

Value-driven co-architecting and tradespace exploration: an aeronautical case study involving industrial systems

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Abstract

To satisfy the demand 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. Within the German-funded Project Dimension, a value-driven co-architecting methodology is exploited and applied to an aeronautical system component, that is the cargo door latching system. The aim is to show the advantages of including industrial systems (mainly manufacturing and supply chain) decisions in the early design phase. A value-driven tradespace is generated: each (co)architecture refers at the same time to a system configuration, materials and processes choice and supply chain combination. The exploration of this value-driven co-architecting tradespace allows to identify the most performant, competitive and sustainable solution by considering multiple stakeholders' perspectives and expectations. This gives aeronautical companies the possibility to make robust and strategic decisions and define cutting edge solutions to remain competitive in the nowadays global aviation market.

Keywords: value-driven tradespace, decision-making, aircraft, supply chain, sustainability

1. Introduction

Public perception of aviation has evolved over years placing greater emphasis on sustainability, efficiency, affordability, and societal impact. These priorities are reflected in the European vision Flightpath 2050, developed by the European Commission, which outlines the transition toward climate-neutral, competitive, and citizen-centric aviation [1]. Achieving these objectives requires not only technological innovation but also a fundamental shift in the way aeronautical systems are designed, built and sustained. A key aspect of this transformation is the imperative to integrate manufacturing and supply chain decisions into the early stage of aircraft design: from the selection of materials and manufacturing processes to the sourcing of components and logistics management to customer delivery.

This consistent integration gives the opportunity to overcome the limitations of the traditional sequential approach in which these industrial systems (i.e. manufacturing and supply chain) are analyzed once the aircraft configuration is fixed. In this case, however, changes in design due to unforeseen production issues drastically increase the overall aircraft cost [2]. In addition, the traditional approach limits the ability to adapt to market changes, technological advancements or excepted disruption. Several companies have faced these issues over years [3] [4] [5], also the aeronautical once [6] [7] [8]. Instead, the concurrent conceptual design of the aircraft (or aircraft components), manufacturing and supply chain systems allows to optimize efficiency, enhance sustainability through the life-cycle and be competitive in bringing cutting-edge solution in the market [9] [10].

Due to this emergent need, several methodologies have been developed in the last decades for the concurrent product design, manufacturing and supply chain [11] [12] [13], also in the aeronautical context [14] [15] [16] [17]. Among others, a value-driven methodology is proposed and applied by

Donelli et all [18]. Differently from others, this methodology proposes a formalization on how to address all the activities of the conceptual design modeling for the aircraft, manufacturing and supply chain systems: from requirements [19], to architectures generation and optimization [20] [21], to tradespace exploration [22] [23] [24].

Within the German-funded Project Dimension, this methodology has been explored and improved by the German Aerospace Center (DLR) to include new performance characteristics related to reliability and sustainability. This methodology has been then applied for the design of a cargo-door latching system, supported by Airbus´ expertise. The latching system is the door component that assures the door remains securely closed during all flights phases, especially when the cabin is pressurized. This component has been selected since representative of the application study and because of data availability.

The application case shown in this paper therefore focuses on the concurrent design of the latching system (system of interest) and its industrial systems, that are manufacturing and supply chain systems. As consequence, choices related to system components, materials, manufacturing processes and enterprises are modelled at the same time. Depending on the choice, different architectures are generated. Each architecture refers at the same time to a specific latching system configuration, to a selection of materials and processes and to a combination of enterprises. From here the *co-architecting* word. Each (co)architecture represents the three systems architectures together: the architecture of the latching system (e.g. choices of components), the architectures of manufacturing system (e.g. choice of materials), the architecture of the supply chain system (e.g. choices of enterprises). Design performance, like the mass, and production performance, like the supply chain risk, therefore characterize each (co)architecture.

A value-model theory, the Multi Attribute Utility Theory (MAUT) [25], is applied to identify the best (co)architecture while considering some of these performance parameters also called attributes. In details, attributes are performance characteristics that stakeholders identify crucial when making decisions. Per definition, stakeholders are people who have interest on the systems under design, for instance engineers and managers [2]. Such stakeholders might have different expectations and also perspectives with respect to the defined attributes. In this research activity, several value-driven tradespaces are generated to trade stakeholders' expectations. The exploration of these tradespaces allows to identify the best solution, i.e. the best (co)architecture addressing multiple attributes related to the design and production of the lathing system.

The aim of this paper is to demonstrate that following the proposed approach more informed and clear decisions can be made to easily identify the most performant, competitive and sustainable architecture. Among others, in fact, also a sustainability index is identified as attribute. For this purpose, more details on the value-driven methodology are provided in Section 2. Here, the stakeholders, their attributes and perspectives are deeply described. Section 3 then, focuses on the co-architecting value-driven tradespace exploration. The main results are therefore presented and discussed. Finally, in Section 4, conclusions are reported.

2. Value-driven Co-architecting Methodology

The application case focuses on the concurrent design of the latching system and its manufacturing and supply chain systems. As shown in Figure 1, choices related to components, materials, processes and enterprises can be made.

The product is the latching system: different components can characterize each latching system architecture. Then, each of this component can be done by different materials and manufacturing processes. Each process can be executed by different enterprises having the competences to do them.

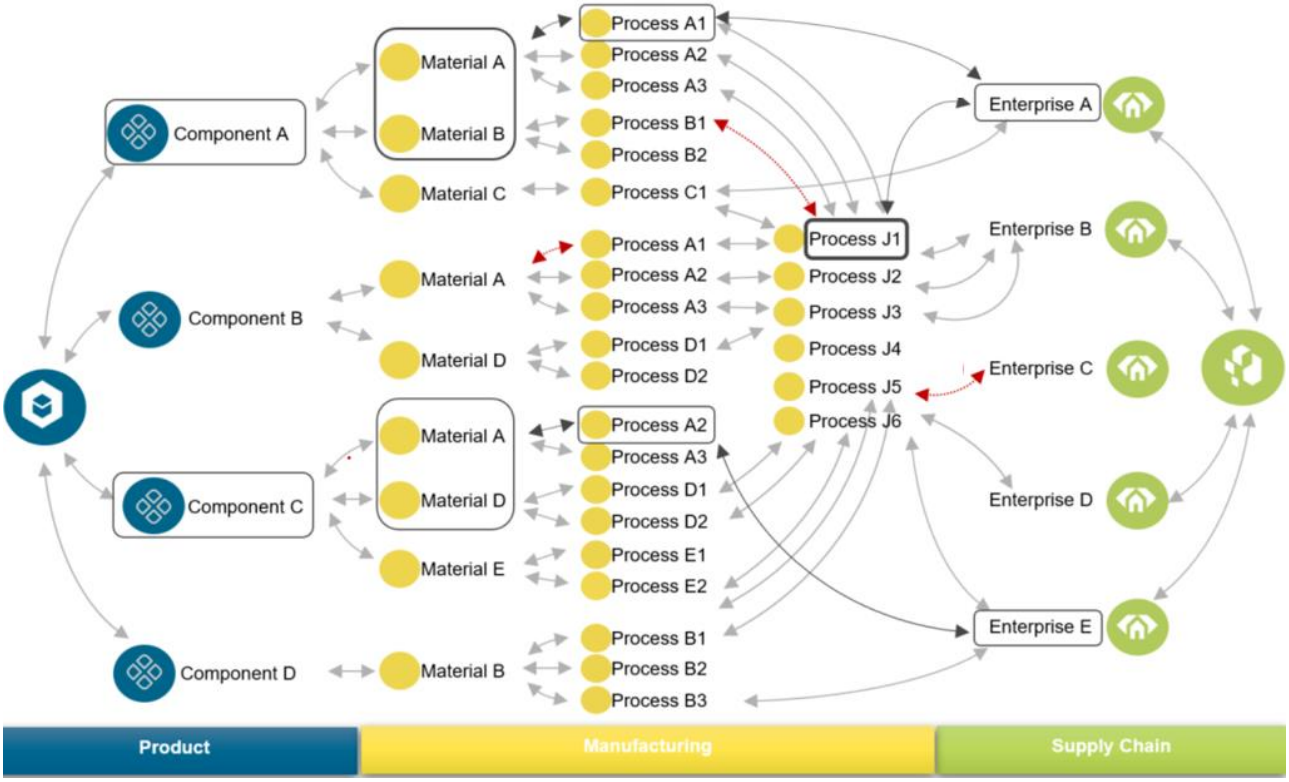
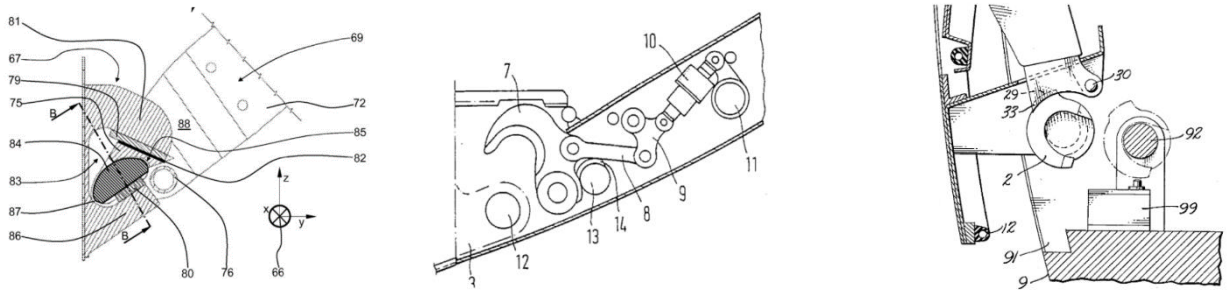


Figure 1 - (Co)architectures choices: from product components, to materials and processes, to enterprises, modified from [26].

The choice of components leads to three different latching system architecture: the Bar Latching System (BLS), the Hook-Spool Latching System a(HLS) and C Latching System (CLS) shown respectively in Figure 2. The main different among these architectures is in the number and type of components involved.



a) Bar Latch [27] b) Hook-Spool Latch [28] c) C Latch [29]

Figure 2 - Latching System Architectures.

To initially simplify the problem, the choice of materials and processes is assumed fixed meaning that for each component of the latching system there is no variability in terms of materials and processes. Instead, OEM (Originally Equipment Manufacturer) sites, suppliers Tier I and Tier II can be selected to generate supply chain architectures. Enterprises are classified as OEM, Tier I and Tier II based on the responsibilities they have. Usually, OEM is responsible for the assembly of the aircraft components while Tier I and Tier II respectively of the main aircraft systems and sub-systems.

In this application case, the OEM and suppliers Tier I/II can be responsible for the manufacturing of the main units of the latching systems (e.g. handle unit, visualization unit).

The suppliers Tier I can be then responsible for the assembly of such main units while the OEM is the only one responsible for the assembly of the latching system. However, instead of considering all the units of the latching system be produced by different enterprises, to reduce the size of the problem, it is first assumed that each enterprise is responsible for manufacturing and/or assembly of the handle unit while all the other units are manufactured/assembled by OEM. The manufacturing of the handle unit components can be also split among suppliers. Based on these assumptions, depending on the enterprises selected, different production scenarios can be generated. The latching system configurations can be made in house, partially outsourced or fully supplied. In the first case, manufacturing and assembly of all the latching systems units are made by OEM. In the second case, the handle units components are manufactured and/or assembled by suppliers and OEM. In the last case, manufacturing and assembly of the handle unit is executed by suppliers.

Choices on components, materials and enterprises lead to the (co)architectures generation. Each (co)architecture therefore refers at the same time to a specific latching system configuration, to a selection of materials and processes and to a combination of enterprises. These architectures are characterized by design and production performance. Some performance parameters, called attributes, are identified by stakeholders as key when making decisions. These attributes are summarized in Table 1 together with the motivation of why they have been selected. More information on how to estimate these attributes can be found in [22] [30].

Attribute	**Meaning**	**Motivation**	**Preference**
Mass	Component kilograms	Key technical performance	Lower, the better
Reliability Index	Risk to failures		Higher, the better
Production Time	Transportation, fixed, manufacturing	Key in supply chain management	Lower, the better
Production Risk	Transportation, fixed, manufacturing		Lower, the better
Production Quality	Fixed, manufacturing		Higher, the better
Production Cost	Transportation, fixed, manufacturing		Lower, the better
Sustainability Index	Greenhouse emission, waste generation, resource depletion, energy consumption	Key for future aviation ecosystem	Lower, the better

Table 1 – Attributes and Stakeholders' Expectations

These attributes are defined by engineers and managers, assumed to be the stakeholders of this application case. For each attribute, a qualitative preference is also included in the table. Stakeholders would like to have low mass, reliability, time, risk and cost and high production quality and sustainability index. To express these expectations, the MAU theory is used. This value model theory estimates the value by assigning a utility function and a weight to each attribute [25]:

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

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:

The weights represent the relative importance of these attributes. The utility functions instead quantify the qualitative stakeholders' expectations of Table 1. Therefore, they model the way stakeholders would take decision when considering each specific attribute. For instance, stakeholders would prefer (co)architectures with low production time instead of a high one. However, before implementing stakeholders' expectations, it is a good practice, to first get a reference case as the one in which the same attributes and linear utility functions are assigned to all the attributes. In this case, in fact, no prioritization of attributes is addressed (same weight) neither expectations are implemented (linear scale transformation). This allows to analytically explore results and validate them. Then, weights combinations and utility functions representing stakeholders´ expectations and perspectives can be implemented and compared.

A preliminary list of the weights combinations analyzed in this study are proposed in Table 2. They are assigned in the way to also express stakeholders' perspectives. For instance, for engineers make sense to overweighting the mass (Case I) or the mass and the reliability index (Case II). For managers, instead, can be interesting to get a detailed look at (co)architectures in which the sustainability index (Case III) or the supply chain performance (Case IV) are overweighted.

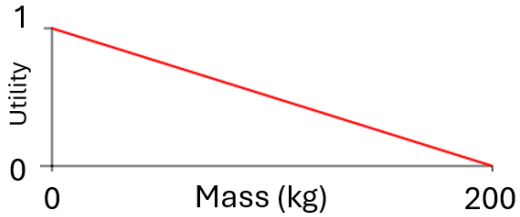
Case Study	**Weights**						**Stakeholders Perspective**
	Mass	Reliability	Sustainability	Quality	Time	Risk	
Ref.	0.2	0.2	0.2	0.2	0.2	0.2	-
I	0.9	0.02	0.02	0.02	0.02	0.02	Engineers
II	0.45	0.45	0.025	0.025	0.025	0.025	Engineers
III	0.02	0.02	0.9	0.02	0.02	0.02	Managers
IV	$0.0\bar{3}$	$0.0\bar{3}$	$0.0\bar{3}$	$0.\bar{3}$	$0.\bar{3}$	$0.\bar{3}$	Managers

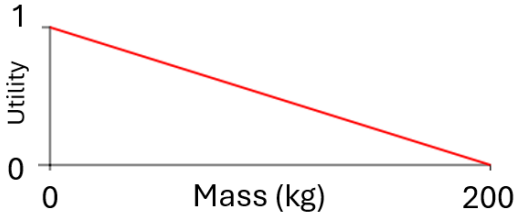
Table 2 – Case Studies: Weights Combinations and Stakeholders' Perspectives

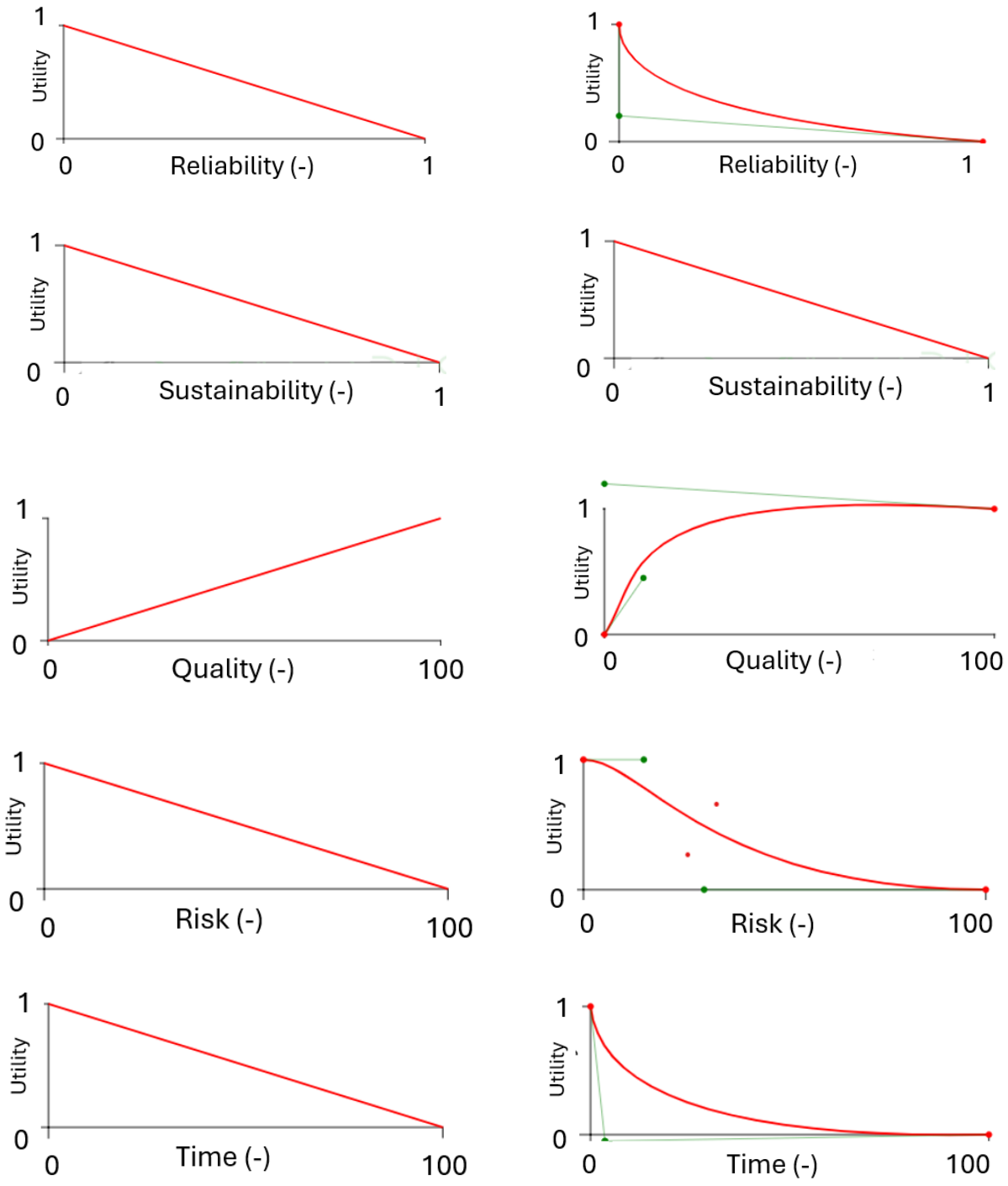
To express stakeholders' expectations instead utility functions are considered. These functions have been simply implemented by using VALORISE, an interactive dashboard developed by DLR that stakeholders can simply use to draw their utility functions [22]. Giving stakeholders the possibility to draw their utility functions is, in fact, the best way to get robust utility functions [31] [32].

The linear utility functions as well as the utility functions provided by stakeholders are provided in Figure 3. For the reference case, linear utility functions are used while for all the other case studies, stakeholders' utility functions are implemented. Weight and utility function for cost are not provided since cost is considered as other independent variable for value vs. cost trade-off studies.

Concluding, several value-driven tradespaces are obtained by implementing the provided utility functions and the four case studies of weights combinations. Each solution of these tradespace is a (co)architecture that is representative, as mentioned, of a specific latching system architecture, choice of materials and manufacturing processes and supply chain combination. The exploration of the value-driven tradespaces therefore allows to identify the most performant, competitive and sustainable (co)architecture. This gives aeronautical companies the possibility to make robust decisions that enhance sustainability, manufacturability, supply chain efficiency unlocking new opportunities for innovation and success in the nowadays global and competitive market.







a) Linear Utility Functions b) Stakeholders Utility Functions

Figure 3 – Reference and Stakeholders Utility Functions.

3. Value-driven (Co)architectures Tradespace Exploration

The value-driven co-architecting tradespaces obtained by implementing the utility functions and weights combinations previously introduced are shown and discussed in this section. In all the value-driven tradespaces, different colored shapes are used to represent the three latching mechanism architectures: the blue rhombus for the HSLM, the orange square for the BLM, the green triangle for the CLM. The letters are instead used to indicate the different production scenarios: in-house (H), partially made in-house and partially outsourced (OH), fully outsourced (O). The enterprises involved in this application case are indicated in Table 3. The combination of such enterprises leads to 29 supply chain architectures for each latching mechanism. Among them, one supply chain is related

with the in-house production scenarios, 14 to the partially made in-house and partially outsourced scenario, 14 to the fully outsourced production scenarios. In the value-driven tradespaces, the number of each (co)architecture refers to the specific supply chain combination. Each combination differ either for the enterprises involved and the components they are responsible for.

Enterprise	OEM	Supplier Tier I	Supplier Tier II
Number	1	6	3

Table 3 – Number of enterprises Involved in the supply chain

First, the value-driven tradespace related with the reference case study – same weights and linear utility functions - is reported in Figure 4. In this case, attributes are not prioritized and stakeholders' expectations are not considered.

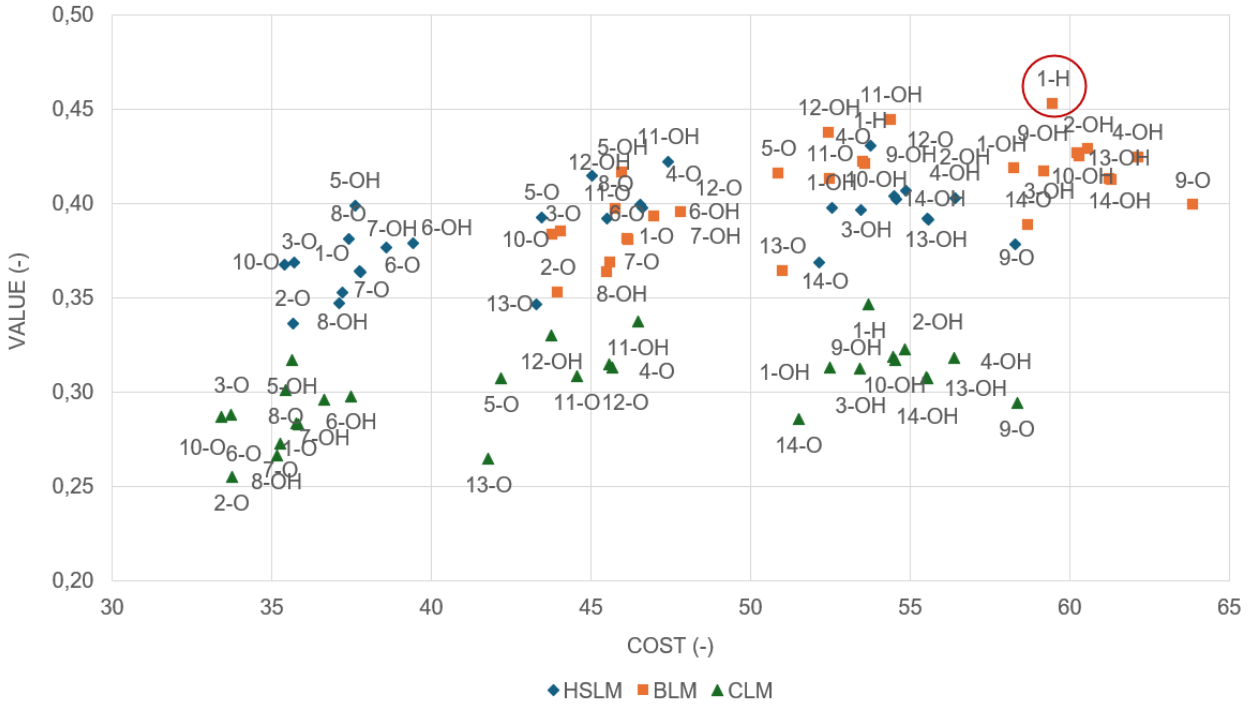
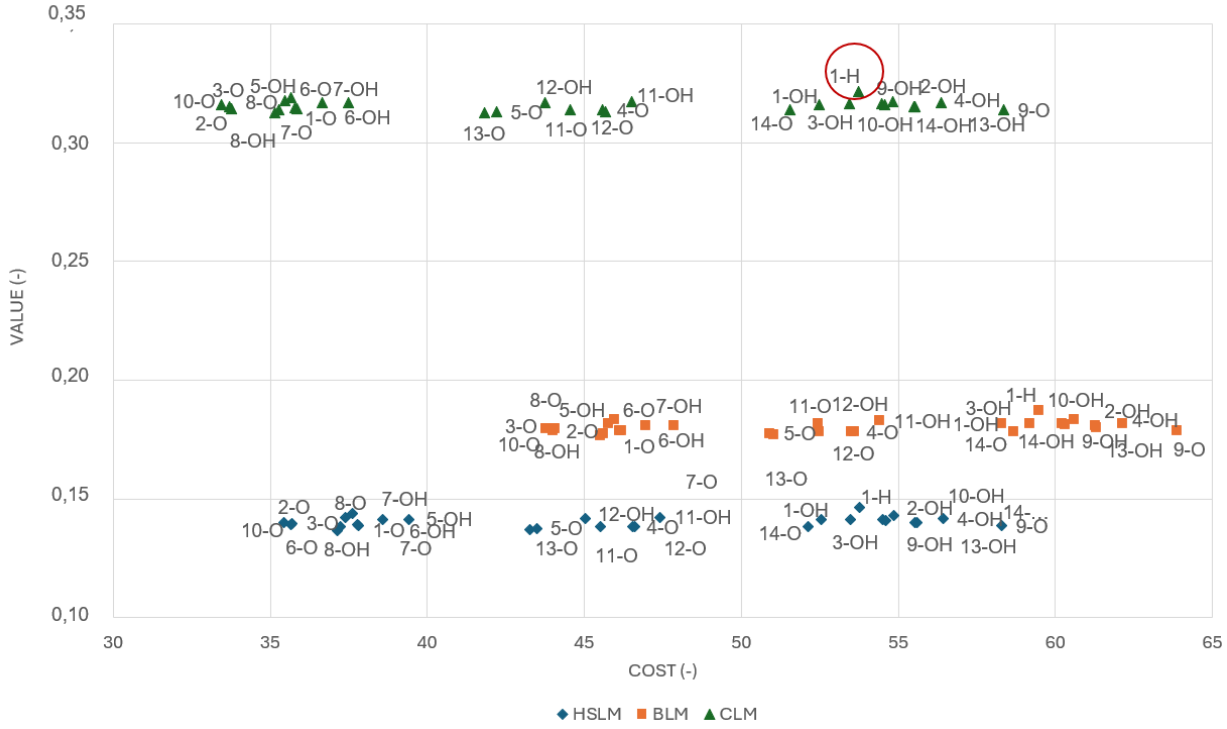


Figure 5 – Reference Value-driven Tradespace: Same Weights and liner Utility Functions.

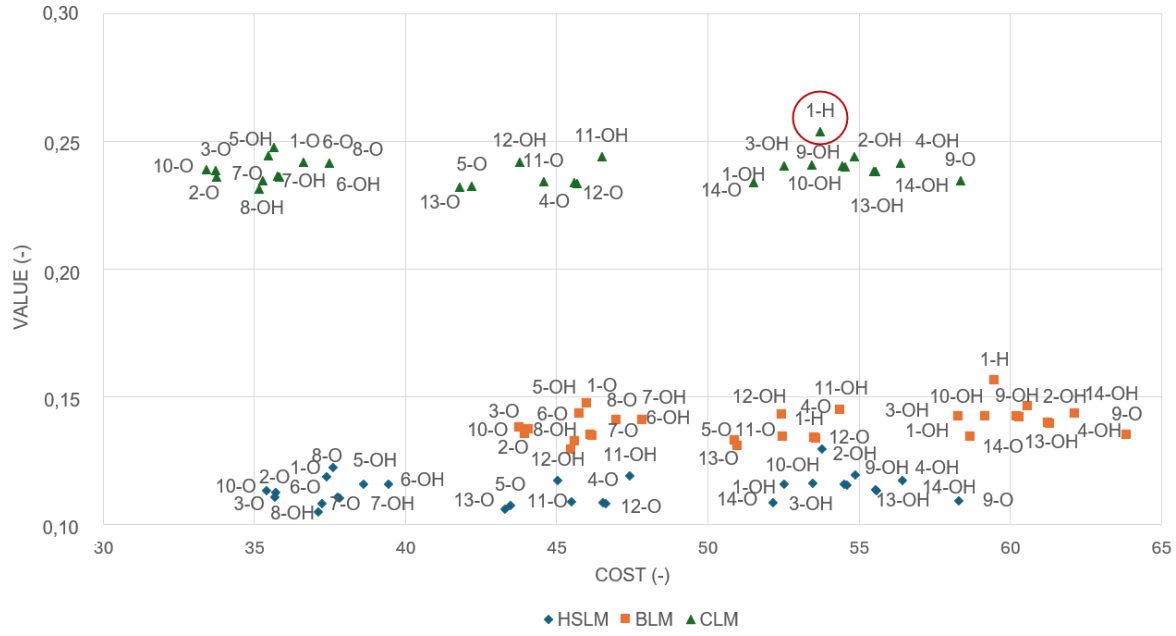
The tradespace shows how the (co)architecture with the highest value, in terms of all the aggregated attributes, is the orange (co)architecture 1-H. This (co)architecture refers to the BLM which is produced fully in house. To understand why this (co)architecture has the highest value, investigation on the attributes aggregated in the value must be done. The BLM, indeed, does not exhibit the highest sustainability and reliability indices — related instead to the HSLM—and it is the heaviest in terms of mass. However, it is characterized by the lowest number of components, which positively affects the supply chain performance (low production time and risk) leading to a significant increase of the overall value. Thus, even if the orange (co)architecture 1-H is not the best architecture in terms of sustainability, reliability and mass, the better supply chain performance makes it the one with the highest value. Different trade-off studies can be therefore performed: stakeholders might prefer a solution with highest sustainability performance instead of those with lower production risk or solutions with lower cost instead of higher value. For instance, the orange (co)architecture 2O, still related to the BLM system but fully outsourced to suppliers, might be considered as interesting alternative to the one with highest value. In this case, the production risk is quite high while the production quality relatively low. As consequence, the value of this (co)architecture is lower, but also the cost. Since the difference in value is much lower than the cost gap, this solution might be a good compromise for stakeholders to be considered when doing the make or buy trade-off study. This reference case study, however, does not consider stakeholders' expectations (utility functions) or perspectives (weight combination). It shows the analytical trend of solutions which helps in validating

the results. In the next case studies, the utility functions provided by stakeholders (Figure 3) are implemented to consider the way stakeholders take decisions with respect to the aggregated attributes. In the following cases, the solution with highest value therefore represents the best solution for stakeholders.

The case study I (mass prioritization) and II (mass and reliability prioritization) reflect the engineers perspectives when their expectations are implemented. The value-driven tradespaces of these two case studies are reported in Figure 6a and Figure 6b respectively.



a) Mass Prioritization, Stakeholders' Utility Functions



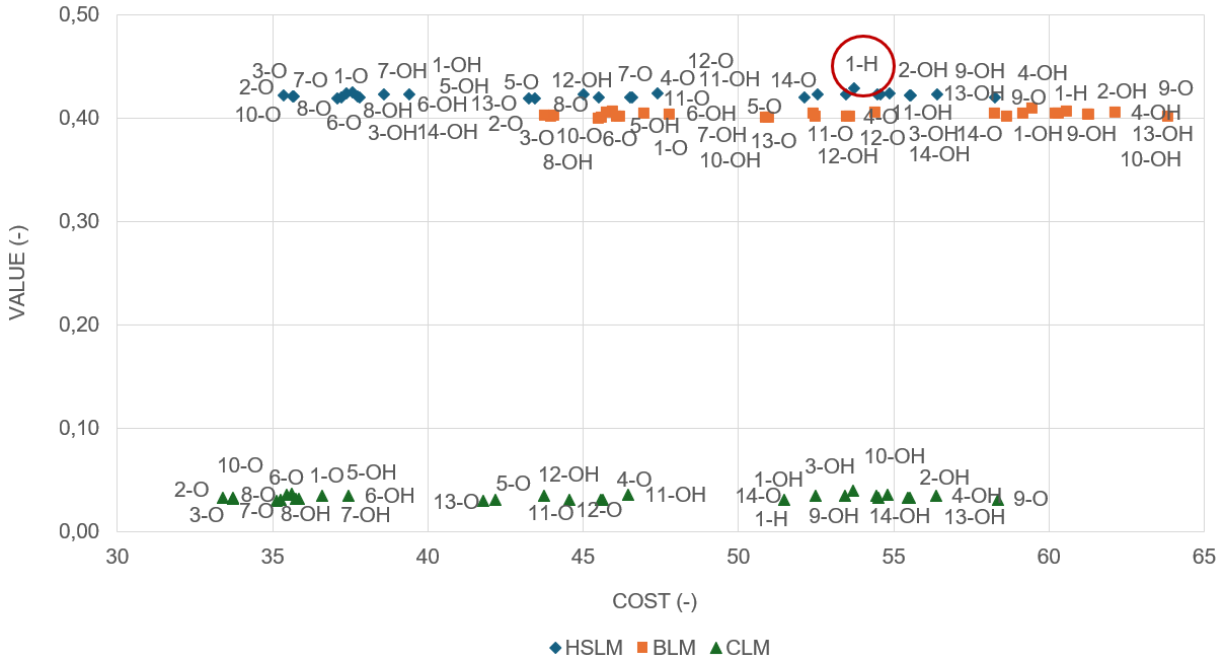
b) Mass and Reliability Index Prioritization, Stakeholders' Utility Functions

Figure 6 – Value-driven Tradespace Case Study I and II: Engineers 'perspectives

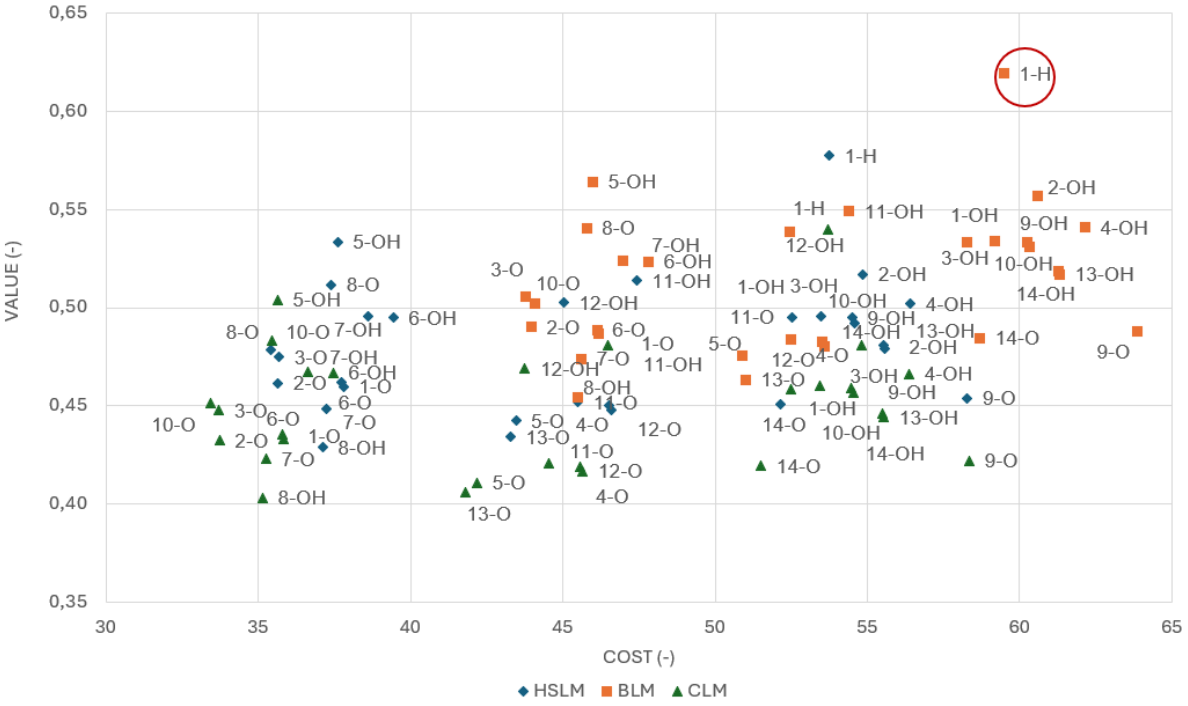
In both cases, the green triangle 1H is the best (co)architecture. This (co)architecture refers to the CLM fully made in house. Indeed, the CLM has the lowest mass even if characterized by the highest

number of components since they are mostly made by aluminum. Therefore, it is expected to have such latching mechanism as the best one when the mass is prioritized. In terms of reliability, instead, the most performant latching system is the HSLM. However, when both the mass and reliability index are prioritized, the best (co)architecture still remains the CLM because the difference in mass among the mechanisms is higher than the difference related with the reliability indices. These two value-driven tradespaces capture the engineers 'perspectives: the main focus is on the technical performance of the latching mechanism while the supply chain performance are not of interest. In this view, the best architectures is the CLM.

Case studies III and IV reflect instead the managers 'perspectives who care about sustainability and production performance. The value-driven tradespaces of these case studies are shown in Figure 7a and Figure 7b respectively.



a) Sustainability Prioritization, Stakeholders' Utility Functions



b) Supply Chain Performance Prioritization, Stakeholders' Utility Functions

Figure 7 – Value-driven Tradespace Case Study III and IV: Managers 'perspectives

Figure 7a shows how the best (co)architecture is the HSLM fully produced in house when the sustainability index is prioritized. The sustainability index is in fact estimated considering the greenhouse gas emissions, the energy consumption, the waist and resource depletion produced during production [30]. These factors are mainly related with the materials: titanium is the worst one, followed by aluminum and steers. Looking at the value-driven tradespace of Figure 7a, the CLM shows the worst value because it is mainly made by aluminum. The amount of aluminum and titanium is lower for the other two architectures in percentage with the total mass. This is why the value of the HSLM and BLM systems is higher and particularly the best for HSLM. Supply chain performance considerations are not discussed since not influencing the value but only the cost: different manufacturing processes lead to different cost. Finally, Figure 7b refers to the value-driven tradespace in which the supply chain performance and therefore the production risk, time and quality are prioritized. In this case the best (co)architecture is the BLM fully produced in house. Due to the lowest number of components to be produced, the BLM is in fact characterized by the lowest production risk and time. However, the manufacturing cost are quite high due to the selected manufacturing processes. Less expensive but with almost same value is the (co)architecture 1H related to the HSLM. In this case, the value is a bit lower due to the higher number of components to produce. However, the cost of the related manufacturing processes is less expensive. The CLM (co)architecture 1H has the lowest value among the three because of the highest number of components to be produced. However, it is also the cheapest one due to the low manufacturing cost characterizing it. Therefore, also in this case, many trade-off studies might be addressed and managers might decide to save cost in favor of value or vice-versa. In addition, they might decide if it worth to produce in house or outsource to suppliers. In fact, the best supply chain architecture turns to be always the one in which production and assembly is made in house, especially because of the lower production time, risk and higher quality. In turn, such supply chain architecture has the highest production cost.

In any case, however, the two value-driven tradespaces matching managers´perspecitves demonstrate how the best solution for managers (HSLM or BLM) doesn´t match with the one proposed by engineers (CLM). This reflects reality: each stakeholder would like to keep the best solution according to their own perspectives making the decision-making process complex and time consuming. The obtained results demonstrate how the value-model theory can be easily used to trade such stakeholder ‘expectations. The follow-up activity aims at identifying a (co)architecture which shows a relatively difference in value when changing the different perspectives. Therefore, a sensitivity analysis on the weight combination will be performed to identify a solution that might represent a good compromise among all the stakeholders.

4. Conclusion

A value-driven co-architecting tradespace exploration is proposed in this research activity. The application case shown focuses on the concurrent design of the latching system (system of interest) and its industrial systems, that are manufacturing and supply chain systems. As consequence, choices related to system components, materials, manufacturing processes and enterprises are modelled at the same time. Depending on the choice, different (co)architectures are generated. Each (co)architecture refers at the same time to a specific latching system configuration, to a selection of materials and processes and to a combination of enterprises. From here the *co-architecting* word. Each (co)architecture represents the three systems architectures together: the architecture of the latching system (e.g. choices of components), the architectures of manufacturing system (e.g. choice of materials), the architecture of the supply chain system (e.g. choices of enterprises). Design and production performance characterize each (co)architectures. Some attributes have been selected among these as key when making decisions by stakeholders (engineers, managers). These attributes are the sustainability and reliability indexes, the supply chain performance (time, risk, quality) and the latching mechanism performance (mass). The best (co)architecture by trading stakeholders’ expectations with respect to all of these attributes are presented and discuss. In particular, the application case shows how the value-model theory can be used to fully match the different stakeholders ‘expectations: the best (co)architecture (highest value) change when considering engineers or managers’ perspectives. For engineers the best (co)architecture is the one minimizing the mass and the reliability index, for managers those optimizing the supply chain performance and the sustainability index. The application case also shows the different trade-off studies that can be

performed by following this approach. For instance, engineers and/or managers might decide to go for solution with lower value but also lower cost increasing a bit the risk related with the production. In fact, in all the cases, the best supply chain is the one in which all the components are produced in house. As next activity, which is already on-going, sensitivity analysis on the weight combinations is performed. Since the best solution change based on stakeholders' expectations, the objective of this follow-up activity is to identify the robust (co)architecture that minimizes the value oscillation when thousands of weight combinations are analyzed. This solution might represent a good compromise among all the different stakeholders' expectations.

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