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Value-driven Systems Engineering Approach addressing Manufacturing, Supply-chain and Aircraft Design in the Decision-Making Process

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Abstract

In the last decades, some studies have highlighted that the integration of the product design and supply chain management leads to an increase of the profitability and efficiency of companies. However, considering manufacturing, supply chain and overall aircraft design variables in the early design

phase increases the size of the solutions tradespace and thus the complexity in performing the decision-making process. This paper, follow-up of previous research activities addressed within the European project AGILE4.0, demonstrates how to leverage the value-model theory to simplify the decision-process when multiple criteria are accounted in the design phase.

1. Introduction

To meet the heterogeneous societal needs, even more complex, innovative, sustainable and circular aeronautical systems are required nowadays. The objective of the sustainable and circular aviation is to reduce the environmental impact in terms of fuel consumption, waste and emissions associated with all the aeronautical system activities and operations (Flightpath2050, 2011). 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 activity. This surely enlarges the design space, having to consider even more variables related to different stages of the aircraft development in the design phase. However, it provides great possibility to aeronautical industries to win the nowadays global and competitive market (Wu & O'Grad, 1999). In this frame, the DLR Institute of System Architecture in Aeronautics aims at developing methodologies enabling the concurrent coupling of multiple domains (e.g. design, manufacturing) in the early stages of aircraft design to achieve solutions optimizing the entire aircraft life-cycle. The first step of this ambitious goal has been addressed within the European funded H2020 project AGILE 4.0 (INEA & Consortium, 2019), follow-up of the AGILE project (AGILE Website, 2022), also led by the DLR. By leveraging Multidisciplinary Design Optimization (MDO) and Model Based Systems Engineering (MBSE) technologies, this project aims at creating a digital representation of the system under design throughout the entire life-cycle (Ciampa & Nagel, 2021). Particularly, one of the challenges is to include all the main pillars of the aeronautical supply-chain during the early stages of aircraft design, with the objective to address innovative trade-off studies never performed before.

With this purpose, a value-driven methodology concurrently coupling manufacturing (MfG), overall aircraft design (OAD) and supply chain (SC) has been developed within one of the AGILE4.0 application cases. A schematic representation of this methodology, applied to the horizontal tail plane (HTP) of a regional 90-pax aircraft (AGILE Consortium, 2016), is reported in Figure 1. The manufacturing domain, dealing with the choice of materials, manufacturing and assembly processes for the HTP, is linked with the supply chain domain through the production quantity (PQ) that each enterprise has to perform. Based on this production quantity and on the characteristics of each individual enterprise, in the supply chain domain, production cost, time, quality and risk for each supply chain architecture, combination of multiple enterprises, are estimated. On the other side, a technology factor (TF) links the manufacturing domain with the overall aircraft design domain. In the OAD domain, the aircraft performance and specifically the aircraft fuel mass consumption (in cruise) is estimated based on this TF, which quantifies the impact that the HTP manufacturing choices have on the HTP mass and drag. The methodology then leverages the value-model theory to allow the concurrent coupling of these domains. Therefore, the production risk, time and quality characterizing the SC domain and the fuel mass consumption characterizing the OAD domain, are aggregated in the *value* by assigning to each one a weight and a single utility attribute (SAU) function. For more information about the methodology itself, reader can refer to (Donelli, et al., 2021). In this study, however, the value-model theory has been leveraged only as weighted-sum function. This means that the same weights and linear utility functions have been assigned to all the attributes before being aggregated in the *value*. As consequence, the value-driven tradespace has not been influenced by stakeholders 'expectations. Therefore, the **solution** with the **highest value**, in this case, might **not be the best** solution for stakeholders. In fact, stakeholders 'expectations are modelled through the utility functions. By using linear utility functions on linearized data, the stakeholders' expectations with respect to the criteria aggregated in the *value* have not been considered.

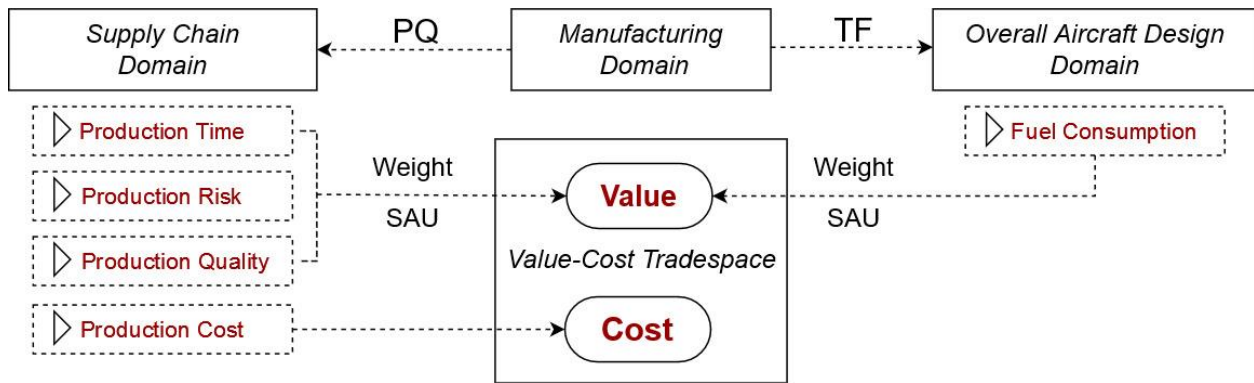


Figure 1 – Value-driven methodology concurrently coupling manufacturing, supply chain and overall aircraft design domain

The focus of this paper, instead, is on the use of the value theory to address and simplify the decision-making process when multiple criteria, also called attributes in the value-model theory, have to be taken in account. In fact, including manufacturing and supply chain decisions in the early development stage of aircraft design increases product competitiveness, giving to aeronautical industries the chance to win the nowadays global market. However, it also complicates the decision-making process having stakeholders consider even more criteria while taking a decision. In this paper, the challenge is to identify the best solution for stakeholders considering not only aircraft performance, but also production aspects being the supply chain and manufacturing domains included in the early design stage. For this purpose, the DLR internal tool, called VALORISE, is used to support stakeholders in modelling their expectations with respect to these criteria. Thus, first stakeholders identify the attributes, meaning the criteria playing a key-role when they have to take a decision. Then, an analysis (e.g. an MDO problem) is executed to numerically estimate these attributes. Finally, stakeholders model their expectations with respect to the defined attributes through the utility functions. Once defined the utility functions and the weights to attributes, the value-driven tradespace is generated by leveraging the value-model theory. In this case, the **solution** with **highest value** is the **best** solution for stakeholders.

In this paper, details on the value-model theory are provided in Section 2. In the same section, the AGILE4.0 MBSE-MDO framework is introduced to clearly describe the role of VALORISE, the interactive dashboard developed at DLR, based on the value-model theory and supporting the multi-criteria decision-making process. An application case addressing the design, manufacturing a supply chain of the HTP is described in Section 3. However, before addressing the decision-making process, the attributes and the MDO problem providing the solutions of interest for the decision-making process are introduced and described in the same section. Finally, conclusions are provided in Section 4.

2. Value-driven Decision-making Process Definition

Including manufacturing and supply chain decisions in the early development stage of aircraft design complicates even more the decision-making process. In fact, identifying the best solution while multi-criteria have to be considered is a great challenge for the decision maker. He/she might prefer an alternative because of one of the criteria, but not others. The objective of this research activity is to leverage the interactive dashboard VALORISE, implemented at DLR, to simplify the multiple criteria decision-making process and easily identify the best solution based on stakeholder's expectations. But, what does **best solution** means? In this study, it is assumed as best solution the alternative on the value-driven pareto-front that perfectly matches stakeholder's expectations with respect to all the selected decision criteria (or attributes). The theory supporting this activity and also implemented in VALORISE is the value-model theory. For this reason, first details on the value-model theory are provided in Section 2.1. Then, the process explaining how VALORISE is leveraged to identify the

best solution on the value-driven pareto-front based on stakeholder's expectations is explained in Section 2.2.

2.1 Value Model Theory

The value-model theory is used in this research activity to simplify the multi-criteria decision-making process. Among all the available techniques presented in literature, the Multi Attribute Utility (MAU) theory is here adopted (Keeney & Howard, 1993). It is a good practice to use MAU when, at least, three criteria (also called attributes) are considered for the decision-making process (Ross & Rhodes, 2010). The MAU formula is the following:

$$U(\underline{X}) = \sum_{i=1}^N \lambda_i U(X_i)$$

In which:

- N is the number of attributes;
- $U(\underline{X})$, $U(X_i)$ are the multi-attribute and single attribute utility function respectively;
- λ_i is the weight associate with attributes X_i :

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

For the *value* estimation, it is important to define:

- Attributes;
- Single Attribute Utility (SAU) Functions;
- Attributes Weights.

Attributes are the criteria (or the expectations) selected by stakeholders for identifying the best solution. Once defined the attributes, the SAU functions are used to quantify stakeholder's expectations with respect to each attribute. They represent the way stakeholders would select a solution by only considering this attribute. For this reason, they are used to translate the qualitative stakeholder's preferences in analytical curves. For the SAU functions elicitation, the function trend and the boundaries of each attribute have to be defined. An example of linear and not-linear SAU functions is reported in Figure 2. Utility (y-axis) usually ranges from 0 to 1 and expresses the stakeholder's satisfaction with respect to the attribute content. The attribute content (x-axis) is the numerical value of the attribute. It is indicated in the entire study as attribute content instead of attribute value for sake of clarity (*value* is the dimensionless measure aggregating all the criteria).

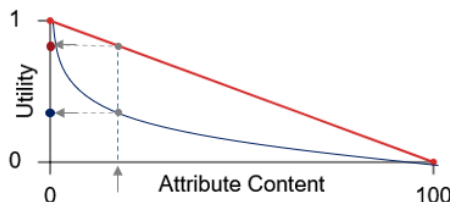


Figure 2 – Single Attribute Utility (SAU) functions: linear (red) and not-linear (blue) trend

Given an attribute content, higher is its utility, higher is the stakeholder's wiliness in accepting a solution with this specific attribute content. As consequence, changing the utility functions trend, it is possible to represent stakeholder's preferences. In the example of Figure 2, for a specific attribute content (grey arrow), the stakeholder's wiliness in accepting a solution with this attribute content drastically reduced by switching from the linear case (red point, higher utility) to the not-linear curve (blue point, lower utility). The elicitation of the utility functions is the most challenging step for the *value* estimation. Several methods are available in literature for the attribute utility function design,

from questionnaire to advanced tools. However, interactive tools in which the decision maker can directly design the utility functions, might support decision makers in well-represent the qualitative preferences (Ross, Rhodes, & Fitzgerald, 2005). For this purpose, the DLR internal tool called VALORISE is used in this research activity as later described. Once assessed the SAU function trend (e.g. linear, exponential), the x-axis boundaries (attribute content) can be also defined to create scenarios of interest. In fact, solutions with an attribute content lower than the lower boundary and/or higher than the upper boundary are excluded from the value-driven tradespace. Finally, the weight combination has to be defined. Weights are associated to attributes to express the relative importance of each other. Therefore, also in this case, several strategic scenarios can be analyzed by prioritizing attributes according to stakeholder’s needs.

2.2 VALORISE supporting the Value-driven Decision-Making Process

As already mentioned in the previous sections, the DLR internal tool called VALORISE is used in this study to support the multi-criteria decision-making process. However, since this tool is part of the AGILE4.0 MBSE-MDO framework, shown in Figure 3, a brief overview of this framework is first provided for reader’s complete comprehension.

The AGILE4.0 MBSE-MDO framework, web-based and therefore accessible from multiple partners, combines several blocks ranging from the system identification, thus identification of stakeholders, needs and requirements to the system exploration, thus the optimization of the system under design. In previous research activities, all the steps of the framework have been already addressed (Donelli, et al., 2022). Briefly, once selected all the stakeholders, needs and requirements, functional requirements have been collected to generate the system architectures in ADORE (Bussemaker, Ciampa, & Nagel, 2020) (Donelli, et al., 2022). To check the consistency between the architectures and the MDO problems, the DLR internal tool called MULTILINQ has been used (Bussemaker, Ciampa, & Nagel, 2022). The MDO problems have been then setting-up by using MDax (Page Risueño, Bussemaker, Ciampa, & Nagel, 2020) and executed within RCE (RCE Website, 2022). The MDO problem set-up and execution has been automatized through CPACS (CPACS Webpage, 2022).

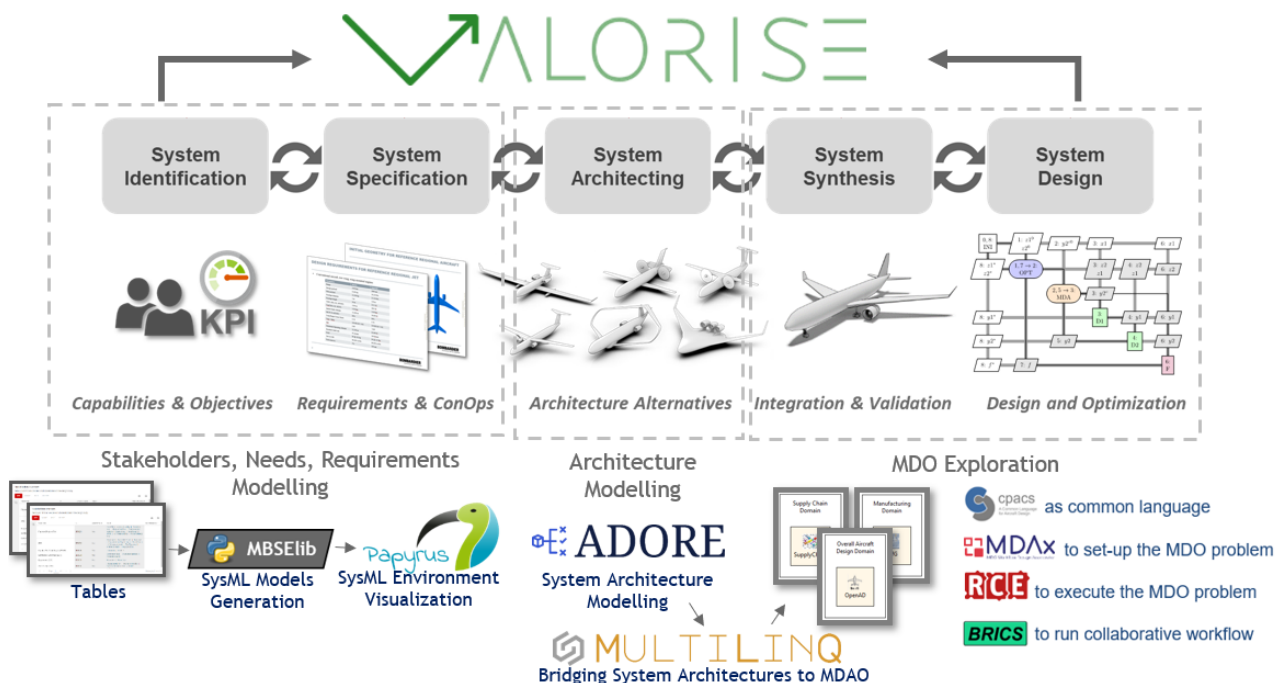


Figure 3 – AGILE4.0 MBSE-MDO Framework including Decision-Making, adapted from (Ciampa & Nagel, 2021)

VALORISE, which stands for Value-driven tradespace visualizatiOn, exploRatiOn and asSEssment is an interactive dashboard, developed by DLR, leveraging the value-model theory to simplify the multi-criteria decision-making process. Within the AGILE4.0 MBSE-MDO framework, as shown in Figure 3, it is used to link stakeholder’s expectations with the MDO exploration to identify the best solution on the value-driven pareto-front. Thus, the best solution is the one on the pareto-front matching stakeholders’ expectations with respect to multiple criteria. Before performing the decision-making process two steps have to be addressed: the definition of the attributes (first block of the AGILE4.0 framework) and the numerical estimation of the attributes through the MDO problem execution (last block of the AGILE4.0 framework). Thus, from one side stakeholders have to define attributes, that are the criteria playing a key role when they have to take a decision. On the other side, an MDO problem is set-up and executed to estimate attributes and achieve the pareto-front. Particularly, the solver SEGOMOE based on Bayesian optimizer has been adopted to solve multi-objective optimization problems (Bartoli, et al., 2019) (Grapin, et al., 2022). In this way, the best solution, matching stakeholders’ expectations with respect to all the attributes, is identified on the value-driven tradespace as the one with the highest *value*. The modelling of this process, shown in Figure 4, is supported by the AGILE4.0 framework technologies. The attributes defined by stakeholders are collected in a CPACS file - called baseline in Figure 4 - then used to run the MDO workflow which provides the attributes contents and pareto-front. All the CPACS files, generated for each solution of this MDO problem, are collected in a .zip file and given as input to VALORISE.

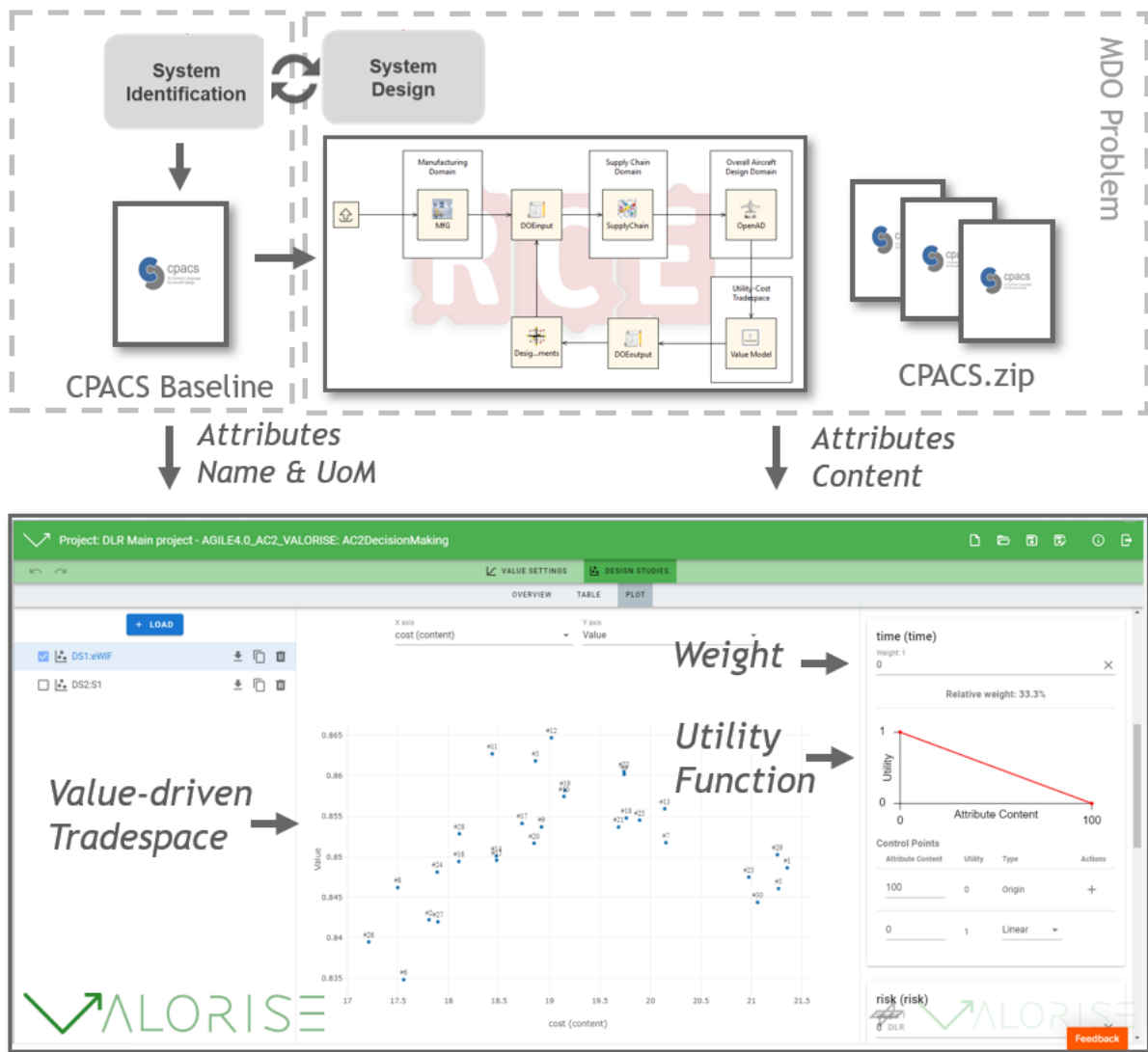
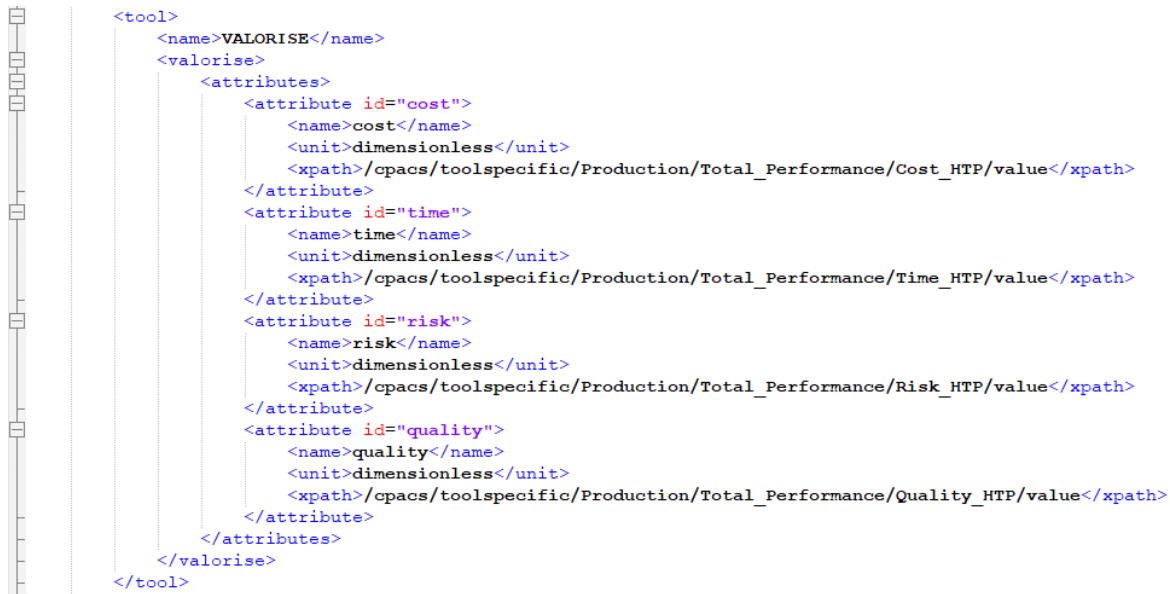


Figure 4 – Value-driven Decision-Making Process and Technologies

Information collected in the CPACS are the attributes name, the unit of measure of each attribute and the path in which the content of the attribute is stored. An example of CPACS structure read by VALORISE is shown in Figure 5. Particularly, the name and unit of measure of attributes are defined in the first step of the AGILE4 framework by stakeholders, while the attributes contents are the outputs of the MDO problem, instead addressed in the last step of the AGILE4.0 framework.



```

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  <valorise>
    <attributes>
      <attribute id="cost">
        <name>cost</name>
        <unit>dimensionless</unit>
        <xpath>/cpacs/toolspecific/Production/Total_Performance/Cost_HTP/value</xpath>
      </attribute>
      <attribute id="time">
        <name>time</name>
        <unit>dimensionless</unit>
        <xpath>/cpacs/toolspecific/Production/Total_Performance/Time_HTP/value</xpath>
      </attribute>
      <attribute id="risk">
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        <unit>dimensionless</unit>
        <xpath>/cpacs/toolspecific/Production/Total_Performance/Risk_HTP/value</xpath>
      </attribute>
      <attribute id="quality">
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        <unit>dimensionless</unit>
        <xpath>/cpacs/toolspecific/Production/Total_Performance/Quality_HTP/value</xpath>
      </attribute>
    </attributes>
  </valorise>
</tool>

```

Figure 5 – CPACS input file for VALORISE tool

Based on these inputs, VALORISE is then used to simplify the multi-criteria decision-making process. All the attributes are aggregated in one single dimensionless measure, which is the *value*, by assigning a weight and a utility function to each attribute. In this way, the value-driven tradespace is generated. In other words, the pareto-front of the optimization problem is translated in the value-driven tradespace in which the best solution is identified as the one with the highest *value*. The settings of the value model, weights and utility functions, can be easily defined by stakeholders directly in VALORISE. Single utility functions, as already mentioned in the previous section, represent the way stakeholders would select solutions based on this attribute. In VALORISE, stakeholders can interactively draw utility functions to represent in the best way possible their expectations with respect to each selected attribute. Instead weight represents the relative importance of each attribute. In VALORISE stakeholders can set several weight combinations to analyze the scenario of interest. In fact, real-time scenarios can be investigated 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. Finally, VALORISE can be also used as stand-alone tool and be integrated in a toolchain with other tools, for instance in RCE, to perform specific analysis. However, this is out of scope since in this research activity, VALORISE has been used by stakeholders as interactive dashboard.

Clarified the process, technologies and information needed to address the decision-making, in the next section an application case is presented. First attributes are defined, then the MDO problem is executed to estimate attributes and finally the best solution is identified on the value-driven pareto-front as the one with the highest *value*.

3. Value-driven Decision-Making Application

As explained in the previous section, to identify the best solution it is necessary to identify the key decision-criteria (attributes) for stakeholders from one side and run an MDO workflow to estimate the attributes and obtain the pareto-front on the other. In this section, an application case addressing the identification of the best solution when multiple criteria have to be considered at the same time is described. In particular, in the first sub-section the attributes selected by stakeholders are

introduced; in the second one the optimization problem executed to obtain the pareto-front is presented and finally the decision-making process allowing the identification of the best solution on the value-driven pareto-front is addressed.

3.1 Attributes Definition

The first step to find the best solution consist in the identification of the key criteria playing a key role when stakeholders have to take a decision. These criteria, also called attributes, are selected by stakeholders (first step of AGILE4.0 framework). In this activity, several attributes, reported in Table 1, are identified by stakeholders. Particularly, the production time, risk, quality and cost, characterizing the SC domain, are selected as attributes by stakeholders because of their significant impact on the production management (Guide, 2001).

Table 1 – Attributes Definition

Parameter	Domain	Role
Production Time	Supply Chain	Attribute
Production Risk	Supply Chain	Attribute
Production Quality	Supply Chain	Attribute
Production Cost	Supply Chain	Attribute

The production risk, time and quality are therefore the key criteria considered by stakeholders in finding the best solution. These criteria, as reported in Section 2.1, are then aggregated in a single dimensionless measure which is the *value*, once a weight and a utility function is assigned to each of them. In addition to these, also the production cost plays a key role for stakeholders in the decision-making process. However, it is used in this research activity, as other variable for the *value*-cost tradespace generation. In this way, stakeholders can perform trade-off studies of interest deciding whenever to go for a solution with lower *value* and cost or spend more to achieve an even more “valuable” solution.

Once defined the attributes, the next step is to numerically estimate the attributes. An MDO problem is here executed to evaluate attributes and identify the pareto-front.

3.2 Attribute contents estimation: MDO problem execution

Once defined the attributes, the next step for the best solution identification relays in the numerical estimation of these attributes. The contents of attributes are estimated by running an MDO problem, addressed in this section.

The MDO problem aims at maximizing the production performance while changing the production quantity assigned to enterprises. In this case, the manufacturing properties are fixed and all the combinations of the enterprises able to perform the selected materials and processes are analyzed, as reported in Table 2. Among all the $9 \cdot 10^6$ possible combinations, 19 solutions are identified on the 4-objective pareto-front. Reader can refer to (Merola, et al.) to know more about this MDO problem since this out of scope for this research activity.

Table 2 – HTP Configuration Description

HTP Components	Number of Components	Materials & Processes	Number of Production Site	Number of Assembly Sites
Skins	2	Sheet Metal Stretch Formed	13	4
Stringers	30	Metal by Z-Extrusion	13	
Spars	2	Machined Aluminium	14	9
Ribs	20	Machined Aluminium, Sheet Metal Stretch Formed	10	

Once estimated the attributes, the next step is to aggregate these attributes in the *value*, defining the utility functions and weights, to identify then the best solution on the value-driven tradespace.

Thus, for the decision-making process the 4-objective pareto-front is “translated” in a value-driven pareto-front. Two strategies could be addressed here as shown in Figure 6: Strategy I in which attributes are estimated through an optimization and then aggregated in the *value* through a weight and a utility function; Strategy II in which attributes are aggregated in the *value* through a weight and a utility function and then the *value* and cost are optimized. However, in case of strategy II, the optimization has to be executed anytime weights and utility functions are changed, as needed to address the decision-making process. In addition, it has been demonstrated that the 2-objective pareto-front is included in the 4-objective pareto-front (Donelli, et al., 2022). Therefore, to reduce the computational time, it has been decided to follow Strategy I in this research activity. Hence, first the optimization is executed and then the value-driven tradespace is generated by changing weights and utility functions. Therefore, in the next section, the 4-objective pareto-front is “translated” in a value-driven tradespace by aggregating the optimized attributes of each solution of the pareto-front in the *value*. Changing the utility functions or the weight combination, it is shown in next section how the *value* of these solutions changes.

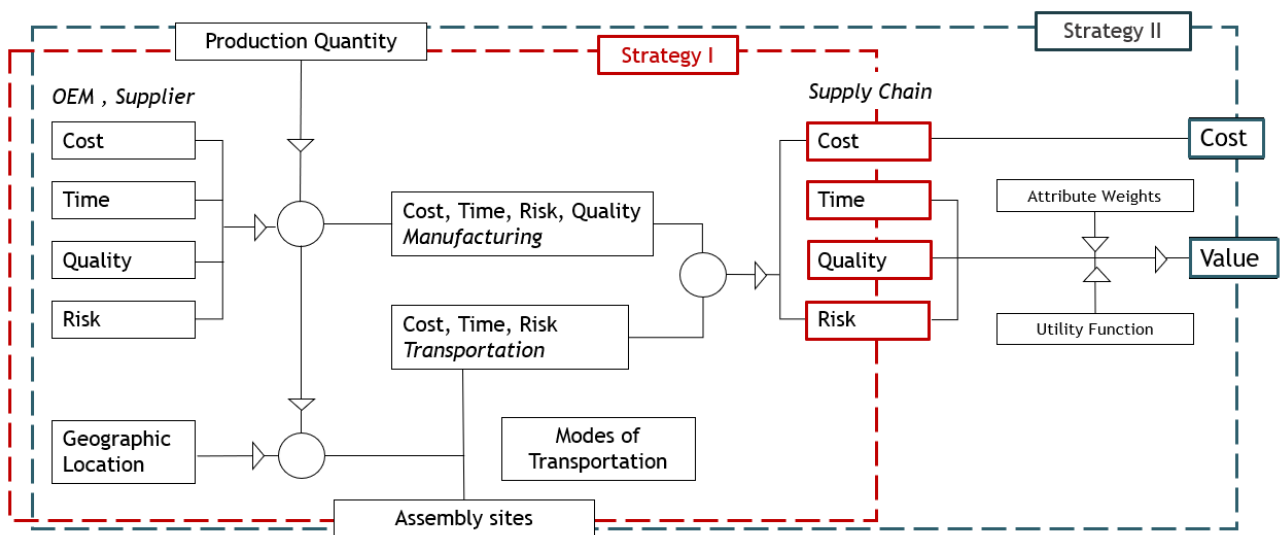


Figure 6 – Strategy I (in red) adopted to perform the decision-making process: first a 4-objective optimization is executed, then strategic scenarios are addressed by changing the value settings

3.3 Value-driven Decision-Making Process Analysis

Once defined attributes and run the MDO workflow, the best solution can be identified on the value-driven pareto-front. From the execution of the MDO problem previously introduced, 19 points have been identified on the 4-objective pareto-front. In this section, the *value* is first used as weighted-sum function to simplify the visualization of the 4-objective pareto-front and then to address and simplify the multi-criteria decision-making process.

To use *value* as weighted-sum function, the hypothesis of linear utility functions and same weights for all the attributes is mandatory. These assumptions are summarized in Table 3, while the utility functions are plotted in Figure 9a.

Table 3 – “Reference” Value-driven Tradespace Characterization

“Reference” Value-driven Tradespace	Attributes	Utility Function		Weight Combination
		Trend	Boundaries	
	Time	Linear	[100,0] [0,1]	0.33
	Quality	Linear	[0,100] [0,1]	0.33
	Risk	Linear	[100,0] [0,1]	0.33

To all the attributes the same boundaries have been assigned (x-axis ranging from 0 to 100) to include all the solutions in the value-driven tradespace. Attributes contents are already normalized (0 to 100) due to industrial partners’ intellectual properties. In this case, utility functions do not represent decision maker’s preferences. They can be read as analytical curves used to translate different parameters having different scale of measures in the same dimensionless one to be correctly compared. In addition, curves follow the logic flow of higher the worst for risk and time, higher the better for quality. In this case, the value-driven tradespace is therefore **not** influenced by decision-maker’s preference. Identified as “reference” value-driven tradespace, it is reported in Figure 7. Higher is the *value*, better is the solution. This value-driven tradespace highlights as solution with highest *value* the alternative 1, red circle in the plot. However, it is worth to underline that this solution might **not be** the **best** solution for stakeholders since decision-maker’s preferences have not been considered yet.

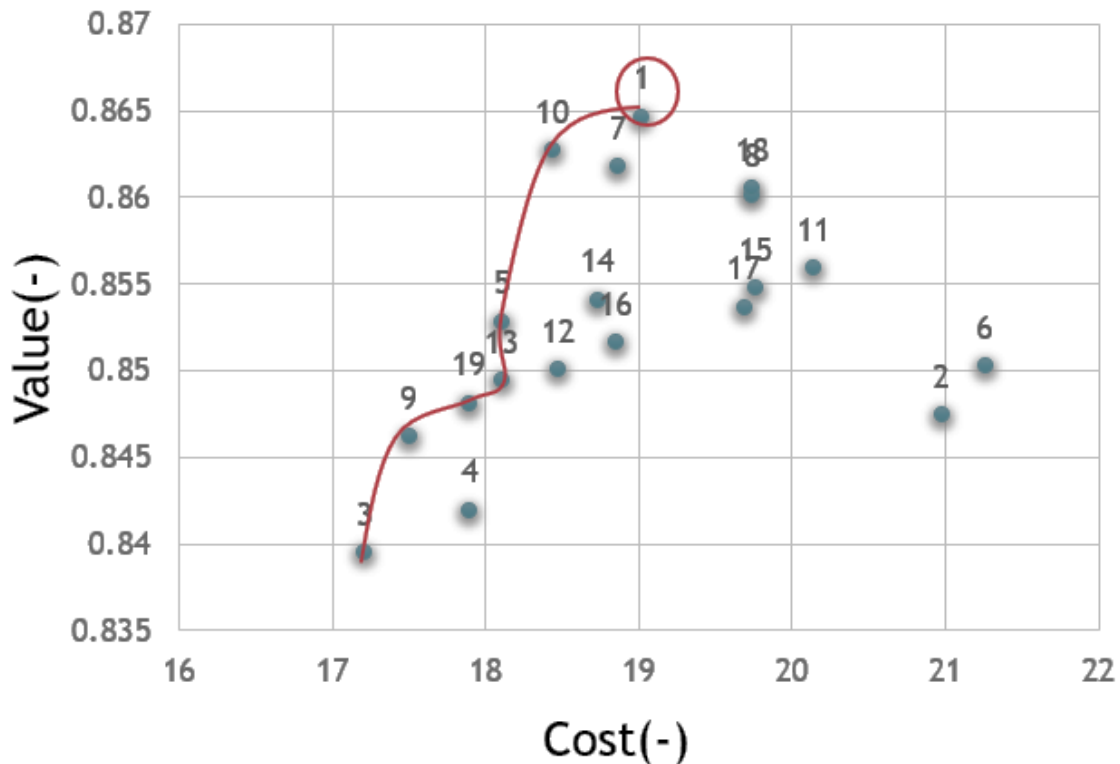


Figure 7 – “Reference” Value-driven Tradespace - same weight and the same linear utility function for all the attributes (production risk, time and quality)

The next step instead is to introduce stakeholders’ expectations to identify in the value-driven tradespace the best solution as the one with the highest *value*. In Figure 8, the qualitative stakeholders’ preferences with respect to the selected attributes are represented. As expected, stakeholders prefer solutions with lower production cost, time and risk but higher quality.

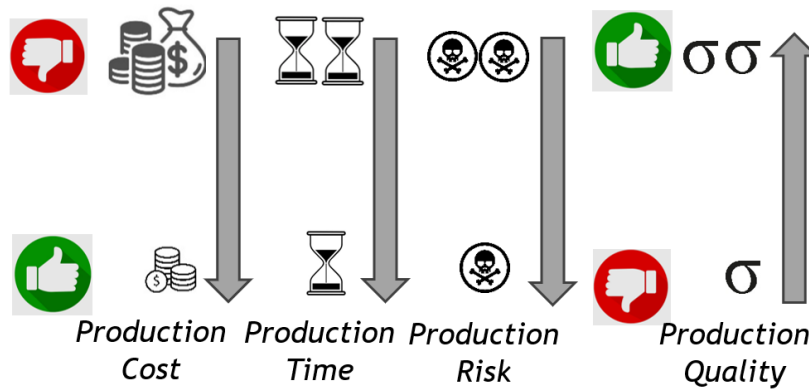
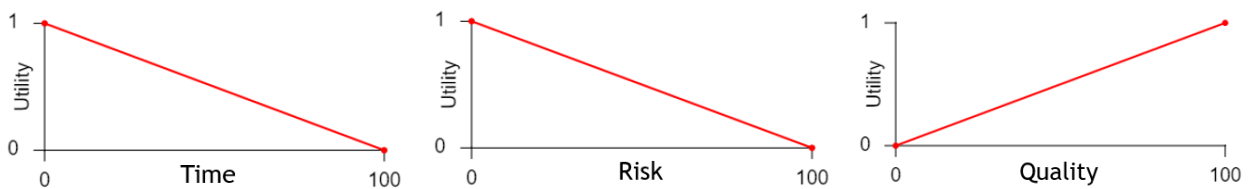
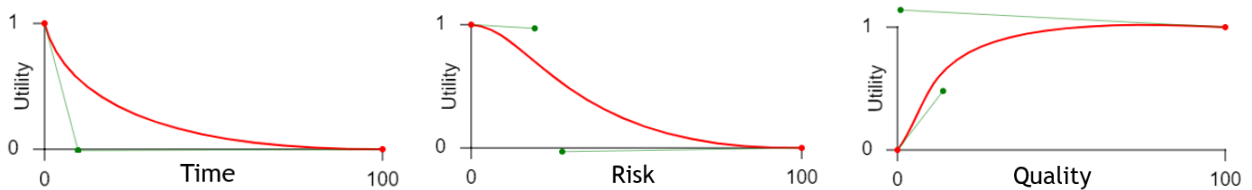


Figure 8 – Stakeholders Qualitative Preferences

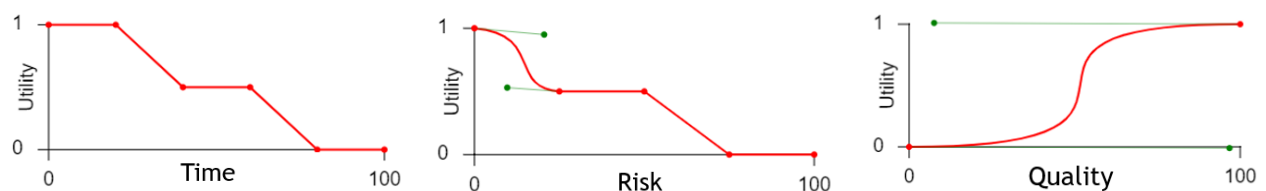
To account for stakeholders' expectations, it is necessary to quantify such preferences with respect to all the attributes. The utility functions are used to quantify such expectations. Particularly, stakeholders used VALORISE to draw the utility functions representing their preferences respect to these attributes. The utility functions defined by two stakeholders, industrial partner supporting this research activity, are respectively reported in Figure 9b) and Figure 9c). Each stakeholder (identified as Stakeholder A and Stakeholder B) define own curves to reflect their preferences with respect to these criteria.



a) Linear Utility Functions



b) Utility Functions for Stakeholder A

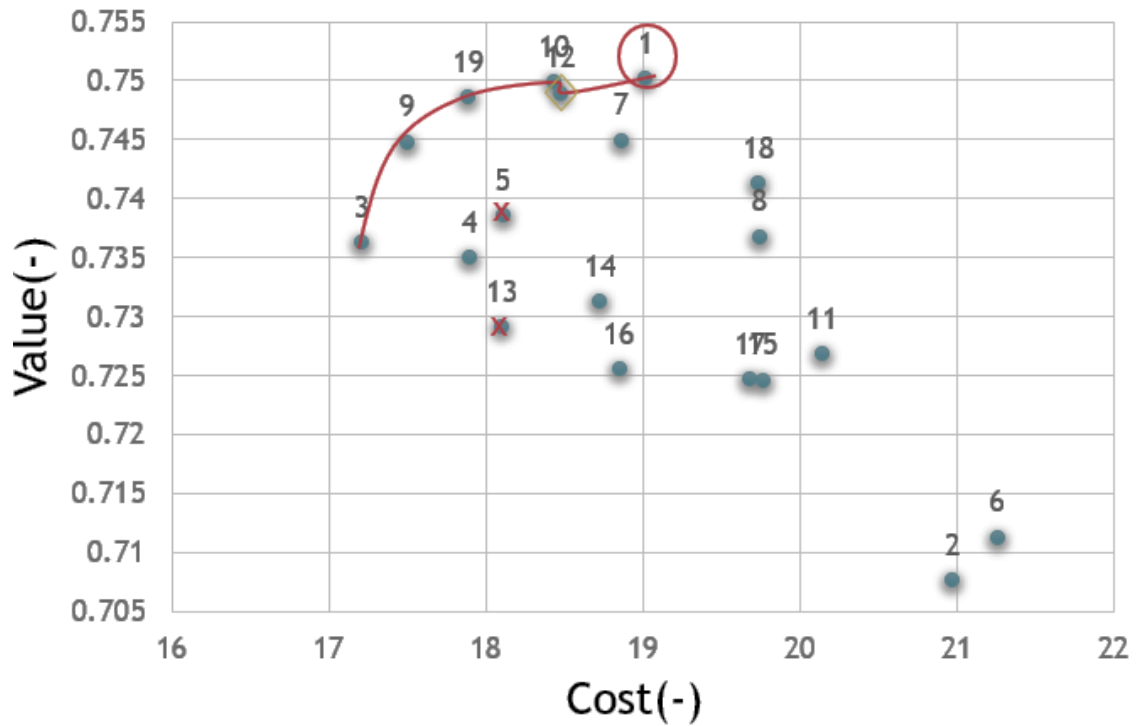


c) Utility Functions for Stakeholder B

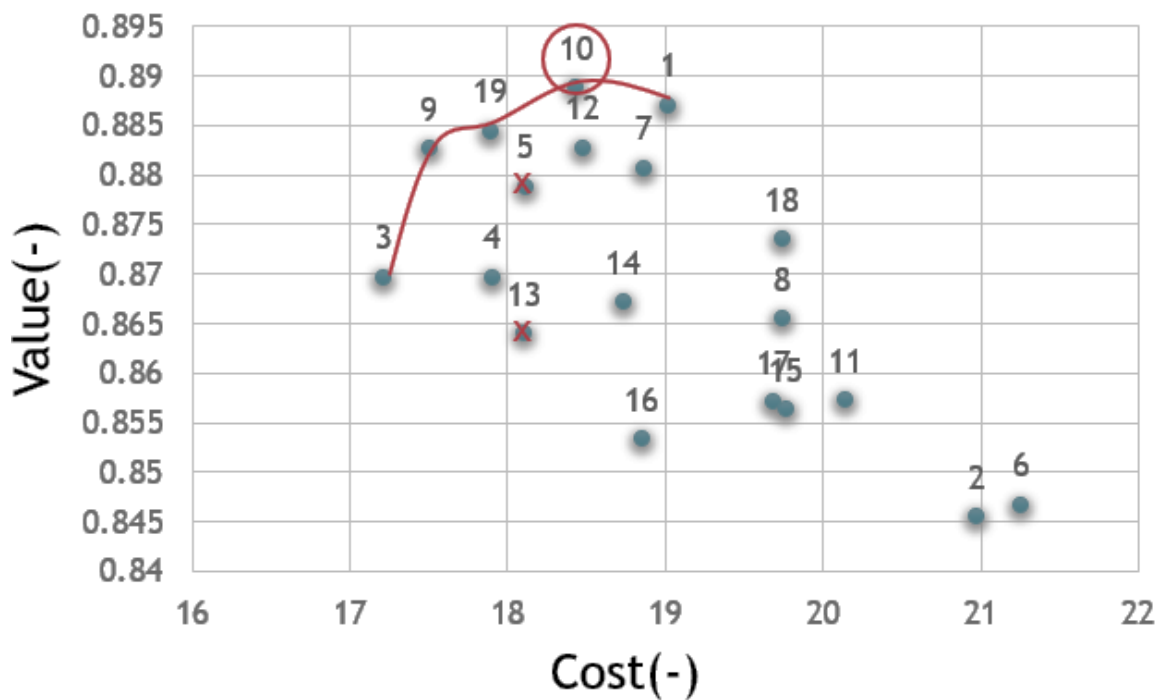
Figure 9 – Utility Functions

The qualitative preferences are the same for both stakeholders (Figure 8), instead the quantification of those expectations change with respect to the each stakeholder (Figure 9a,b). In fact, a different utility is associated by each stakeholder to each attribute and attribute content. For example, referring to the quality utility functions, stakeholder A wiliness in accepting solutions with low quality is higher than stakeholder B, who instead assigned a low utility to solutions with low quality. These

curves defining stakeholders' expectations impact the value-driven tradespace. With the assumption of same weight for all the attributes, the value-driven tradespace implementing stakeholders' expectations are represented in Figure 10. In this case, the solution with the highest *value* is the **best** solution, meaning that this solution matches stakeholders' expectations with respect to all the attributes.



a) Value-driven Tradespace - Stakeholder A Utility Function



b) Value-driven Tradespace - Stakeholder B Utility Function

Figure 10 – Value-driven Tradespace influenced by Statekholders' preferences

In both plots of Figure 10, the best solution is highlighted by a red circle: the solution 1 for the value-driven tradespace implementing stakeholder A utility functions (Figure 10a), by alternative solution 10 in the value-driven tradespace implementing stakeholder B utility functions (Figure 10b). The best solution is different because of the different stakeholders' expectations with respect to all the attributes. These two solutions are related to supply chain, involving enterprises performing the selected HTP materials and manufacturing processes. In details, both solutions involve the same enterprises, but the processes they perform are different as shown in Figure 11.

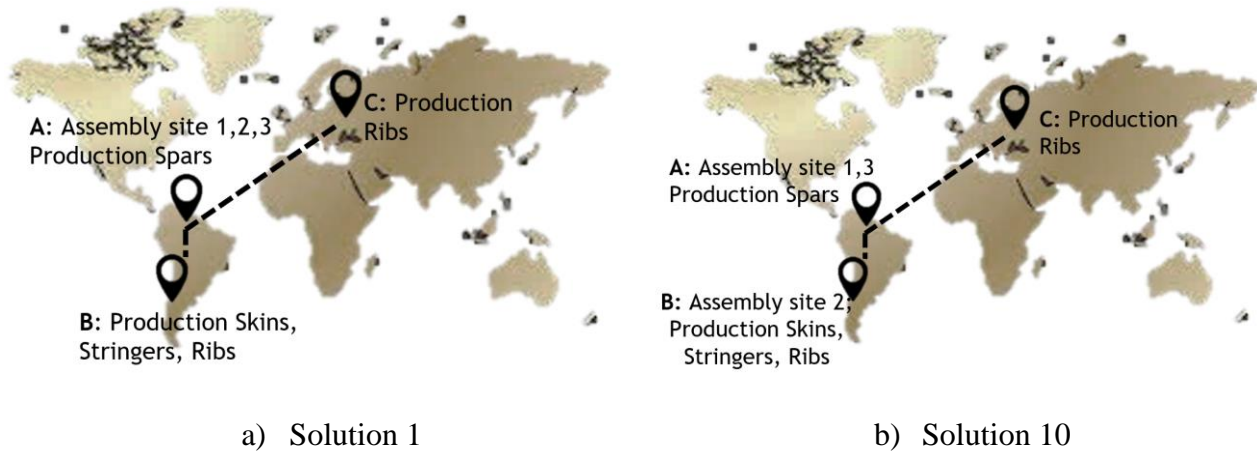


Figure 11 – Value-driven Tradespace influenced by Stakeholders' preferences

Stakeholders will therefore choose a different option in case they decide to go for the best solution, thus the one with highest *value*. However, a trade-off is always possible. For instance, stakeholder A might decide to go for solution 10 instead of solution 1 being the reduction in *value* very small with respect to the reduction in cost. Going in a solution with lower *value* implies, of course, to lose something in terms production time, risk and quality being these criteria aggregated in the *value*. In this way, the decision-making process is simplified. In fact, stakeholders can perform the trade-off studies considering multiple criteria (aggregating in the *value*) but only considering the *value* vs. cost pareto-front. In fact, the way stakeholders would select solutions with respect to each of those criteria are implemented in the *value* through the single utility functions. Thus, the challenge in well-design utility functions that perfectly match stakeholders' expectations.

In addition, in both value-driven tradespaces of Figure 10, solutions 5 and 13 are crossed. These two solutions are in fact not part of both pareto-front but instead they are included in the "reference" pareto-front. Similarly, solution 12 is included in the pareto-front of stakeholder A, but not in the "reference" and "Stakeholder B" pareto-front. The motivation always relays in the implementation of the stakeholders' expectations and thus on the utility curves defined by them. The utility of each attribute associated to each solution for the three different cases are summarized in Table 4.

Table 4 – SAU and Value for specific solutions of the value-driven tradespace

ID	SAU (-)								
	Linear			Stakeholder A			Stakeholder B		
	Time	Risk	Quality	Time	Risk	Quality	Time	Risk	Quality
1	0.86	0.84	0.89	0.47	0.78	1	1	0.67	0.99
5	0.85	0.84	0.87	0.44	0.77	1	1	0.64	0.99
10	0.86	0.84	0.89	0.47	0.78	1	1	0.67	1
12	0.86	0.84	0.85	0.47	0.78	1	1	0.66	0.99
13	0.84	0.83	0.88	0.44	0.75	1	1	0.60	0.99

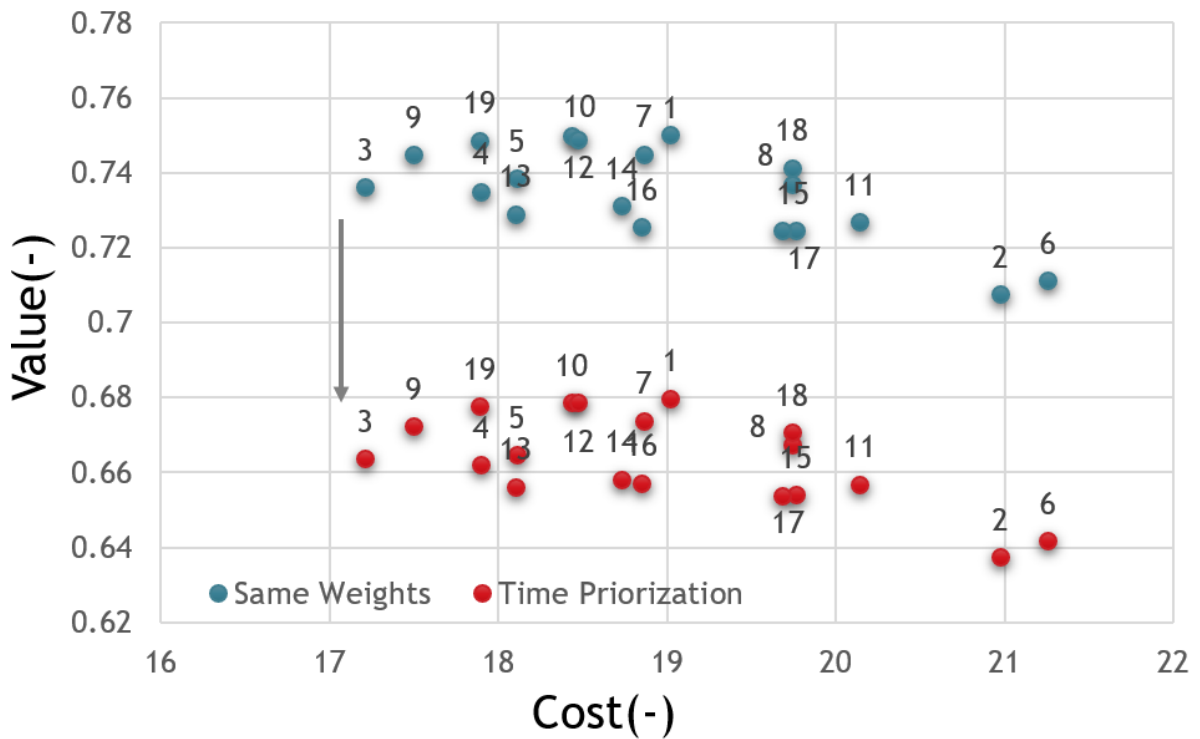
The value-driven tradespaces reported in Figure 10 have been obtained by assuming the same weights to all the attributes. This assumption implies is no prioritization among attributes and, as

consequence, the value-driven tradespace is influenced only by the implementation of the utility functions representing stakeholders' expectations. However, once defined the utility functions, more strategic scenarios can be analyzed by prioritizing attributes in different ways. This can be easily done in VALORISE since it gives the possibility to check real-time the value-driven tradespace changes. As example, a value-driven tradespace is represented in Figure 12 when time is prioritized with respect to the other attributes. The weight combination analyzed is reported in Table 5 while the utility functions are the same plotted in Figure 9a, b.

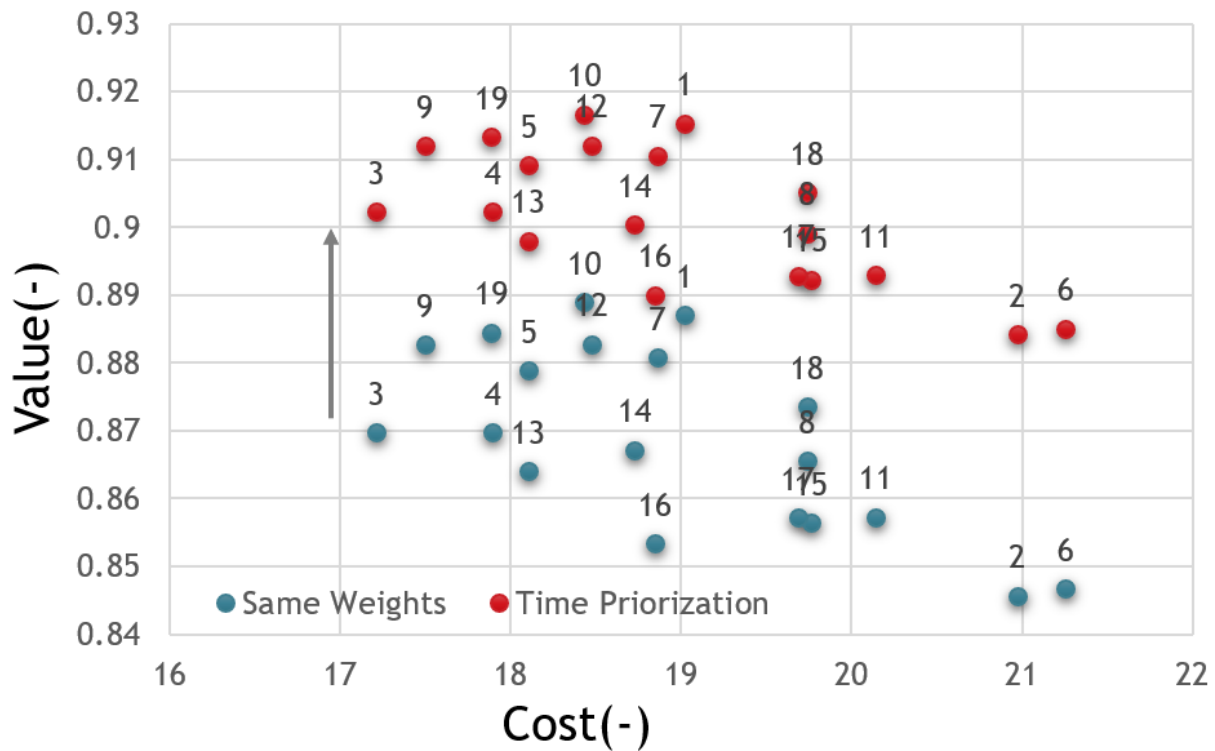
Table 5 – Weight Combination Prioritizing Time

Attributes	Weight
Time	0.50
Quality	0.25
Risk	0.25

As shown in Figure 12, in this case solutions on the value-driven tradespaces move down for the stakeholder A and up for the stakeholder B with respect to the case of same weights. Therefore, the best solutions for stakeholders are the same previously identified: solution 1 for stakeholder A and solution 10 for stakeholder B.



a) Stakeholder A



b) Stakeholder B

Figure 12 – Value-driven Tradespaces prioritizing Time

From the mathematical point of view, the shift of solutions (up and down) is related to the utility functions chosen by stakeholders. In this case, in fact, utilities reported in Table 4 for some of the solutions are still valid, being the utility functions always the same. The *value* of each solution now changes because of the weight assigned to each attribute. From Table 4, it appears that solutions for the stakeholder A always have a utility for time lower than the one of risk and quality. Thus, the *value* of these solutions goes down when prioritizing the attribute with lowest utility, that is time. Similarly, for the stakeholder B, in which the trend is opposite, time has utility higher than others. For this reason, the *value* of these solutions goes up when prioritizing time. In any case, what is worth to underline here is that with this analysis stakeholders can easily identify the best solution in any scenarios of interest. For some stakeholders, in fact, quality might be even more important than time and risk or risk than quality and time, and so on. In VALORISE, these scenarios can be easily set and visualized since any change in weights and utility functions is real-time plotted in the dashboard.

Finally, as already mentioned, other scenarios can be investigated by changing the boundaries of the x-axis of the utility functions, thus the boundaries of the attributes contents. This allows stakeholders to visualize on the value-driven tradespace only solutions of interest. In this application case, the boundaries have been not changed since solutions are characterized by attributes contents really close to each other. That's because the attributes contents have been estimated in an MDO problem.

4. Conclusions

The research activity aims at leveraging the value-model theory to simplify the multi-criteria decision-making process. The DLR internal tool called VALORISE is used to support decision-maker in identifying the best solution, thus the alternative on the tradespace perfectly matching the decision-maker's preferences. First attributes, that are the criteria playing a key role when stakeholders have to take a decision are identified. Then, an MDO problem is set-up and executed to achieve the

numerical quantification of the attributes and the pareto-front. At this point, attributes are aggregated in the *value*, through a weight and a utility function. In the application case, first the *value* is used as weighted-sum function to obtain the value-driven tradespace not influenced by stakeholders' preferences. In this case the solution with the highest *value* might be not the best solution for stakeholders. Then stakeholders' expectations have been implemented through utility functions. Therefore, two value-driven tradespaces have been shown in Figure 10, one implementing utility function of each stakeholder. The solution with highest *value* in the "reference" tradespace is the best one for stakeholder A, but not for stakeholder B which is instead represented by solution 10. Thus, implementing stakeholders' expectations lead to identify different best solution for each stakeholder. However, in this case, the same weight has been assigned to all the attributes meaning that stakeholders are not prioritizing any of them while taking a decision. To show how the value-driven tradespace change when an attribute is prioritized, an example related to the time prioritization has been addressed in Section 3.3. This analysis allows stakeholders to easily identified the best solution when one of the criteria has to be prioritized. The multi-criteria decision-making is so simplified. In fact, criteria are aggregated in the *value* and stakeholders can perform trade-off studies accounting for multiple criteria while only referring at *value* or cost. In fact, the way stakeholders select solutions based on each criterion are represented by the single utility functions. Making a single utility function for time means to represent how stakeholders expect to select a solution if only looking at this attribute. From here, it appears clear how important is to well-design the utility functions. That's why VALORISE has been implemented. By using VALORISE stakeholders can directly draw their own curves for each attribute thinking how they would take solutions based on that attribute. Unfortunately, it was not possible to instead analyze scenarios in which the boundaries of the utility functions were limited to exclude solutions from the pareto-front. That's because solutions analyzed in the decision-making process are output of an optimization problem. It can be interesting in future, to address decision-making after the system architecting (third block of the AGILE4.0 framework). In this case the best solution is identified on the tradespace and it might be not an optimal solution. However, once defined for the best solution, thus the best architecture, an MDO problem might be performed. In addition, further studies might deeply analyze the relation between the two optimization strategies presented in Section 3.2 and understand which solutions always relay on the pareto-front. Furthermore, it is already in progress activities including the fuel consumption, characterizing the OAD domain, in the decision-making process. From the decision-making perspective, the process is the same, the only difference is in the number of criteria aggregated in the *value*. In fact, by running the MDO problem addressed in this research activity, the fuel consumption mass of the aircraft doesn't change. As consequence, it doesn't make sense to consider the fuel consumption in the decision-making process since there is no variation of stakeholders' expectations with respect to this attribute. Last, but not least, uncertainty can be included in the value estimation, especially on the design on the utility functions and weight set. In any case, in a society in which even more criteria will be considered in the early aircraft design stage because of the circular and sustainable requirements to address, the value-model theory can represent a powerful mean for a first decision-making analysis.

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Biography



Giuseppa Donelli graduated in Aerospace Engineering at the University of Naples Federico II in 2018. Currently she is a researcher at the DLR System Architecture in Aeronautics in Hamburg, Germany. She is investigating on how to leverage Model-Based System Engineering (MBSE) and Multi-Disciplinary Optimization (MDO) technologies for the Value-driven Concurrent Coupling of multiple domains: manufacturing, design and supply chain of aeronautical systems.



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Nathalie Bartoli received the Eng. Diploma and Ph.D. Degree in applied mathematics from the National Institute of Applied Sciences of Toulouse, France, in 1997 and 2000, respectively. She worked as a researcher in the Electromagnetism Team at CERFACS before joining ONERA in 2005. Her research interests include surrogate models, multidisciplinary optimization and numerical schemes. She is in charge of some courses at ISAE-SUPAERO in the field of optimization and numerical simulation. Since 2017, she is a member of the AIAA MDO Technical Committee.



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