more related to the evaluation and optimization of the architectures generated in the upstream phases for the identification of the best one for decision-makers. The key criteria to consider when making decisions considering the aircraft and manufacturing systems are already identified for this application case, as summarized in Table 5.20. Related to the aircraft domains, there is the fuel consumption mass of the seaplane in cruise and the emission released during the mission. These have been identified as key criteria when considering a configuration like the seaplane. Instead, for the manufacturing domain, the quality, automation and cost are selected. The quality of the manufacturing process reflects how efficiently it is executed. A high score indicates a smooth process with minimal waste, producing components ready for direct installation. A low score suggests inefficiencies, resulting in higher waste and the need for further refinement. Automation, instead, reflects the extent to which the process can be automated, minimizing the need for operator interactions. A low score implies frequent operator involvement (loading, moving, or removing parts), while a high score denotes a process that is highly automated or that can be easily automated, requiring little to no operator intervention. Finally, the manufacturing cost follow the definition provided in Section 3.5.3. In this case, however, only one single enterprise is involved.

Table 5.20: Manufacturing and Aircraft criteria to identify the best alternative on the design space, seaplane application case.

Domain	Criteria	Meaning
Aircraft Design	Fuel Mass	Fuel mass consumption in cruise
	Emission	Emission during mission
Manufacturing	Quality	Readiness of product use
	Automation	Level of manufacturing process automation
	Cost	Cost related to manufacturing processes

Decision-makers also express their qualitative expectations with respect to these criteria, as shown in Table 5.21.

Table 5.21: Decision-makers´expectations with respect to manufacturing and aircraft criteria, seaplane application case.

Criteria	Expectation
Fuel Mass	Lower the better
Emission	Lower the better
Quality	Higher the better
Automation	Lower the better
Cost	Lower the better

These qualitative preferences will be quantified through the elicitation of the utility functions in VALORISE. However, first simple cases with linear functions will be explored. Before going to the decision-making activities, however, it is essential to estimate these criteria per each architecture. These activities are already on going and Figure 5.39 already shows the XDSM workflow that will be executed for the estimation of these criteria [124]. This XDSM is very close to the one described in Section 4.3.1, but the aircraft design domain is expanded with more specific tools (instead that only OpenAD).

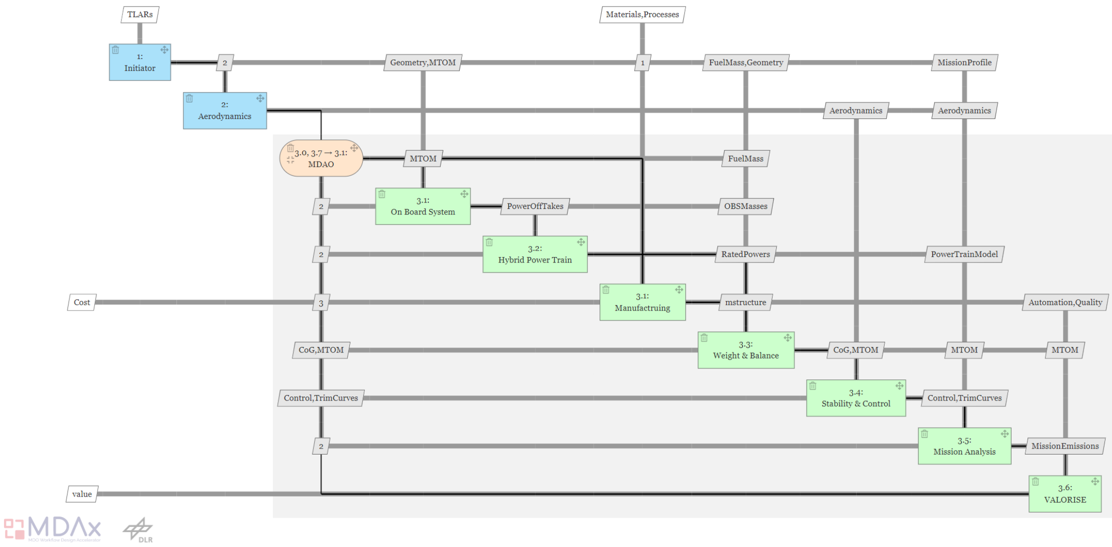


Figure 5.39: XDSM Workflow to perform manufacturing and aircraft concurrent design evaluation for the seaplane application case, MDAx model, modified from [121]

The criteria provided in Table 5.20 will be aggregated in the value, except for the cost that will be used as other independent variable to perform the value vs. cost trade-off studies. These criteria will then propagated at the SoS level and more trade-off studies would be possible to address. More results will come during the Colossus Project.

Author Contribution & Reference - AGILE4.0 Application

- **Donelli, G.**, Mello, J. M., Odaguil, F. I., Lefebvre, T., Bartoli, N., van der Laan, T., Nagel, B. (2022, September). A value-driven quantitative framework coupling aircraft design, manufacturing and supply chain by leveraging the MBSE-MDO framework. In ICAS 2022.

  This paper shows an application of the aircraft, manufacturing and supply chain systems stakeholders, needs and requirements. In addition, a model of the architectures of these systems is proposed, an optimization problem executed and the main results presented to highlight the benefits of the trade-off studies that can be performed.
- Bartoli, N., Lefebvre, T., Lafage, R., Saves, P., Diouane, Y., Morlier, J., Bussemaker, J., **Donelli, G.**, Mello, J., Mandorino, M. Della Vecchia, P. (2023, July). Multi-objective bayesian optimization with mixed-categorical design variables for expensive-to-evaluate aeronautical applications. In AEROBEST 2023 (Vol. 1, No. 1, p. 436).

  This paper describe the results on one optimization problem of the MDO Case I related with the concurrent optimization of the manufacturing and supply chain domains with a focus on the optimization algorithms used.

Author Contribution & Reference - Colossus Application

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  This paper shows the results of the value-driven decision-making process when considering at the same time design and production criteria for the identification of the best alternative according to decision-makers´expectations.
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  This paper focuses on the formalization of the System of Systems architectural design space when considering the level of decision-making management including architectural choices at the SoS and constituent system behaviour.
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  This paper shows how to leverage ARMADE for the modelling of System of Systems Problem Definition and Systems Specification. Therefore, how to formalize and implement stakeholders, needs and requirements models.

6
Conclusions

6.1 Summary

This thesis proposes a holistic systems engineering methodology to enable the concurrent conceptual design of aircraft, manufacturing, and supply chain systems. This integrated approach aligns with the Flightpath 2050 goals of fostering a financially sustainable aviation industry that stimulates economic growth and innovation, maintains global competitiveness, ensures the timely introduction of innovative aviation solutions to address societal and market needs, and promotes international collaboration to achieve a culture of innovation within the aerospace sector. The objective is to develop this systems engineering approach to overcome the limitations of the traditional sequential method, through which manufacturing and supply chain considerations are addressed after the aeronautical system design is finalized. However, once the design is frozen, any changes become extremely costly and time-consuming as experienced by several industries including Airbus and Boeing in aerospace and Toyota and Honda in automotive (Chapter1).

To develop the proposed concurrent approach, a literature review is conducted to identify existing gaps. Systems engineering frameworks are examined to check for guidelines supporting the development of these systems according to standards. Additionally, methodologies enabling the concurrent evaluation of alternatives that account for both design and production variables are explored, along with value model techniques and their applications. Based on this review, Ciampa's MBSE-MDO Framework is selected as it closely matched the research objectives. However, it has been properly modified to support the concurrent design of the three systems. The S4S Framework is proposed to close the key gaps existing in literature and demonstrate the advantages of leveraging a systems engineering approach to formalize the concurrent design of the supply chain, manufacturing and aircraft systems to enhance aeronautical systems value (Chapter2).

The formalization of the systems engineering Framework is proposed in Chapter3. First, the definition of the supply chain (a set of companies) and manufacturing systems (the set of machines necessary to produce the aircraft) is provided to clarify their role as enabling systems, meaning systems that support the system of interest (the aircraft) during production. Therefore, the concept of "systems for system" is introduced: enabling systems (systems) provide support to the system of interest (system). Then,the definition of concurrent design is addressed from a systems engineering perspective. It requires the execution of the concept stage processes simultaneously for the three systems. These processes, formalized in the S4S Framework in an upstream and downstream phase, include gathering stakeholders and their needs, translating those needs into requirements, generating and evaluating architectures. For the upstream phase, covering processes until system architecting, the existing literature has been extended to all three systems. More effort required the activities of the downstream phase. A new methodology based on Multi-Attribute Utility Theory (MAU) is proposed within this context to enable concurrent design evaluation, optimization, and decision-making for alternatives that account for both design and production variables. This methodology generates an analytical, value-driven tradespace, with the solution of the highest value representing the good compromise across all aggregated criteria. A value-driven Pareto front is instead obtained by introducing optimization algorithms in the methodology. A collaborative optimization campaign is introduced to manage the concurrent optimization through three MDO cases which integrate domains first in pairs and then together. The same value-model theory is then used to perform decision-making activities that consider both product and production criteria. In this case, the value-driven tradespace reflects decision-makers' preferences, making the solution with the highest value the best match for their expectations across all criteria. Finally, three case studies illustrate how to propagate uncertainty into value through weights and/or utility functions for the identification of robust and flexible solutions.

To execute all the processes of the S4S Framework, a model-based approach has been used. Several technologies are therefore used to implement all the Framework processes, with a focus on those applied in the case studies presented in this research activities. In details, technologies, like Ke-Chain or MBSE-Env, are proposed to connect all the tools of the upstream and downstream phases. Instead, Ke-Chain in combination with Papyrus or ARMADE, are used to model and visualize stakeholders, needs and requirements. ADORE is the tool used to model the architectural design space and generate all the possible architectures. Finally, several tools and technologies are used to automatize the concurrent design evaluation, optimization and decsion-making activities. Among other, CPACS as common language to exchange information among tools; MDAx to formulate and set-up the MDAO problem; RCE to execute such workflows. In the same workflow, VALORISE can be integrated to perform uncertainty propagation analysis or used as dahsboard to address decision-making activities. Finally, BRICS or UPLINK allows the collaborative execution of such analysis through the automatically exchange of CPACS file through the tools owned by different partners (Chapter4).

Concluding, The S4S Framework is applied within the European Project AGILE4.0 to enable the concurrent design, manufacturing, and supply chain of the horizontal tail plane. A description of the stakeholders´needs, requirements, architectures and possible trade-off studies that can be performed while exploring the value-driven tradespace is provided in Chapter5. In same chapter, an application of the S4S Framework is also applied in a broader system of systems context within the European Project Colossus. Although the activities are ongoing, the modeling of stakeholders, needs, requirements, and architectures is presented. In this application case, however, only the aircraft and manufacturing systems are considered.

6.2 Implications & Findings

The evolving market and increasing demands to meet strict societal standards are prompting aeronautical companies to adjust their strategies by integrating production assessment during the design phase. This approach aims to create robust, efficient, and competitive aeronautical systems, ensuring sustained market leadership. The S4S Framework introduced in this research addresses these industrial demands.The formalization of the S4S Framework streamline all the processes required for the concurrent conceptual design of the manufacturing, supply chain and aircraft systems: from defining stakeholders and their needs, translating these needs into requirements, generating architectures, and ultimately evaluating them to identify the best one for decision-makers. In details, in the upstream phase, existing methods are effectively extended and successfully applied to the three systems, encompassing stakeholders identification, needs assessment, requirements gathering and architecture generation. As a result, stakeholders interested in the manufacturing and supply chain systems are also considered to ensure their needs are incorporated into the conceptual design. This approach guarantees that requirements for both the product (aircraft) and production (supply chain and manufacturing) are taken into account during the conceptual design phase. This is the key difference from the traditional sequential approach, where the aircraft design is driven exclusively by the TLARs. From requirements, the architectural design space and the related architectures are generated based on design and production choices: from the number of components, to materials, processes and enterprises. The main challenges arise during the downstream phase, which involves methodologies necessary for evaluating, optimizing, and selecting the best architecture. A new value-driven methodology is developed to address the simultaneous evaluation of design and production performance. Formulating this methodology, however, necessitates experts´knowledge for defining the supply chain and manufacturing domains models. Despite the challenges in translating experts' tacit knowledge into mathematical models, the resulting methodology, which also formalizes the connections between domains, seems flexible enough to have broad applicability across various sectors beyond the aeronautical field. A key role in this methodology is however played by the Multi Attribute Utility theory, the value model technique applied in this study. In particular, this theory is used for the following key reasons:

- aggregate product and production performance into a single dimensionless measure, that is the value, allowing for the easy identification of the best alternative based on all aggregated criteria in the generated analytical value-driven tradespace as the solution with highest value;
- combine objective functions (product/production performance) of multi-objectives MDO problems into a single dimensionless measure, that is the value, to simplify the analysis of the multi-objective Pareto front by examining the 2D value-driven Pareto front;
- aggregate decision-makers' criteria (which can be selected from product and production performance) to easily identify in the value-driven tradespace the best solution that aligns with their expectations as the alternative with highest value;
- perform uncertainty propagation analysis when decision-makers wish to explore how solutions behave under different scenarios or preferences, enabling the identification of robust and flexible solutions.

In addition, the use of this methodology proves its effectiveness for carrying out all the proposed analyses in the downstream processes and linking with all the processes of the upstream phase. From an implementation perspective, to execute of all the processes of the S4S Framework, a model-based approach has been used. This approach provides a structured, integrated, and dynamic way of modelling, representing and analyzing complex systems throughout their lifecycle. Information is captured in centralized digital models that are continuously updated. Several technologies are leveraged to connect all tools in the S4S Framework, model stakeholders, define needs, requirements, and architectures, and implement the methodology for concurrent design evaluation, optimization, and decision-making. For the upstream processes, the model-based approach enhances traceability by linking requirements directly to a specific component, process, or function within the model, allowing for clear tracking of where and how requirements are implemented. For the downstream processes, digital models instead allow for automation of simulations, analyses, and optimizations, which can be performed rapidly and iteratively to test and validate system performance.

Finally, the application of the S4S Framework to two case studies highlights the benefits associated with its use. The early selection of materials, processes and enterprises lead to a solutions tradespace in which the most efficient and competitive aeronautical system can be selected. This alternative is derived from design and production requirements and matches stakeholders´needs. Components that are not only driven by technical performance but also cost-effective to produce can be so designed. In this way, the assessment of the production performance, thus manufacturing and supply chain, is part of the results of the tradespace exploration rather than further steps performed after the design phase. This allows designers to make informed decisions that optimize the product for manufacturability and supply chain efficiency than only the overall aircraft performance. In addition, by embracing this integrate approach, which accounts for the choices of materials, processes, sourcing of components and logistic management, potential production bottlenecks or constraints can be proactively addressed avoiding increase of cost and increasing the value of the aeronautical system. Indeed, the approach also supports decision-makers in identifying the solution based on the criteria they consider important in "value" the system. The results of the AGILE4 application case then show how the best solution depends on the scenario of interest analysed, thus on which attributes are prioritized and on the decision-makers´preferences quantification, thus on the way decision-makers would take decisions. For this reason, the approach also supports the investigation of the solutions in terms of value behaviour through uncertainty propagation to identify the robust solution, meaning the alternative whose value does´t change too much. Indeed, the application case, demonstrates that the best solution in a specific scenario may not necessarily be the robust alternative. These insights enhances decision-makers´awareness when making strategic decisions.

Users of this approach can be all the aeronautical industries, within the aerospace sector. The original equipment manufacturers (OEMs) responsible for the design, manufacturing and assembly of the whole aircraft, can leverage the approach to strategically define and assess the production plan, i.e. make or buy, while the product is still under design. This leads to OEMs the advantages of exploring all the scenarios of interest and decide, at the same time, for an efficient but also competitive aeronautical system. OEMs can also leverage the proposed value-driven approach to easily communicate to their stakeholders the system design that best meets their needs based on the multiple criteria they use to 'value' the system. For Tier I suppliers—medium-sized companies engaged in the manufacturing and assembly of aircraft components—the approach can be used to analyze their role within the supply chain and enhance the value of their offerings for OEMs, promoting a more robust and sustainable partnership. These companies can similarly leverage the proposed methodology to make strategic decisions regarding whether to outsource production to smaller Tier II suppliers, who handle the manufacturing and assembly of aircraft sub-components. This reasoning can be applied iteratively across all entities involved in the supply chain. Therefore, this approach not only enhances system efficiency and competitiveness but also boosts improvement throughout the entire supply chain, encouraging collaboration and long-term relationships among OEMs and suppliers reducing risks, cost and unlocking new synergies.

Concluding, an holistic systems engineering approach ensuring the concurrent supply chain, manufacturing and aircraft systems conceptual design has been developed in this activity. The application of this approach at the system of systems level also shows the flexibility of the approach to be used in different context. In addition, its application demonstrates, as widely outlined, how the value of aeronautical systems increases when concurrently designing the three systems. This gives an answer to the research questions and it allows to state that:

Making more decisions in the early life-cycle increases the value of complex aeronautical systems leading to more competitive, affordable and resilient aeronautical systems.

Indeed, design decisions that have into account that take into account material availability, production processes, supply chain logistics can help mitigate risks associated with production delays, supply chain disruptions and quality issues leading to more cost-effective solutions, reduce the time to market, giving companies a competitive advantage in the fast aerospace industry. By considering more systems of the other life-cycle stages, aerospace industries can leverage the full spectrum of opportunities to then minimize waste and enhance sustainability across the entire aircraft life-cycle.

6.3 Future Activities

The S4S Framework is developed to facilitate the concurrent conceptual design of supply chain, manufacturing, and aircraft systems. Its formulation follows the processes outlined in the ISO 15288. However, other processes or activities are not yet fully formalized, such as the mission analysis for the overall problem definition or the use case definition, scenario modelling or requirements validation activity, implicitly addressed without providing clear formalized guidelines. In details, for the upstream processes, some activities are already underway to verify the existence of standards that can be applied for the enabling systems modelling. For example, different standards may exist and could potentially be applied for the enabling systems requirements modelling. Regarding downstream processes, instead, simple models are used to formalize the supply chain, aircraft and manufacturing domains Therefore,more complex models could be integrated into the proposed methodology, such as those for calculating transportation or manufacturing costs. From an optimization perspective, more complicated MDO problems can be formalized, for instance taking capacity into account as a constraint. Additionally, the efficiency of the optimization algorithms can be enhanced for larger database, and new formalization using hierarchical variables could be explored to reduce the problems dimension. Furthermore, other value modeling techniques could be explored for decision-making activities and perform more advanced uncertainty propagation analyses. Uncertainty could also be propagated in the supply chain model to analyze how the supply chains behave in case production issues arise (e.g., changes in capacity or geographical disruptions) as well as in the aircraft and manufacturing domains to analyse the behaviour of the alternatives in terms of performance in case of new design and manufacturing choices. The behaviour of solutions in terms of value can be analysed.

From the implementation perspective, a model-based approach is used. However, the technologies discussed in this thesis mainly consist of in-house tools or those associated with European research projects. Therefore, it is suggested as future activity, to explore and investigate commercial tools. Among others, examples widely used in the industrial context include IBM Doors, CAMEO Systems Modeler, Dassault 3D Experience and ESTECO platforms. In this frame, some activities are already in progress, especially for the upstream Framework processes.

In terms of applications, the Framework is applied to an existing aircraft configuration in the AGILE4.0 case study. In this context, simple application cases have sometimes been executed to validate the approach or technologies. It would be beneficial to conduct more complex application cases to identify the best way to manage the huge amount of data generated.In addition, it´s recommended to perform more complex uncertainty propagation analysis. In this case study, uncertainty is propagated through one utility function (time). However, uncertainty might be added in more functions to investigate the behavior of solutions in terms of value. Furthermore, the reference Pareto-front used to perform these analysis is obtained considering same weights and linear utility functions for all the criteria to simplify the validation of the results. Further analysis can be done using as

Reference Pareto front, those obtained by considering the utility functions provided by stakeholders. Results from the Colossus application case may also illustrate how the approach works when a new configuration, such as a seaplane, is under design. In this scenario, applying uncertainty propagation analysis would be particularly interesting due to the high level of uncertainty associated with the data.

Both case studies, however, are limited to a research context, sometimes characterized by simplifications and assumptions. Future studies could focus on implementing the proposed Framework in an industrial environment to evaluate the scalability of the approach and identify the key challenges involved. This activity could also support the quantification of the benefits that the proposed Framework could bring to aeronautical companies if compared to the traditional commonly used once. Indeed, in this thesis, the advantages of applying the Framework have been assessed and highlighted. However, a precise numerical estimation of the time savings achieved by considering design and production decisions at the same is lacking.

Appendices

A

Multi Attribute Utility Theory in Optimization Activities

The Multi Attribute Utility (MAU) theory traditionally used to perform decision-making activities, it is also adopted in this study to simplify the investigation of multi-objective Pareto front by aggregating the objective functions in a single dimensionless measure, that is the value. Therefore, the multi-objective Pareto front obtained from the MDO problems execution, is converted in a 2D value-driven Pareto front to simplify the visualizing and discussion of the results. However, the hypothesis of same weights and linear utility functions for all the attributes is mandatory. These assumptions ensure that no order of priority is applied to attributes (same weights) and that no influence of decision-makers is considered (linear utility functions). In addition, they guarantee that the value-driven Pareto front is part of the multi-objective Pareto front, as mathematically demonstrated in [115].

As example, the 2D value-driven Pareto of the MDO Case I addressing the concurrent optimization of the manufacturing and supply chain domains, described in details in Section 5.1.6 is here-after shown.

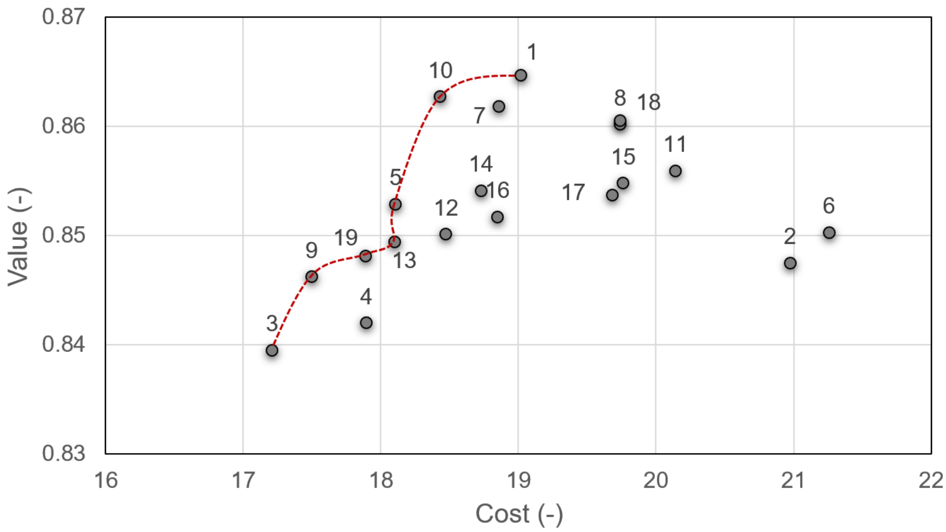
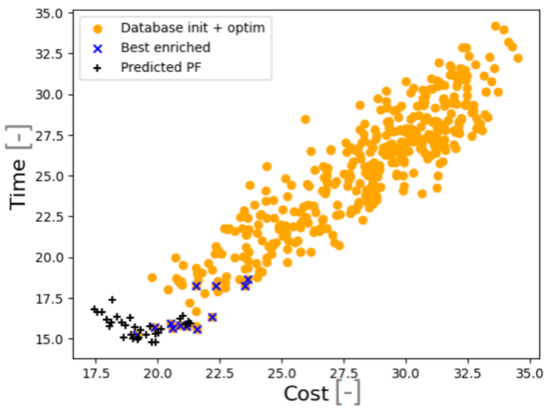
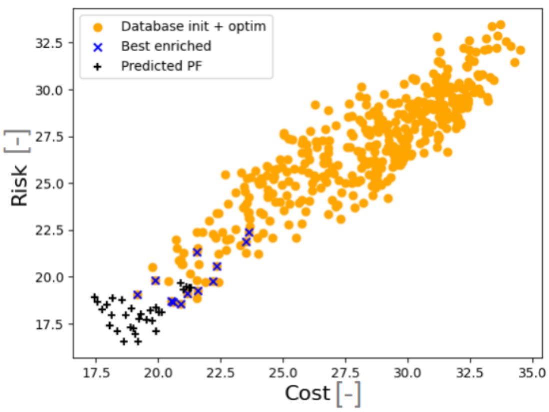


Figure A.1: Manufacturing and supply chain MDO problem: value-driven Pareto front.

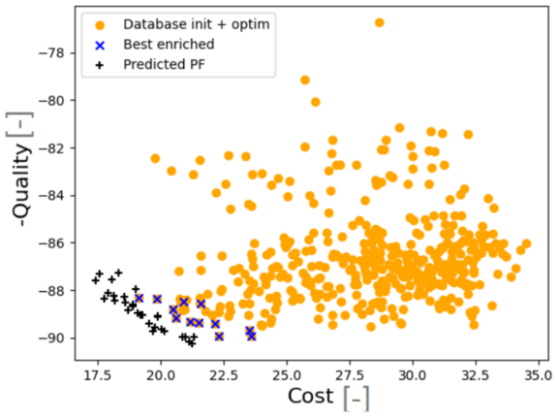
This value-driven Pareto front (Figure A.1) is the simplified visualization of the multi-objective Pareto front reported in the Figure A.2 obtained under the hypothesis of same weights and linear utility functions (see Figure 5.5). A sub-set of 19 solutions, among the 30 solutions of the multi-objective Pareto front (black crosses) in Figure A.1, are part of the value-driven tradespace. These solutions are the optimal alternatives when aggregating the objective functions in a single dimensionless measure, that is the value. Then, 7 of these solutions characterize the value-driven Pareto front which represent the non-dominated solutions on the value-driven tradepsace (red line in Figure A.1).



(a) Fuel Burn vs Cost



(b) Risk vs Cost



(c) Time vs Cost

Figure A.2: MDO Case I Multi-objective Pareto front, REF

The investigation of the multi-objective Pareto front requires the analysis of several plots depending on the number of the objectives involved in the optimization. In this example, four objective functions characterize the MDO problem, but quality, risk and time are aggregated in the value while cost is used as other independent variable. By leveraging the value model theory, the trade-off analysis in the value-driven Pareto front can be easily executed by exploring one single 2D plot.

B

MDO Problems Formal Description and Optimizer Introduction

The MDO Problems are formalized as multi-objective constrained optimization problems. The mathematical description for these MDO Casees is the following one:

$$\begin{cases} \min\limits_{\in \Omega \times S \times \mathbb{F}^l} \quad () := [f_1(), f_2(), \cdots, f_n()] \\ \text{s.t.} \quad g_1() \leq 0 \\ \qquad \vdots \\ \qquad g_m() \leq 0, \end{cases} \tag{B.1}$$

where Ω represents the bounded continuous design set for the d continuous variables, S represents the bounded integer set, and $\mathbb{F}^l := \{1, \ldots, L_1\} \times \{1, \ldots, L_2\} \times \ldots \times \{1, \ldots, L_l\}$ is the design space for l categorical qualitative variables with their respective $L_1, \ldots, L_l$ levels [125]. The objective functions, denoted as $f_i : \mathbb{R}^d \to \mathbb{R} \quad \forall i = 1, \ldots, n$ with n representing the number of objectives, and the constraints, designated as $g_j : \mathbb{R}^d \to \mathbb{R} \quad \forall j = 1, \ldots, m$ with m as the count of constraints (either inequality or equality), collectively form the mathematical framework for optimization. Owing to potential conflicts among objectives, the optimization process yields a non-unique solution, presenting a range of feasible solutions. The trade-off among these solutions is delineated by the concept of dominance: a solution is said to dominate another solution $'$ and denoted by $\preceq'$ if $f_i() \leq f_i(') \quad \forall i = 1, \ldots, n$. The ensemble of solutions associated to the optimal trade-off is denoted as the Pareto set, while the corresponding projection of the Pareto set onto the objective space is acknowledged as the Pareto front: Pareto front $:= \{()| \in$ Pareto Set$\}$. For mono-objective problem ($n = 1$), the algorithm is similar except the optimal point is reduced to one point. As categorical variables are involved in the optimization problems, gradient-based optimizers are irrelevant. Evolutionary algorithms capable of handling both multi-objective and categorical variables [126] in the pymoo framework [127] may be considered when function evaluation is not too costly. In this study, the execution of the MDO problems through the workflow showed in Section 4.3 requires around few minutes to evaluate one design point, so an interesting alternative to minimize the number of function evaluations is to consider a Bayesian optimizer (BO).

To deal with all these specifications (mono & multi objective BO, categorical variables, non-linear constraints), the SEGOMOE algorithm is therefore used. SEGOMOE [128] is a constrained Bayesian optimizer where the costly black boxes (objective and constraint functions) are approximated by a surrogate model. SEGOMOE stands for Super Efficient Global Optimization using Mixture Of Experts [107], combining efficient global optimization proposed by Jones [108] and constraint management introduced by Sasena [109]. This algorithm has been successfully applied to various test cases in a mono [110–112] or multi-objective [113, 114] context. In this study, SEGOMOE is applied to handle a large number of categorical design variables for mono or multi-objective problems as given by constrained problem (B.1). Surrogate models based on Gaussian processes are built using the latest version of the SMT [129] toolbox capable of handling such categorical variables. An overview of the optimization process with 9 identified steps is given in Algo. 1.

Algorithm 1 SEGOMOE for constrained multi-objective Bayesian optimization framework.

1: **Inputs:** Initial DOE $i = 1, \ldots, \text{max\_iter}$
2: Build GP surrogate models for each of the objective and constraint functions
3: Maximize an acquisition function within the feasible domain to find x^{i+1}
4: Evaluate objective and constraint functions at x^{i+1}
5: Update the DOE
6: **Post-process**: Use the final database to build GP models and apply NSGA-II algorithm to construct the predicted Pareto front
7: **Post-process (option)**: Evaluate the points of the predicted Pareto front with the objective and constraint functions to construct the true Pareto front
8: **Outputs:** The predicted Pareto front (and optionally the true Pareto front)

Starting from an initial Design of Experiments (step 1), Gaussian processes (GP) are built for the objective and constraint functions (step 3). Based on theses GP, an optimization problem under constraints is solved to find interesting point $x^{(i+1)}$ in the feasible domain able to improve the Pareto Front (increase of the Hyper Volume for instance in step 4). Then in step 5, objective and constraint functions are evaluated at point $x^{(i+1)}$ and added to update the Design of Experiments (DOE).The adaptive process (from step 2 to step 6) iterates until the total budget is exhausted. The feasible points within the concluding database constitute the catalog to identify Pareto optimal points. Subsequently, leveraging the sequentially enriched set of known points from step 6, the final database is employed for constructing Gaussian Process (GP) models for both objectives and constraints in a post-processing phase (step 8). These final GP models can be integrated with an evolutionary algorithm to address the multi-objective constrained problem, facilitating the retrieval of the approximated Pareto front. Specifically, the widely recognized NSGA-II algorithm (Non-dominated Sorting Genetic Algorithm II, as described in [126]) from the pymoo toolbox [127][1] is employed for this purpose. Notably, this approach yields the predicted Pareto front based on GP with minimal additional computational overhead. If a certain computational budget is still available, the points of the predicted Pareto front can be evaluated with the expensive functions (objectives and constraints) to obtain the true Pareto front. Concerning the acquisition function defined in step 4, different BO criteria relative to the Hypervolume Improvement have been proposed in the literature to find interesting point on the Pareto set such as the Expected Hyper-Volume Improvement (EHVI [130, 131]), the Probability of Improvement (PI [132]), and the Minimum of Probability of Improvement (MPI [133]) as some multi-objective extensions of the well known Expected Improvement (EI [108]) for mono-objective optimization. Some setup choices have been made within SEGOMOE to deal with these optimizations. First, as categorical variables are involved, the GP surrogate models have to be adapted to deal with. Here, a continuous relaxation approach was used to replace categorical variables by continuous ones and Partial Least Squares technique was also applied to handle the increase of dimensionality. The continuous relaxation introduced by [134] uses a one-hot encoding strategy [135] and transforms integer and categorical inputs into continuous ones, so some classic continuous correlation kernels can still be used. Regarding the choice of the BO criteria relative to the Hypervolume Improvement, the Minimum of Probability of Improvement (MPI) was applied.

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