



VALUE-DRIVEN TRADESPACE EXPLORATION FOR AIRCRAFT DESIGN, MANUFACTURING AND SUPPLY CHAIN

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Abstract

To meet the requirements of innovative, sustainable and circular aircraft configurations, nowadays it is essential to investigate the entire aircraft life-cycle from design to production, to the disposal after the end of the system operation. This surely enlarges the design space making the decision-making process even more complex: multiple criteria have to be considered at the same time while taking decisions. However, making decisions on future design configurations exploring all the possible solutions on the design space is essential to drastically reduce the overall aircraft cost. In this context, a value-driven methodology has been developed to support and simplify the multi-criteria decision-making process when addressing the concurrent manufacturing, supply chain and aircraft design. This research activity proposes an application of this methodology with the objective to identify the best alternative while trading, at the same time, decision-makers' expectations related to the aircraft design, manufacturing and supply chain criteria. Decision-makers can so identify the most performant but also competitive aircraft configuration since the early life-cycle stages.

Keywords: supply chain, manufacturing, aircraft design, value engineering, decision-making

1. Introduction

The nowadays heterogeneous societal needs require even more complex, innovative, sustainable and circular aeronautical systems. The objective is to reduce the environmental impact in terms of fuel consumption, waste and emissions associated with all the life-cycle stages of the aeronautical system [1]. Hence, the necessity to extend the branches of the aeronautical research to the entire aircraft life-cycle, from the design to the production, to the disposal after the end of the system operations. In this context, the DLR Institute of System Architectures in Aeronautics aims at developing methods, processes and tools leveraging Model-Based Systems Engineering (MBSE) and Multidisciplinary Design and Optimization (MDO) technologies to support the design of aeronautical systems while considering different life-cycle stages [2]. The challenge is to enable the *concurrent* design of the system of interest (aircraft) and the enabling systems, defined as systems supporting the aircraft in one or more life-cycle stages [3]. The enabling systems analyzed in this research activity are the supply chain and manufacturing systems. The supply chain is defined as combination of enterprises involved in the production of the aircraft; the manufacturing system consists of machines needed to manufacture the aircraft. Indeed, the design of these systems traditionally starts once the preliminary aircraft design is already defined [4]. For instance, the choice of which enterprises are needed to produce the aircraft is made once the aircraft configuration in terms of components, materials and processes has been already fixed. With this *sequential* approach indeed the most performant aircraft (e.g. in terms of weights, fuel mass) is identified. However, there is a high risk that this solution does not match, for instance, the production constraints (feasibility of realizing the product). This leads to an unforeseen re-design of the aircraft with a consequent increase of cost [3] [5]. In case of high production rate, these hidden sources of increasing cost can also have a huge impact on the profits of companies [6]. On the other side, instead, the concurrent analysis of manufacturing, supply chain and aircraft design avoid re-work with a consequent reduction in the overall cost and increase of supply chain's gains and product competitiveness [7] [8]. This gives

aeronautical industries a great possibility to win the nowadays global and competitive market [9] [10]. In this context, a value-driven methodology for the concurrent aircraft, manufacturing and supply chain design has been already developed by DLR [11]. A flowchart of this methodology is shown in Figure 1. Once defined the materials, processes and enterprises involved in the design of the product (e.g. aircraft), the supply chain and aircraft performance are estimated. The Multi Attributes Utility (MAU) theory is then applied to aggregate the supply chain and aircraft performance in a single dimensionless measure, that is the *value*. As shown by the red box in Figure 1, the value is estimated by assigning weights and utility functions to the supply chain and aircraft performance. Weights usually represent the relative importance of criteria (also called attributes). Utility functions, instead, quantify decision-makers' expectations with respect to these criteria. Once applied the MAU theory, a ranked ordering of design alternatives is generated and the best solution on the value-driven design space is easily identified as the one with the highest value [12]. The **best** solution is therefore proposed as the alternative on the design space well matching decision-makers' expectations with respect to all the criteria aggregated in the value.

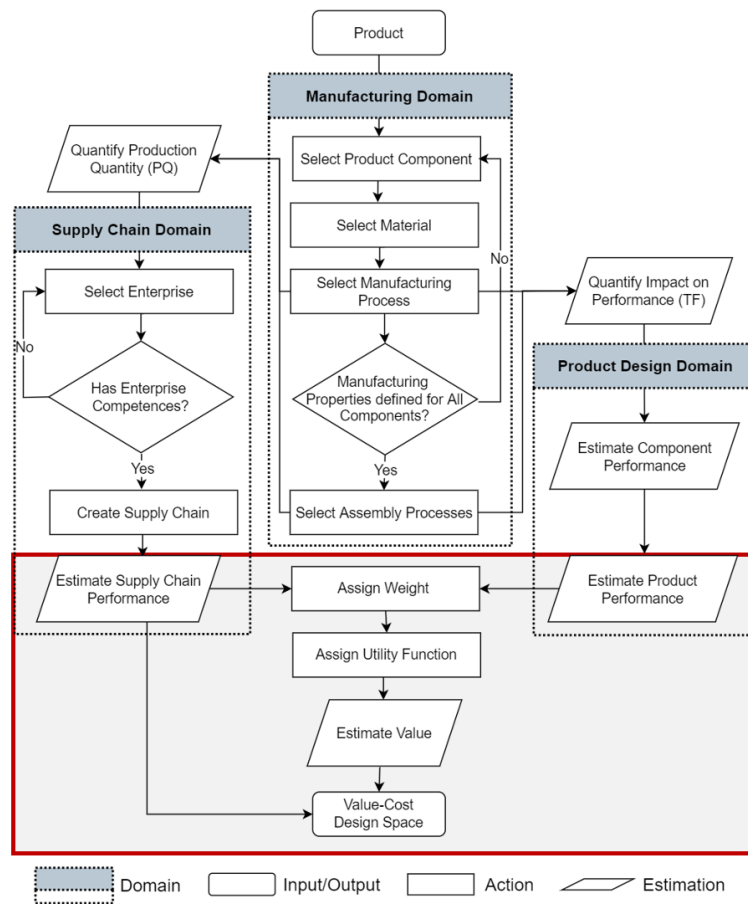


Figure 1 – Value-driven Concurrent Methodology: Value-model Theory to aggregate Supply Chain and Aircraft Performance, modified from [11]

In previous studies, same weights and linear utility functions have been assigned to the supply chain and aircraft performance to validate the methodology [13] [14]. In fact, under these assumptions, the value-cost design space is investigated without considering decision-making expectations. These studies facilitated the methodology validation and have been used as reference for the follow-up activities. In fact, some analyses have been then performed to trade decision-makers' expectations with respect to the supply chain performance [15]. Therefore, utility functions for the supply chain performance have been provided by decision-makers and included in the methodology to investigate the solutions behavior and compare it with the reference case [16]. This paper increases even more the complexity of the investigations aiming at trading decision-makers' expectations with respect to supply chain and aircraft performance at the same time. Therefore, utility functions for the aircraft performance are considered in addition to those related to the supply chain.

In the last decades, much effort has been placed in the research of concurrent methodologies simultaneously trading criteria related to the product and/or supply chain and/or manufacturing [17]

[18] [19], also in the aeronautical context [20] [21]. These methodologies, collected under the VDD (Value Driven Design) term [22] [23], range from Tradespace Exploration [24] [25] [26], to Value Centric Design [27] and Value Driven Optimization [28] [29]. They have a unique interpretation, quantification and representation of the term value but they share the same objective of identifying the best possible outcome when considering multiple and different criteria important for decision-makers [28] [30] [31]. In this activity, as already mentioned, the MAU theory is applied since it well suits the aim to increase the decision-makers' awareness during trade-off studies involving multiple criteria. Two decision-makers, that are the industrial partners involved in this study, provide their own utility functions for the supply chain and aircraft performance. The best solution for these decision-makers is so identified as the one with the highest value on the value-cost tradespace. However, trade-off studies can be performed also considering the cost related to each alternative.

In this paper, details on the criteria selected to perform the decision-making processes and on the utility functions provided by decision-makers are described in Section 2. In Section 3, the technologies supporting the multi-criteria decision-making processes are introduced. The value-cost design space and the identification of the best solution for decision-makers when considering the design, manufacturing and supply chain of a specific aircraft component is presented in Section 4. Finally, conclusions are reported in Section 5.

2. Value Model Theory Formulation: Attributes and Utility Functions Definition

In the methodology represented by the diagram of Figure 1, the MAU theory is applied to aggregate the supply chain and aircraft performance in a single dimensionless measure that is the *value*. In fact, the application of the MAU theory is recommended when the number of attributes is higher than three. The formula to estimate the value according to the MAU is the following one [32]:

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

In which:

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

Thus, to estimate the value, a weight and a utility function is assigned to each criteria. The weights represent the relative importance of attributes. The single attribute utility (SAU) functions, instead, are used to quantify decision-makers' expectations with respect to each attribute.

Criteria for the identification of the best aircraft configuration are usually related to the operation of the system and thus to its performance (e.g. thrust, fuel consumption). More challenging is instead the identification of criteria related to the aircraft production, thus with the supply chain and manufacturing, due to the difficulty in capturing the tacit knowledge from the specialists [6]. However, the production risk, quality and time have been selected as criteria for the identification of best supply chain because of the key role they have in the supply chain management [33]. These criteria, here also called supply chain performance, are estimated considering the transportation, manufacturing and fixed contributions [11]. Since the manufacturing contributions are included in the supply chain performance, criteria related to the manufacturing have been not explicitly considered for the best solution identification. A summary of criteria is reported in Table 1. These criteria are used to identify the best solution among all the alternatives populating the design space.

Table 1 – Decision makers' criteria to value the system

Criteria	Motivation	Description
<i>Production Risk</i>	Key Role in Supply Chain Management	Risk related to Transportation, Manufacturing and Geographic Location
<i>Production Time</i>	Key Role in Supply Chain Management	Time related to Transportation, Manufacturing and Geographic Location
<i>Production Quality</i>	Key Role in Supply Chain Management	Quality related to Manufacturing and Geographic Location
<i>Fuel Consumption</i>	Key Parameter for Regional Aircraft	Fuel Consumption Mass in Cruise

For each of the 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 2. As expected, the best solution is supposed to be the alternative with lowest production risk, time and fuel consumption but highest production quality.

Table 2 – Decision-makers' expectations

Attribute	Decision-makers' expectation
<i>Production Risk</i>	Lower the better
<i>Production Time</i>	Lower the better
<i>Production Quality</i>	Higher the better
<i>Fuel Consumption Mass</i>	Lower the better

These qualitative expectations have been translated into utility functions. 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 [24]. VALORISE, the interactive dashboard introduced in the next section, has been developed in-house to support decision-makers in easily represent their own utility functions. These functions are reported in Figure 2 for three cases studies. The first case study, Reference Case, includes linear utility functions. It is used to create a reference value-driven tradespace not influenced by decision-makers expectations. The other two cases studies instead implement decision-makers' expectations with respect to each criteria. The two cases studies, Decision-maker A and Decision-maker B, therefore consider the utility functions provided by the industrial partners involved in this research activity.

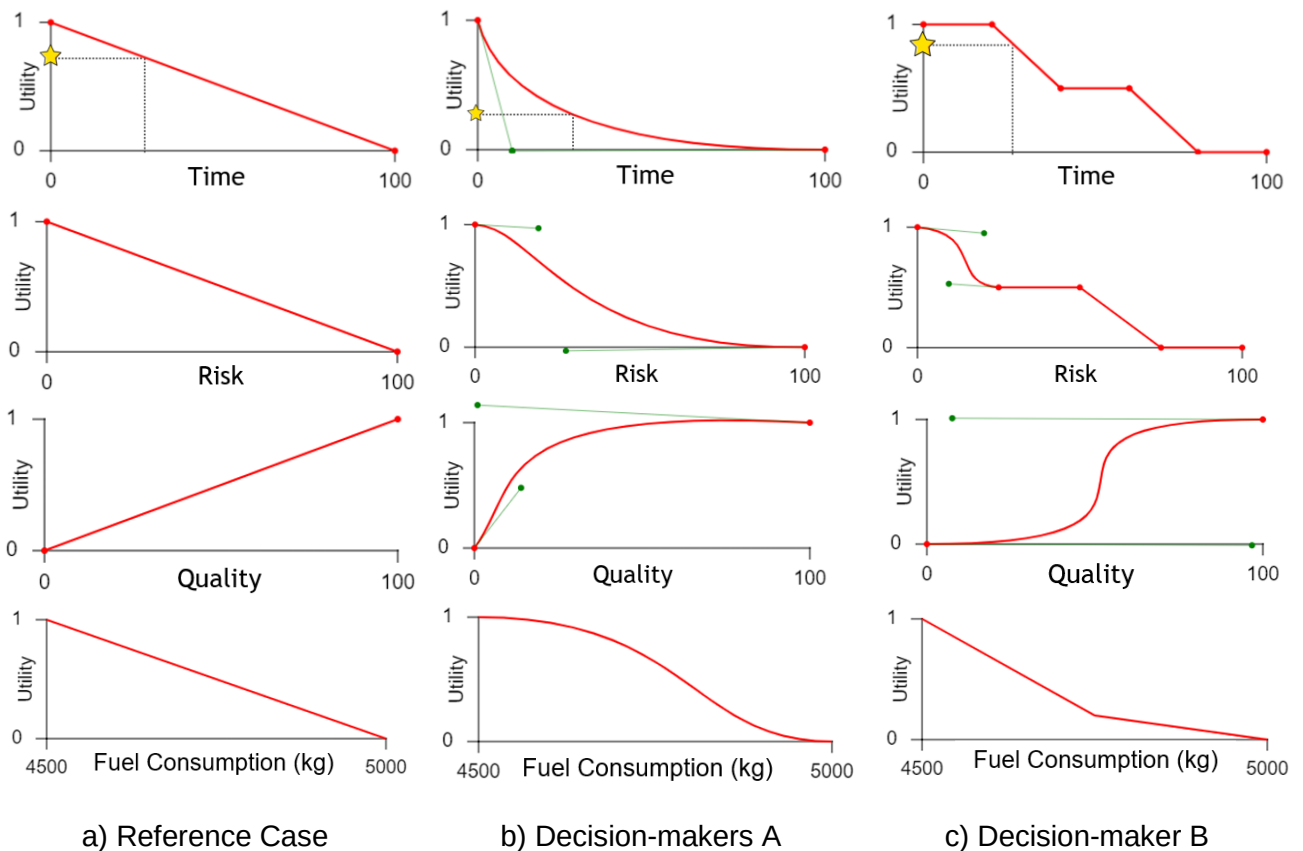


Figure 2 – Single Attribute Utility Functions quantifying Decision-makers' expectations

As shown in Table 2, the qualitative expectations are the same for both decision-makers. Instead, looking at Figure 2, 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, 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. The exploration of the value-driven tradespace is fully supported by the DLR internal tool developed to simplify the multi-criteria decision-making process. More details are provided in the next section.

3. Value Model Theory Implementation: VALORISE

The methodology introduced in Section 1 and used for the concurrent exploration of a value-driven tradespace is part of an extended Framework, shown in Figure 3. This Framework is built to address the concurrent design of aircraft, manufacturing and supply chain starting from the stakeholders, requirements and architecture modelling until the tradespace evaluation and exploration. Several methods and tools are therefore developed to support each step of the Framework [34] [35]. The methodology shown in Figure 1 supports the last step of this Framework, thus the evaluation of the alternatives populating the design space. Instead, to identify the best solution on the design space (last step of the Framework) by trading decision-makers' expectations with respect to multiple criteria (first step of the Framework), VALORISE has been developed by DLR.

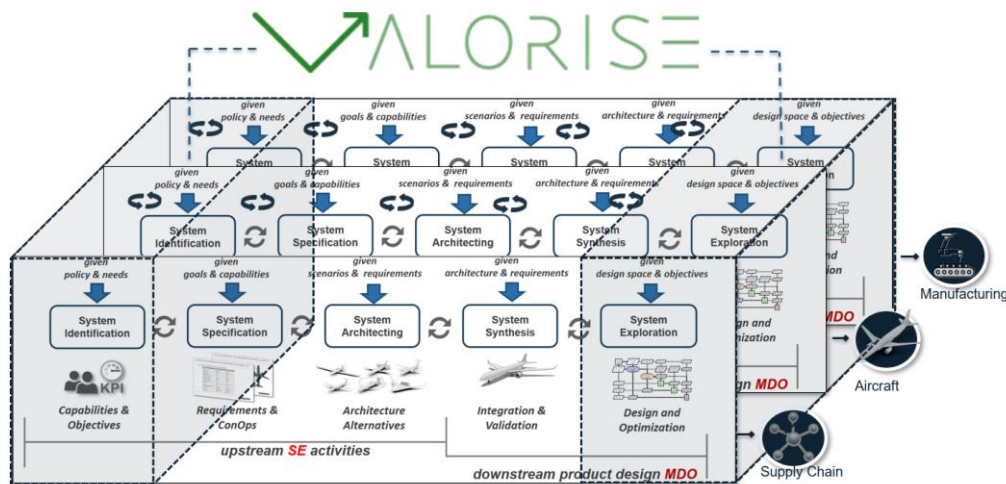


Figure 3 – Framework for the Concurrent Aircraft, Manufacturing and Supply Chain Design: VALORISE as dashboard to trade decision-makers' expectations, modified from [36]

VALORISE, which stands for Value-driven trAdespace visualizatiOn, exploRation and aSsessment, is an interactive dashboard based on the MAU theory. It has been implemented to simplify and automatize the multi-criteria decision-making process, analyze real-time strategic scenarios and easily explore the value-driven trade-space for the best solution identification.

Inputs needed by VALORISE, collected in different files format – among others CPACS files [37] - are 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. The settings of the value-model, thus the assignment of weights and utility functions can instead be defined by decision-makers directly in VALORISE, as shown in Figure 4. 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 so investigated real-time in VALORISE since 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, a comparison is shown among five different scenarios in which the weight combinations or the utility functions have been changed. This allows decision-makers to investigate the behavior of the alternatives in different scenarios before taking strategic decisions.

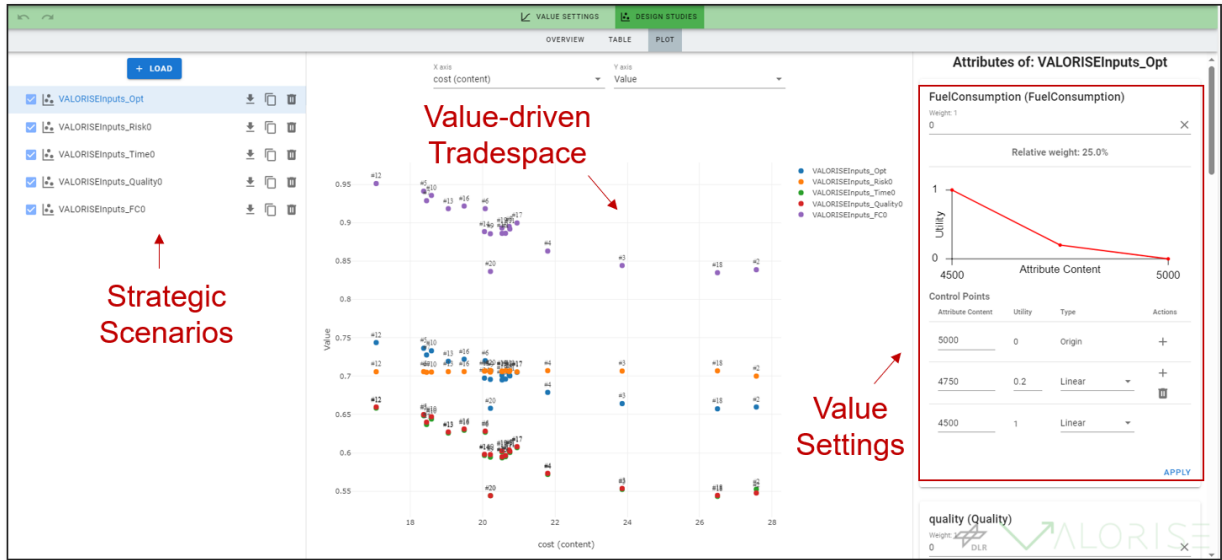


Figure 4 – VALORISE Dashboard supporting the Multi-Attributes Decision-Making Process

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. Finally, VALORISE can be also used as stand-alone tool to be integrated in a toolchain with other tools. This is useful when, for instance, uncertainty propagation or sensitivity analysis on weights and utility functions have to be performed for the identification of the robust solution. In this case, since a huge number of combinations have to be explored, using VALORISE as stand-alone tool instead of a dashboard reduce the computational time. In fact, decision-makers don't have to manually set all the possible combinations. In this research activity, however, VALORISE is used as dashboard and the utility functions drawn by decision-makers in VALORISE has been already shown in Figure 2.

4. Aeronautical Application Case

The methodology shown in Figure 1 is applied to an aeronautical application case. The product under design is a specific component, the Horizontal Tail Plane (HTP), of a regional 90 passenger aircraft. The aim of the application case is to identify the best solution on the design space while trading decision-makers' expectations in terms of aircraft and supply chain performance. However, before going deeply in the identification of the best solutions, the assumptions needed to generate the alternatives of the value-cost design space are briefly discussed here-after. The first assumption is related to the number of materials and processes that can be selected for each of the main HTP components. The second assumption, instead, is related to the number of enterprises that can be choose to perform the selected manufacturing processes. As shown in Figure 5, several combinations of materials and processes are considered for each of the main HTP components while 21 enterprises can be selected to perform each manufacturing process selected for each component.

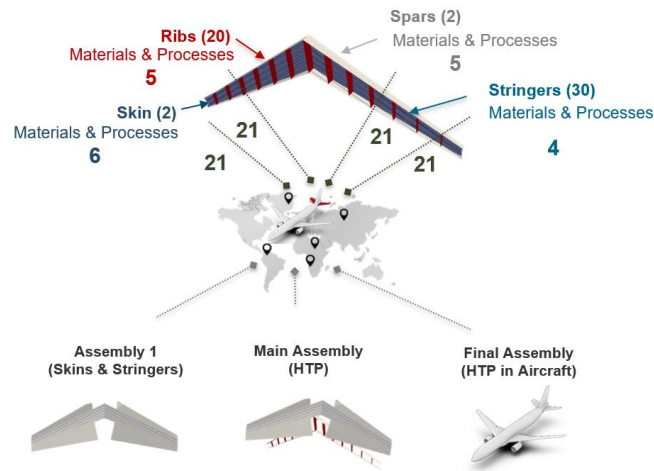
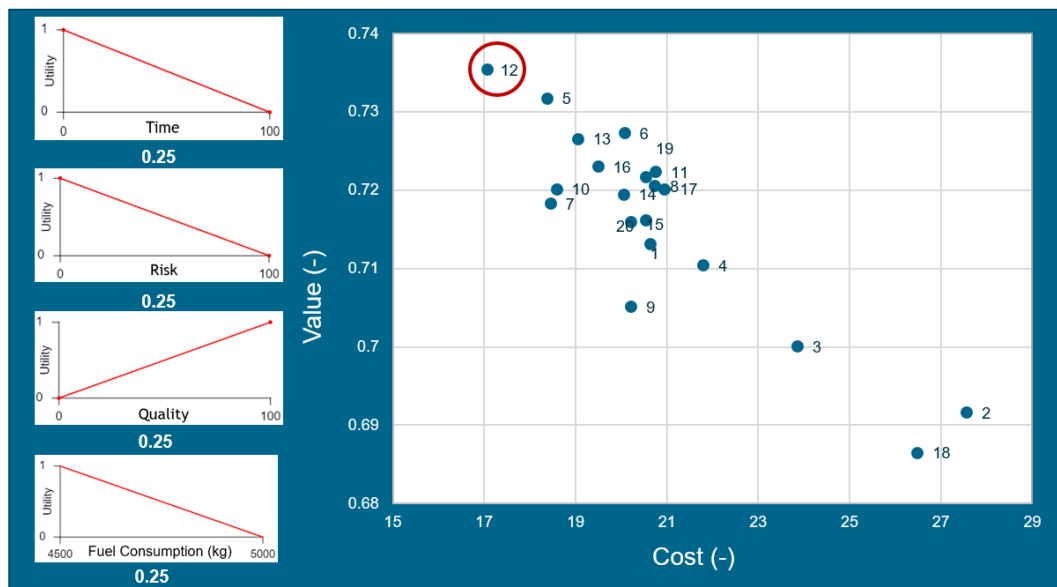


Figure 5 – Application Case Assumptions.

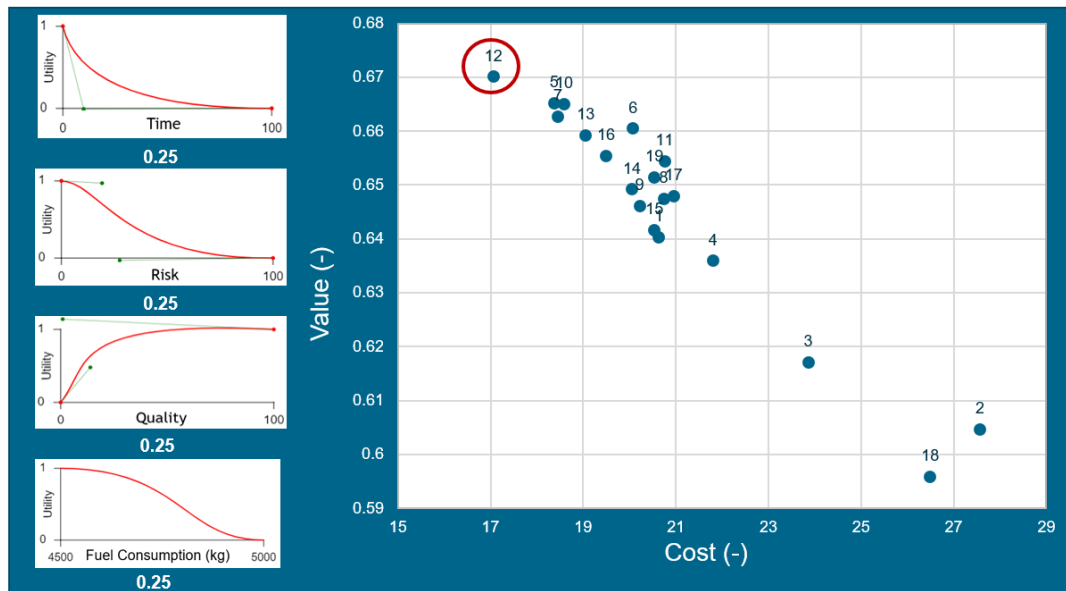
Combining all the possibilities, a design space of 11×10^6 alternatives is generated. Among the 11×10^6 alternatives, however, only 20 alternatives are on the Pareto Front. These solutions represent the optimal solutions in terms of aircraft and supply chain performance simultaneously [38] [39]. The 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. In particular, three case 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) [40]. The aim, here, is just to show readers how the value-driven tradespace can change depending on the weight combinations analyzed.

4.1 Case Study I

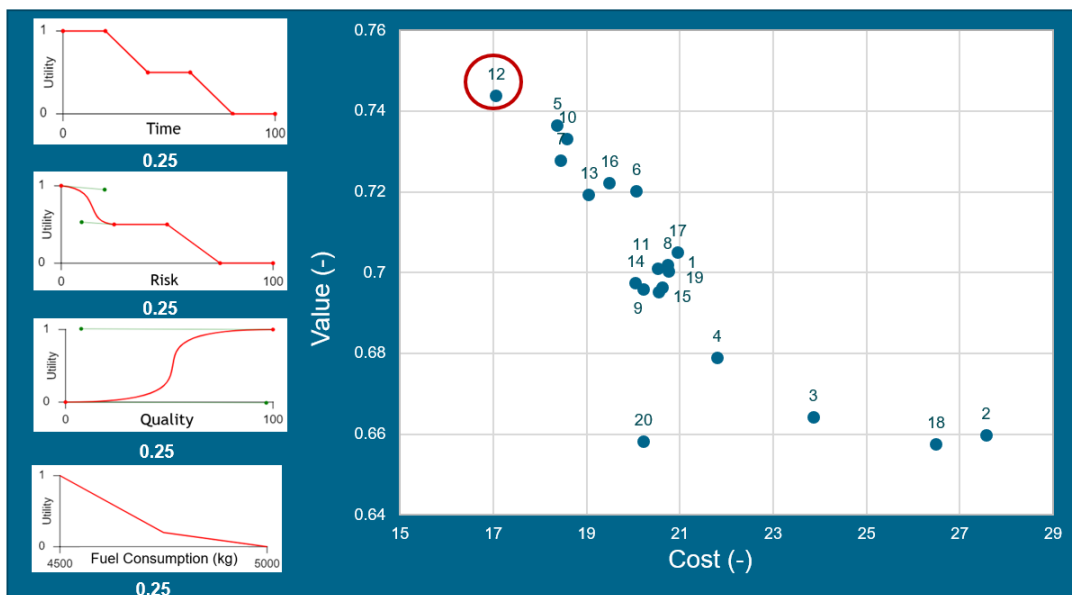
The value-driven tradespaces generated by implementing the utility functions reported in Figure 2 and the same weights for all the attributes are reported in Figure 6 a, b, c. These figures respectively represent the reference value-driven tradespace (no influence of decision-makers), the value-driven 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. This solution refers to an HTP configuration in which both Aluminum and Composite have been selected for the main HTP components. From the aircraft performance perspective, this solution is not the one minimizing the fuel consumption. In the value-driven tradespace, in fact, other solutions have a fuel consumption which is lower than the one of this solution. However, all the manufacturing and assembly processes are performed in house, at one site. This makes this solution extremely competitive when considering the supply chain performance, thus the production risk, time and quality. This detail can be also seen in Figure 8 and Figure 10, in which a comparison with other solutions is provided due to the analysis related to the weight combinations.



a) Reference Case



b) Decision-maker A



c) Decision-maker B

Figure 6 – Value-driven Tradespaces without Attributes Prioritization

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

4.1 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 7 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.

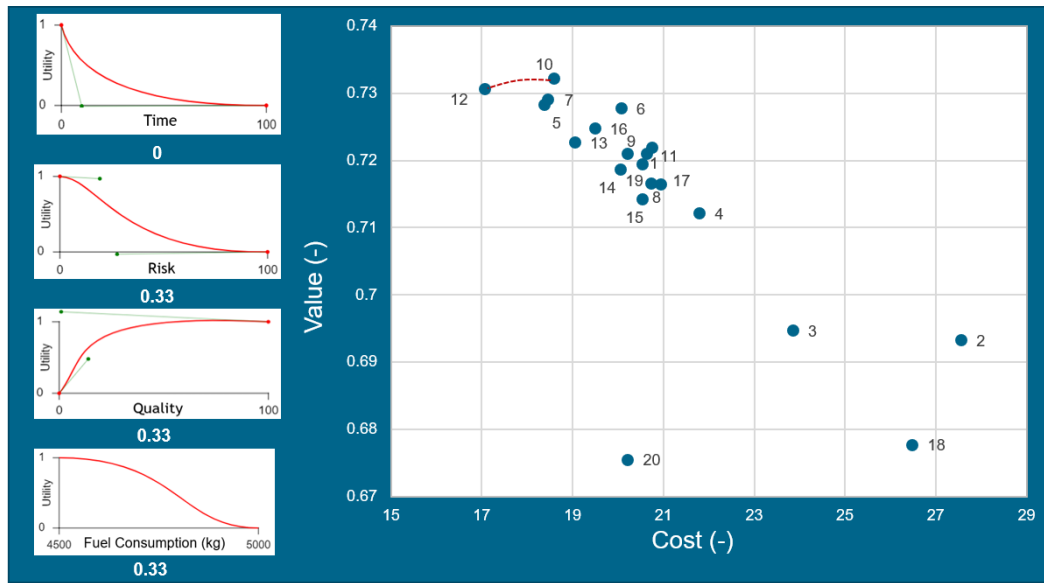


Figure 7 – Decision-maker A Value-driven Tradespace Exploration when Time Weight is Null

A detailed comparison between the two solutions is reported in Figure 8. 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 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 performant than solution 10. However, the aircraft configuration provided by solution 10 is less 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.

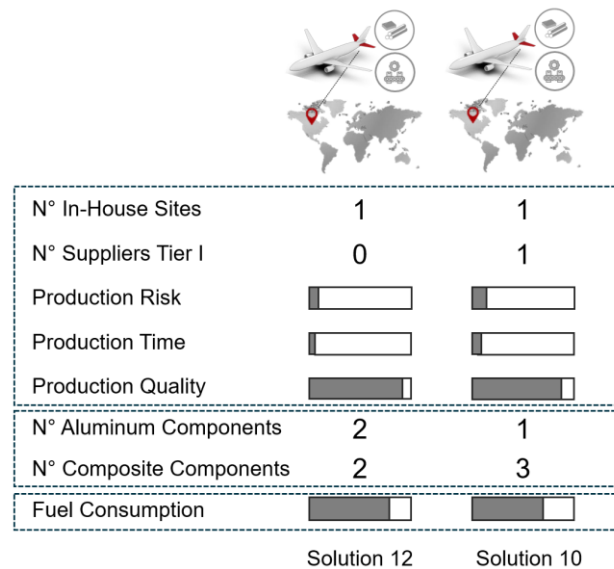


Figure 8 – Decision-maker A Value-driven Tradespace Exploration when Time Weight is Null: Comparison between the Pareto Front Solutions. Location of enterprises is qualitative due to industrial intellectual properties.

4.1 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 9 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 20 and not the solution 12 as in the first case.

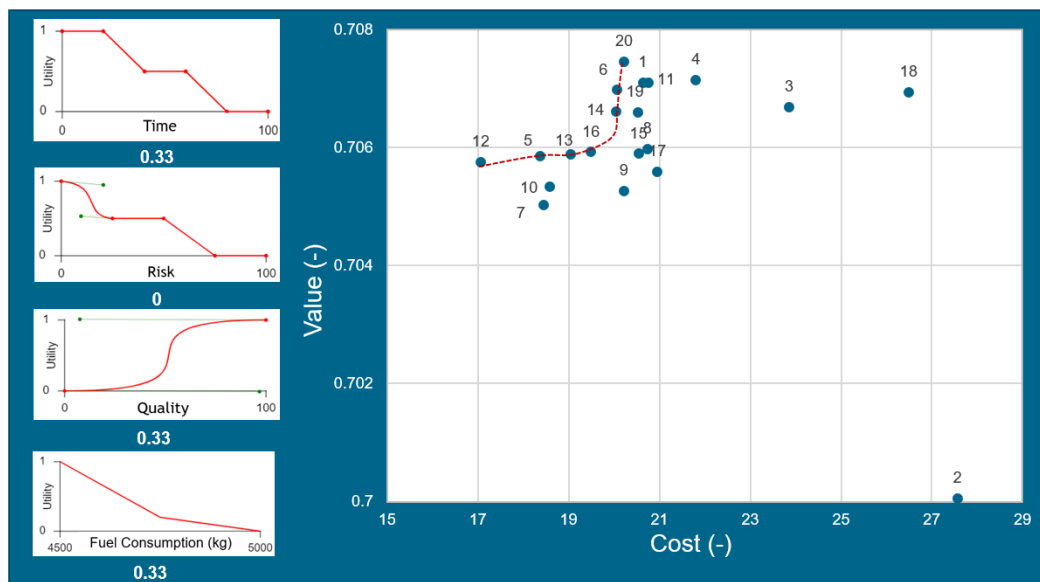


Figure 9 – Decision-maker B Value-driven Tradespace Exploration when Risk Weight is Null.

A detailed comparison among the solutions of the value-cost Pareto Front is reported in Figure 10. 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.

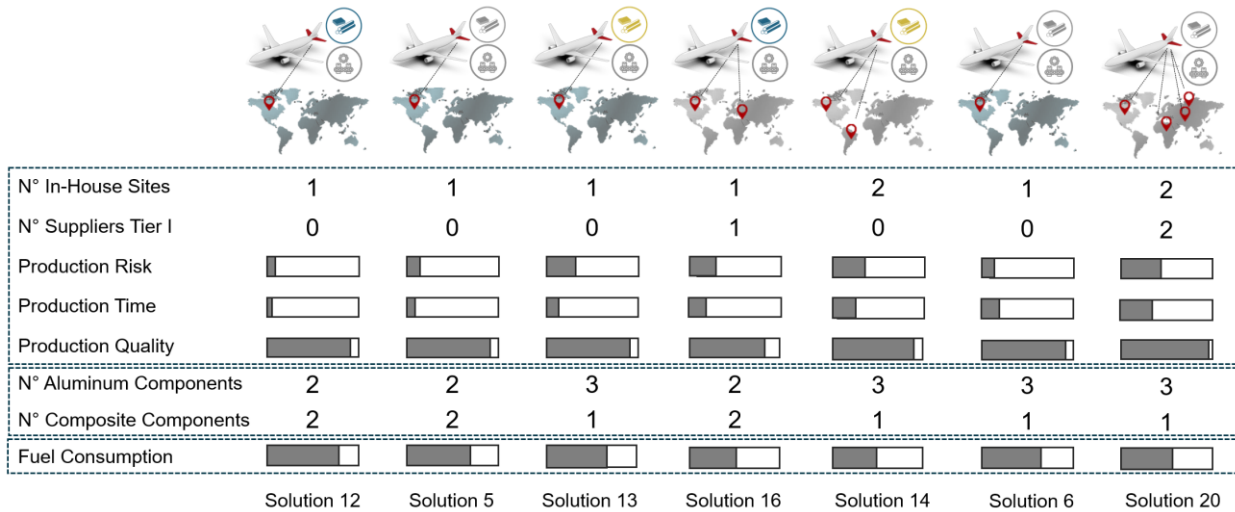


Figure 10 – Decision-maker B Value-driven Tradespace Exploration when Risk Weight is Null: Comparison between the Pareto Front Solutions. Location of enterprises is qualitative due to industrial intellectual properties while same colors of materials, manufacturing and world icons highlight the similarities among solution.

As shown in Figure 10, 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. Conclusions

This paper shows an exploration of a tradespace in which each solution refers, at the same, to the operational and production performance of an aircraft. The aim is to overcome the limits of the traditional sequential approach, in which decisions on production are addressed once fixed the design of the aircraft. The MAU theory is adopted to simplify the multi-criteria decision-making process. In particular, the dashboard called VALORISE, developed by DLR, is leveraged to give decision-makers the possibility to easily implement their own utility functions that represent the way they take decisions with respect to each attribute. VALORISE also supports decision-makers in exploring and comparing the different scenarios obtained, for instance, by changing the weight combinations. The approach is applied to an aeronautical case study. It highlights the advantages of modelling production aspects in the early aircraft life-cycle stages focusing on the possible trade-off studies that decision-makers can address. In addition, it shows how the value-driven tradespace changes depending on the analyzed scenario, meaning on the weight combination evaluated. The approach has been tested on an already existing aircraft configuration and well-assessed manufacturing processes for validation purpose. In this case, the investigation of the solutions part of the value-driven tradespace can support companies in improving already existing supply chains, for instance by investing more in the house machines or suppliers training. However, the same approach might be used for new aircraft configuration, for instance hydrogen configurations, to verify if companies of supply chains are ready for changes.

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