

AIRCRAFT AND INDUSTRIAL SYSTEMS CO-ARCHITECTING BASED ON VALUE-DRIVEN MBPLE APPROACH

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Abstract

Traditionally, decisions related to the manufacturing and supply chain are taken after the design of a new aircraft configuration is completely defined. This sequential approach, however, limits the ability to adapt to market changes, technological advancements or unexpected disruptions, causing a drastic increase of cost. Integrating production decisions in the early design phase is therefore crucial for overcoming these limitations and making informed decisions that optimize the product for manufacturability and supply chain efficiency rather than only aircraft performance. In this frame, this paper proposes and applies a methodology combining the Model-Based Product Line Engineering with a value-driven trade-off analysis for the aircraft and industrial systems, mainly manufacturing and supply chain systems, co-architecting. With this approach, a value-driven tradespace of (co)architectures or variants representing at the same time an aircraft configuration, a combination of materials and manufacturing processes and a supply chain is generated. Therefore, decisions related to design and production can be addressed at the same time while trading stakeholders' expectations for the identification of the best (co)architecture. An aeronautical application case shows the advantages of using the proposed approach.

Keywords: Aircraft Design, Supply Chain Management, Manufacturing, Model-based Product Line Engineering (MBPLE), Industrial Systems Co-architecting.

1. Introduction

Traditionally, decisions regarding the manufacturing (e.g. which processes can be used to produce a component) and supply chain (e.g. which enterprise select to execute processes) are taken after the design of a new aircraft has been completed. This sequential approach, however, restricts the possibility to quickly respond to market changes, technological advancements or unexpected disruption causing a drastically increase of cost [1] [2]. Indeed, once the design is finalized, any modifications become highly expensive and time consuming [3]. Many companies, in different sectors, experienced these issues. Among others, Airbus [4] [5], Boeing [6], Toyota [7], Honda [8].

To overcome the limitations of such traditional sequential approach, an integrated approach considering production decisions early in the design is crucial. In fact, by integrating production performance assessment into the design phase, designers can make robust decisions that can enhance manufacturability and supply chain efficiency. This integrated approach also helps proactively identifying and addressing potential production bottlenecks earlier in the design phase [9], reducing costs [10] and increasing the overall value of the aeronautical systems. In this frame, several research studies investigate how to include manufacturing and supply chain decisions during the aircraft conceptual design [11] [12] [13] [14] [15]. Among them, a new value-driven methodology is proposed by Donelli et all [16] for the concurrent conceptual design of the system of interest (aircraft) and enabling systems (manufacturing and supply chain) also indicated as industrial systems. In this study, all the processes characterizing the conceptual design phase - from requirements to architectures generation and evaluation to tradespace exploration - are formalized to be addressed at the same time for the aircraft, manufacturing and supply chain systems.

A value-driven tradespace is proposed as way to make decisions considering design and production performance at the same time. In fact, each point of the tradespace refers, at the same time, to an aircraft 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 combination of the three systems architectures: the architecture of the aircraft system (e.g. choices of components), the architectures of manufacturing system (e.g. choice of materials and production processes) and the architecture of the supply chain system (e.g. choices of enterprises). Operational performance, like the mass, and production performance, like supply chain risk, therefore characterize each (co)architecture. As consequence, decisions related to system components, materials, manufacturing processes and enterprises can be made at the same time.

The follow-up activity, here presented, is to investigate how a Model-Based Product Line Engineering (MBPLE) approach can be applied to support the system of interest and industrial systems co-architecting. Even if MBPLE is traditionally used to model families of the same product, the objective is to demonstrate that such approach can also support the complexity of modelling the numerous variants generated from the co-architecting of multiple systems.

In details, MBPLE is the approach based on Product Line Engineering (PLE) enhanced by Model-Based Systems Engineering (MBSE) [17]. It is an ISO-standard approach supporting, through industrial standard formats [18], the development of systems family (also called product line) with variations in features that represent the variability of the specific characteristics of each system of the family that distinguishes it from the others [19].Therefore, MBPLE supports the modelling of the systems variability with the advantage of sharing commonalities. In this way, common assets like requirements, SysML models or CADs can be re-used. MBPLE is successfully applied in several sectors like defence [20], automotive [21] and aeronautics [22]. In these applications, MBPLE is used to model variability in different dimensions, mainly four: variability in system hierarchy levels, variability in development lifecycle, variability in layers of abstraction and co-variability in product, manufacturing and services [23]. This paper is framed within the last variability dimension. In this case, variability affects not only the product (e.g. aircraft) but also its manufacturing and extended services. Even if this dimension variability is widely described in [23], a practical application case is still missing and thus here presented.

The aim of this paper is therefore to demonstrate, also through an application case, how MBPLE can support the co-architecting of aircraft, manufacturing and supply chain systems. Various (co)architectures – or variants or product member in the MBPLE approach - are generated by adding variability in these systems, for instance in the choices of materials, enterprises or aircraft components. Furthermore, a value-driven tradespace exploration, i.e. a trade-off study, is proposed as additional step to the traditional MBPLE approach. So, once created the (co)architectures, differently from the traditional MBPLE approach, a value-model theory is applied to allow the co-architecting tradespace exploration and the identification of the best solution by trading stakeholders' expectations. Such proposed approach allows to combine the advantages of the MBPLE approach with thus related with the application of the value model theory. This means that by leveraging such proposed approach, systems variability can be easily modelled and stakeholders have the possibility to take decisions considering at the same time design and production criteria. An application case focusing on the modelling of the design, manufacturing and supply chain of an aircraft component that is the horizontal tail plane is addressed in this paper to concretely show how to apply such approach. The term (co)architectures, variants and product members have the same meaning in this research activity, thus it´s assumed to be interchangeable.

In details, the proposed tailored MBPLE approach is introduced in Section 2. Here, the steps characterizing such approach are described in a generic way considering the aircraft as system of interest, i.e. the system under design. Then, in Section 3, the application case is presented. Therefore, all the steps explained in Section 2 are applied to the design, manufacturing and supply chain of the horizontal tail plane. Tools and models are presented in this section. Finally, conclusions are reported in Section 4.

2. Value-driven MBPLE Approach for Co-architecting Exploration

A tailored MBPLE approach is proposed in this paper for the system of interest and industrial systems co-architecting modelling. The system of interest is the aircraft. The industrial systems are the manufacturing and supply chain systems. The manufacturing system is meant as combination of processes needed to produce the system of interest while the supply chain as combination of enterprises executing such processes. The objective is to model the variability of these systems for instance in the choice of components, materials, enterprises.

The proposed approach includes the four recommended main steps of an MBPLE approach plus the one related with the application of the value-model theory for the tradespace exploration and the identification of the best (co)architecture [23]. These five steps are described here-after, while an application case of them is shown in Section 3.

Step 1 – Define Product Line Feature Models: create feature models that capture the variability needs of the involved stakeholders and the feature constraints (e.g. feature A requires or conflicts feature B). The main objective of this step is to identify the variability of the systems and the possible or conflicting relationships. A schematic representation is shown in Figure 1. Variability can be included in the system of interest but also in the industrial systems. In the system of interest, the choice of the components or the number of components can be a variability. In the manufacturing systems, the materials and processes can vary. Instead, in the supply chain system, variability relays in the enterprises that can be selected to execute the processes. Figure 1 also represents the relationships that exists also among the different systems. For instance, the choice of material might constraint the process to select. If aluminium is selected as material, then a thermoplastic process must not be selected (red line between Material A and Process A1 in Figure 1). Similarly, when an assembly process is selected to join different product components. The combination of material and process for Component A might not be suitable to join it with Component B if done by selected materials and processes (red line between Component A/Material A/Process A1 and Component B/Material B/Process B1). At the same way, not all the enterprises can be selected to execute manufacturing processes. This depends on the competences that enterprises have. If an enterprise has no machines to execute the needed manufacturing or assembly processes, then it must not be selected (red zero in Figure 1).

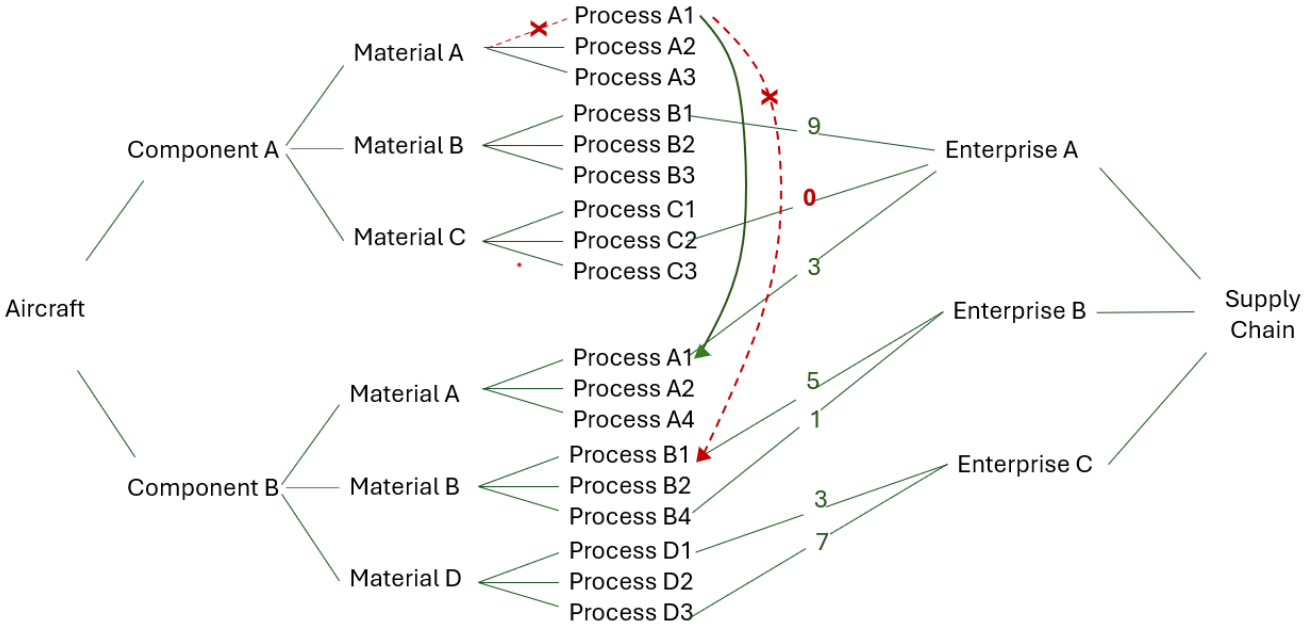


Figure 1 – System of Interest and Industrial System Feature Model, modified from *[24]*

Step 2 – Define Product Line Assets: define assets comprising all the product line features. This mean developing the so-called “150% models” representing the whole product line. These models include the whole variability of the product line.

In this step, the assets, which are the requirements and the architectural design space of the three systems, are created by following the technical processes proposed by Boggero et all [25]. This means that the collected stakeholders' needs are translated in formalized, unambiguous and clear technical requirements. Stakeholders involved can be either Original Equipment Manufacturer (OEM) sites responsible for the production of the aircraft or suppliers which are instead responsible for the production of aircraft components. A need of the OEM might be for instance related with the production cost, that should be minimized as much as possible. This need can be translated in a design constraint requirement which has, for example, the following pattern:

The *SYSTEM* shall have *CHARACTERISTICS* of *PERFORMANCE*

In this case the system is the supply chain system, the characteristic is the production cost while the performance the specific amount of dollars that the OEM (manager) is looking for. The design constraint requirements can be written for the system of interest and the industrial systems and they drive their design. Other types of requirements can be also included, for instance functional requirements or performance requirements which respectively express a function that the system shall perform or a performance it might have. The collection of all the requirements of the three systems represent the 150% model of the product line.

From the functional requirements, then, the (co)architectural design space can be built, as shown in Figure *2*. From these functional requirements, in fact, high-level functions (white boxes on top) are derived. Such functions are then fulfilled by components (grey boxes) that can induced other functions. The functions-components link allows to create the 150% model that shows indeed variability (architectural choice expressed by blue dotted lines in Figure *2*) in terms of material, manufacturing processes and enterprises in line with the feature model defined in step 1.

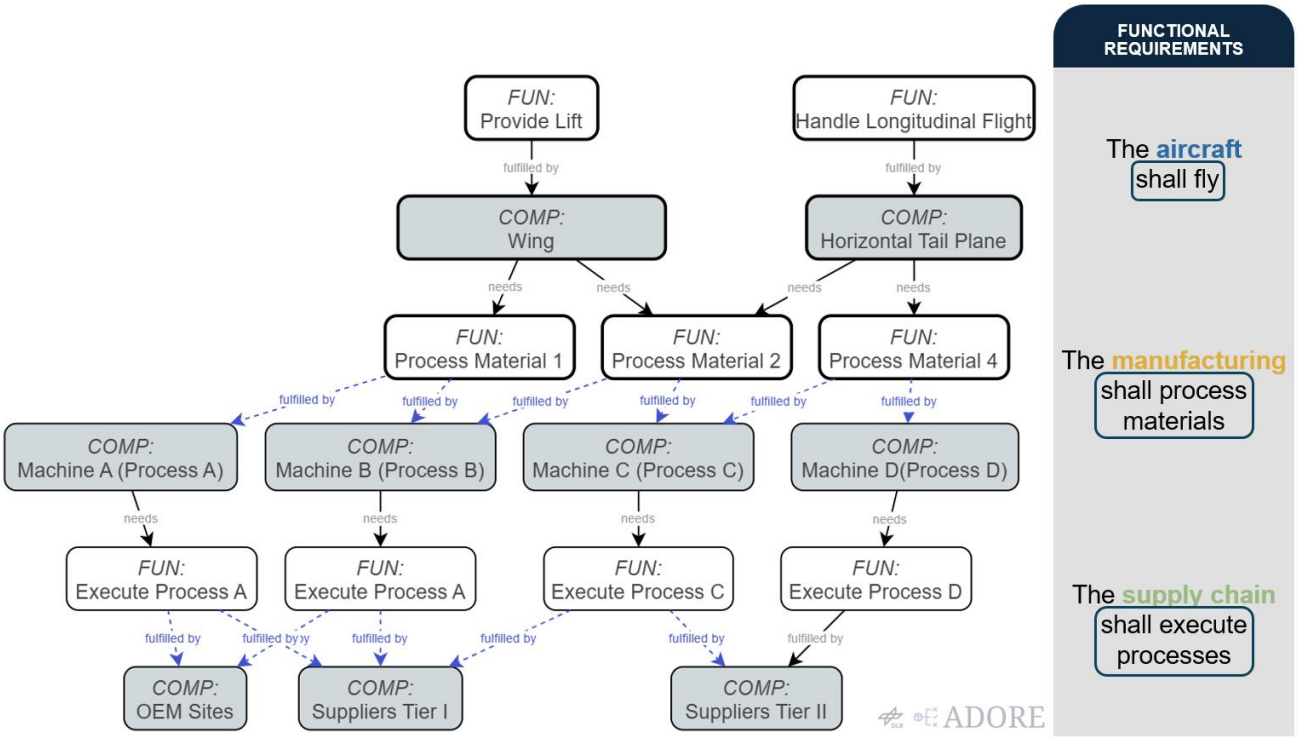


Figure 2 – Formalization of the 150% (co)architectural model of the system of interest (aircraft) and industrial systems (manufacturing, supply chain) in ADORE [25]

Step 3 – Select Member Product Feature Configuration: features are selected from the feature models, hence creating feature configurations for specific member products.

In this step, the choices in terms of materials, processes and enterprises are made and (co)architectures are created. A generic example of two variants is shown in the following table.

Variants	Components	Materials	Processes	Enterprises
Variant 1	Component A	Material A1	Process A1	Enterprise A
	Component B	Material A1	Process A1	Enterprise B
Variant 2	Component A	Material A1	Process A1	Enterprise A
	Component B	Material A1	Process A2	Enterprise A

Table 1 – System of Interest and Industrial Systems (Co)Architectures/Variants Example

In this case, the difference between the variants is in the choice of processes and enterprises of components B. Many other variants can be created. The number of possible variants that can be created depends on the number of materials, processes and enterprises characterizing the application case.

Step 4 – Derive Member Product Assets: all the assets of the specific member products (variants) are derived according to the feature model. This means deriving 100% models from the 150% models created in step 2.
An example of 100% model is reported in Figure 3 and it´s related to a specific (co)architecture in which the aircraft components are made by three different materials that can be processed by two different manufacturing processes that can be executed by OEM and Suppliers Tier II.

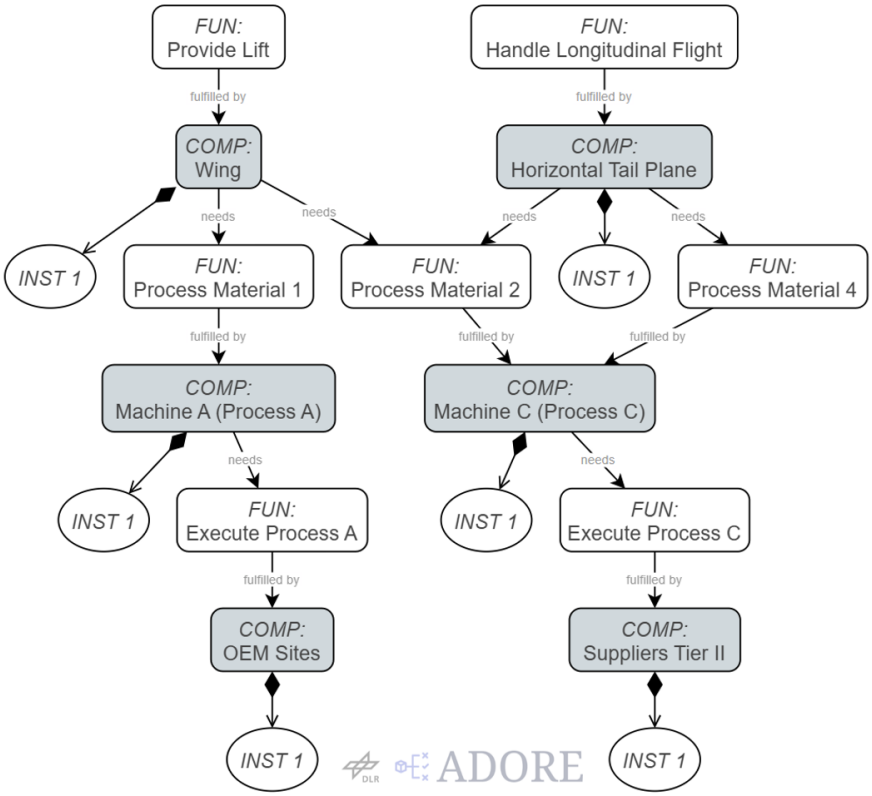


Figure 3 – Formalization of the 100% (co)architectural model of one (co)architecture/variant created in ADORE [25]

Step 5 – Explore and Assess Member Products: all the member products are traded and assessed considering stakeholders' expectations.

In this step, the best (co)architecture by trading stakeholders' expectations is identified. Each created variant is characterized by design and production performance. Among such performance parameters, some might be of extremely importance for stakeholders when making decisions. These parameters are also called attributes. To identify the best (co)architecture for stakeholders by considering all of these attributes, the value model theory, namely the Multi Attribute Utility Theory (MAUT), is used.

This value model theory estimates the value by assigning a utility function and a weight to each attribute as follow [26]:

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

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 attributes. The utility functions instead quantify the stakeholders' expectations with respect to these attributes, thus the way stakeholders would take decision when considering each specific one [27]. The (co)architecture with the highest value represents the best solution for stakeholders when considering all of these attributes at the same time.

3. Application Case

The application case focuses on the design, manufacturing and supply chain of a specific aircraft component that is the horizontal tail plane. Therefore, the horizontal tail plane (HTP) is assumed as system of interest while its manufacturing and supply chain systems as industrial systems.

In the next paragraph, the five steps described in Section2, are addressed in relation with this application case.

Step 1 – Define Product Line Feature Models: The tailored MBPLE approach starts with the creation of the features model representing the variability regarding the system of interest and the industrial systems. For sake of clarity, a simplified feature model – representing a limited set of choices of materials, processes and enterprises - is shown in Figure 4.

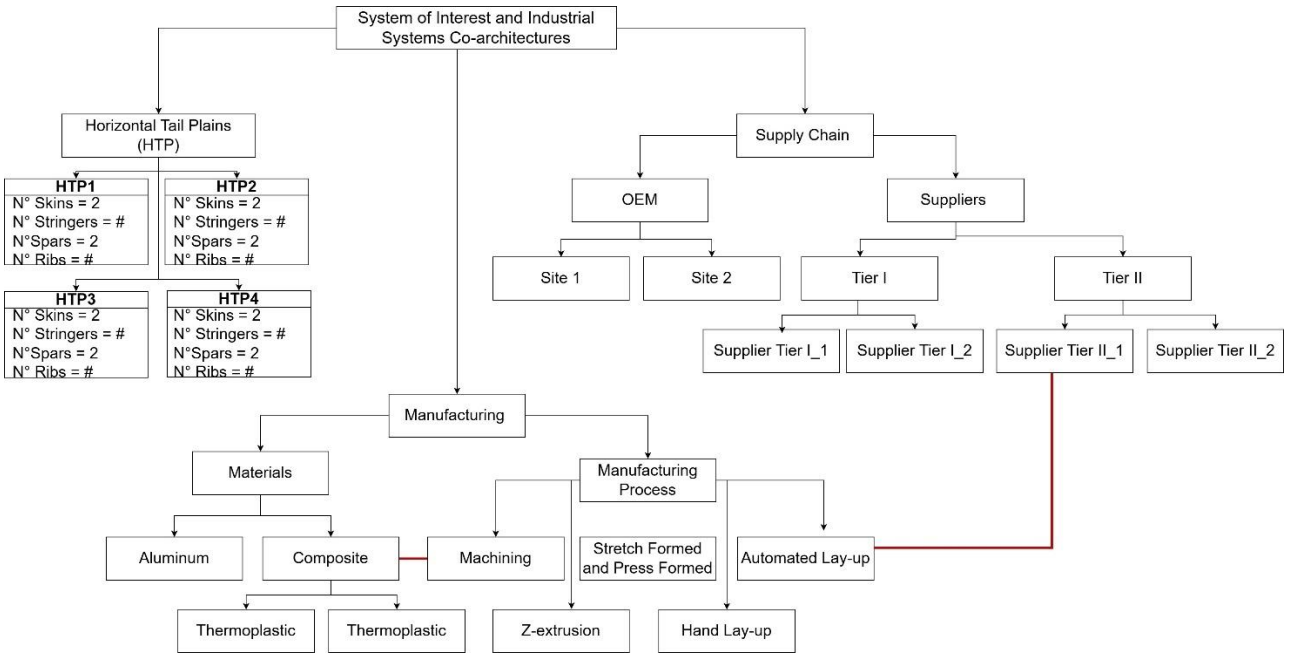


Figure 4 – Diagram representing the feature model of the horizontal tail plane and its industrial systems, mainly manufacturing and supply chain systems

For the system of interest, variability is added in the number of the main components characterizing the horizontal tail plane thus in the number of skins, stringers, spars and ribs. The numbers are not specified due to intellectual properties of industrial partners who provided data. This reflects in a

different mass and drag of each horizontal tail plane and, thus, in a different fuel consumption mass of the aircraft. These quantities are of interest for stakeholders. The structural layout of the horizontal tail plane is instead assumed to be fixed. Therefore, the different variants of the horizontal tail plane have some geometric characteristics in common (e.g. the area, the span). For the industrial systems, variability is included in the choices of materials, manufacturing processes and enterprises. The full variability is instead specified in Table 2 in which the number of materials, processes and enterprises for each of the main horizontal tail plane components is specified.

Variability	Skins	Stringers	Spars	Ribs
Number of Materials	2	3	3	4
Number of Manufacturing Processes	6	4	5	5
Number of Enterprises	21			

Table 2 – Variability in terms of materials, manufacturing processes and enterprises

The diagram in Figure 4 finally shows also example of constraints (red line). Such constraints are also shown in Figure 5 representing part of the feature model realized in *pure::variants*. The creation of such features model is a key aspect of the whole MBPLE approach. It is in fact important to model and handle all the variations along the entire product line.

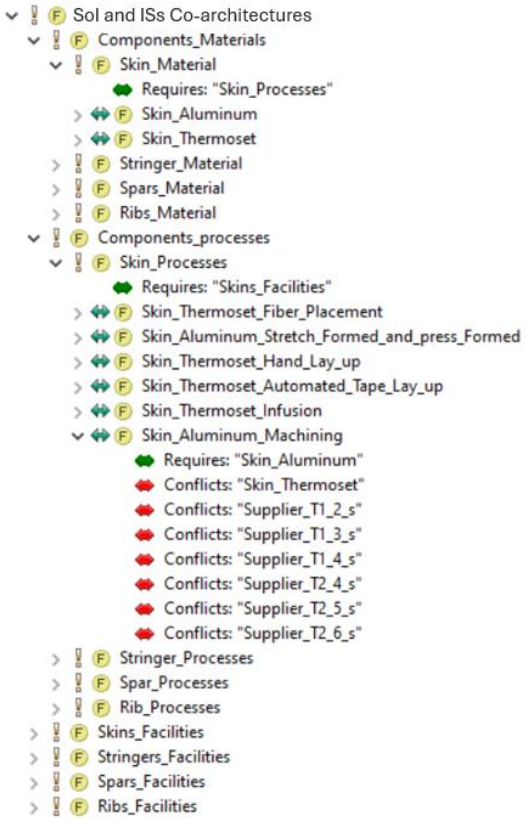


Figure 5 – Part of the Feature model created in *pure::variants* including relationships

The tool selected in this paper for this purpose – i.e. pure variants – not only supports with the creation of the features model, but also with the management of the variants and assets, as shown in the next steps.

Step 2 – Define Product Line Assets: The assets and thus the requirements and the architectures of the product line, consisting of the horizontal tail plane and its industrial systems, are generated. The 150% model of requirements, addressing all variants of the product line, is shown in Figure 6. These requirements, mainly design constraints (blue bubbles in *name* column) and functional (red bubbles in *name* column) requirements, are related with all the variants of the horizontal tail plane, manufacturing and supply chain systems. The *link* column specifies to which horizontal tail plane

variant the specific requirements is related with.

ID	Name	Statement	Links:
RQ-10	Span	The htp shall have the span of maximum TBD m	HTP_4 HTP_3 HTP_1 HTP_2
RQ-19	Production Duration	The htp supply chain shall have the production time of maximum TBD h	HTP_4 HTP_1 HTP_2 HTP_3
RQ-8	Mass HTP2	The htp shall have the mass of maximum 420 kg	HTP_2
RQ-11	Mass HTP3	The htp shall have the mass of maximum 456 kg	HTP_3
RQ-17	Material Composite	The htp shall have material of composite	HTP_3 HTP_1
RQ-6	Production Risk	The htp supply chain shall have the production risk of maximum TBD	HTP_4 HTP_1 HTP_2 HTP_3
RQ-12	Mass HTP4	The htp shall have the mass of maximum 412 kg	HTP_4
RQ-16	Material Aluminum	The htp shall have material of aluminum	HTP_4 HTP_2
RQ-18	Production Cost	The htp supply chain shall have the production cost of maximum TBD $	HTP_4 HTP_1 HTP_2 HTP_3
RQ-7	Mass HTP1	The htp shall have the mass of maximum 458 kg	HTP_1
RQ-20	Production Quality	The htp supply chain shall have the production quality of maximum TBD	HTP_1 HTP_3 HTP_4 HTP_2
RQ-1	Provide lift	The htp shall provide lift while in flight	HTP_3 HTP_1 HTP_2 HTP_4
RQ-21	efficient operation	The htp supply chain shall operate efficiently while in case of disruption	HTP_4 HTP_2 HTP_3 HTP_1
RQ-9	longitudinal stability	The htp shall guarantee longitudinal flight while in flight	HTP_3 HTP_4 HTP_1 HTP_2

Figure 6 – Part of the 150% direct model of the horizontal tail plane and its industrial systems (manufacturing, supply chain) requirements

As explained in Section 2, from the functional requirements then the architectural design space of the horizontal tail plane, manufacturing and supply chain systems is built. Part of the 150% model of the (co)architectural design is shown in Figure 7.

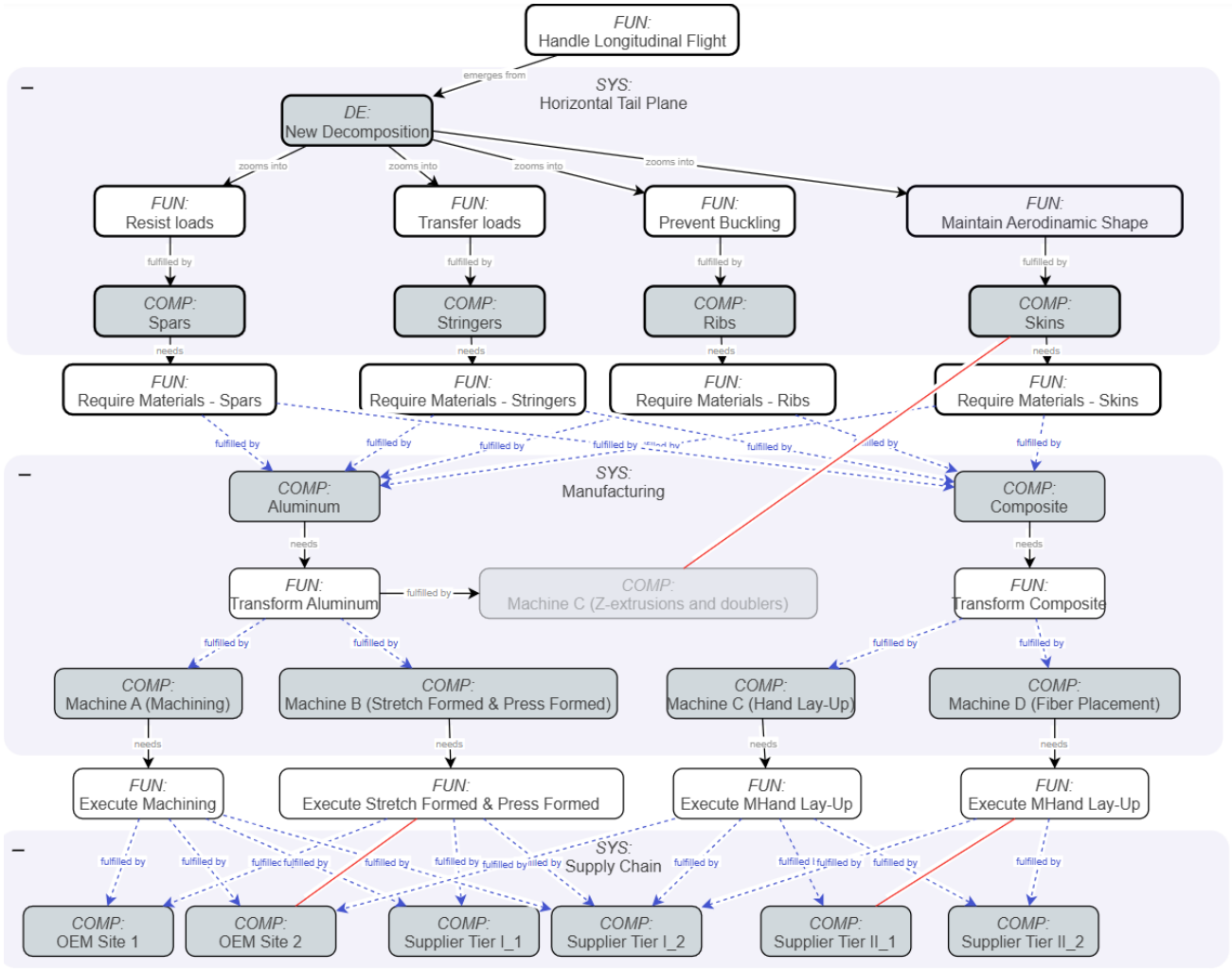


Figure 7 – Part of the 150% (co)architectural model of the horizontal tail plane and its industrial systems, manufacturing and supply chain

The variability in the number of the main horizontal tail plane components is implicitly modelled through quantity of interest as shown in Figure 8.

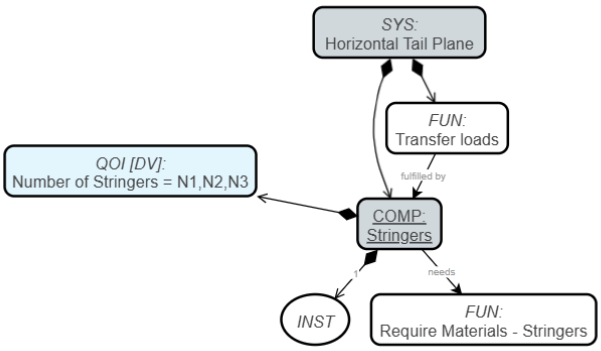


Figure 8 – Variability of stringers expressed through Quantity of Interest (QoI)

Step 3 – Select Member Product Feature Configuration: features are selected from the feature models and (co)architectures, variants, are created. In total, 28 feasible variants are generated: each one is characterized by materials, processes, enterprises. The software *pure::variants* is used to select the features and create the member product variants, as shown in Figure 9.

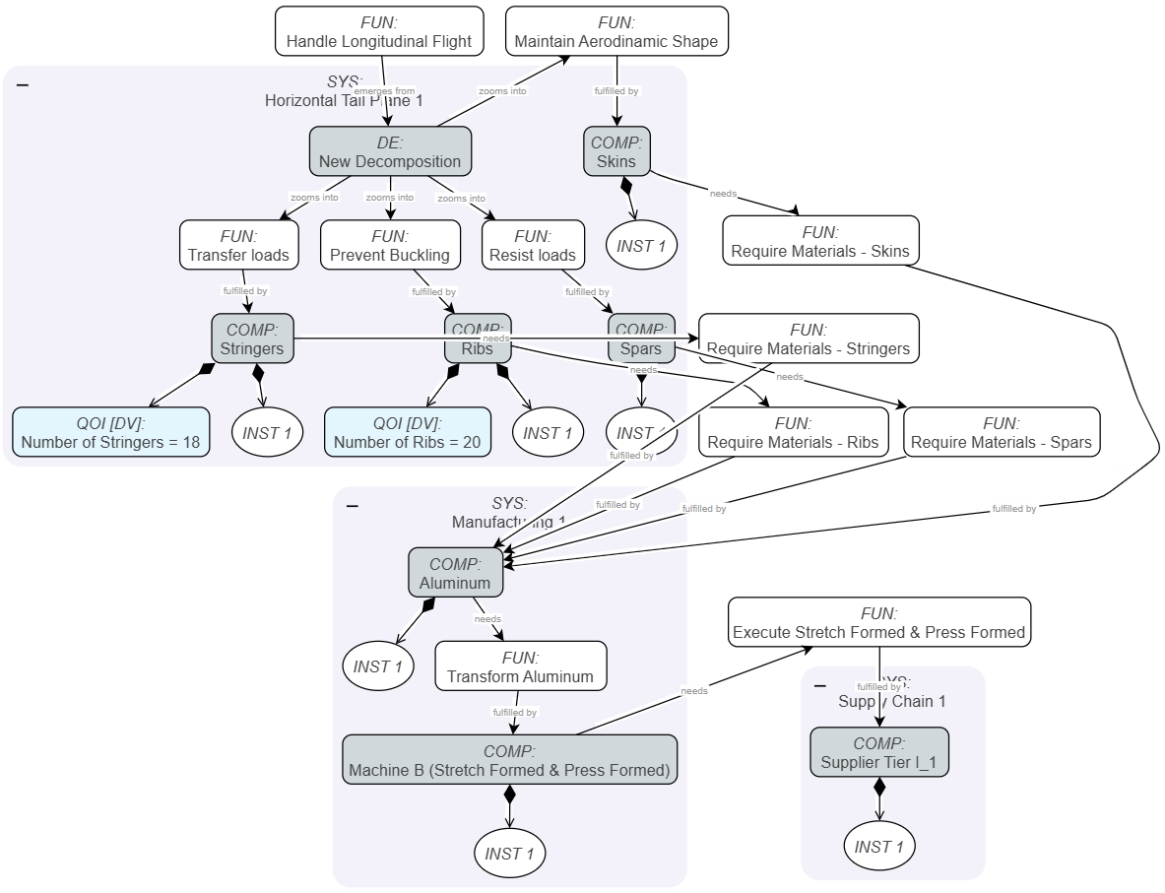
Model Elements	Level	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant	Variant
prova_on_repo																	
SoI and ISs Co-architectures		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Components_Materials	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ribs_Material	1.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Skin_Material	1.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Spars_Material	1.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Stringer_Material	1.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Components_processes	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	☑	✓	✓	✓	✓	✓	✓
Rib_Processes	2.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Rib_Aluminum_Machining	2.4.1	☑	☒	☒	☑	☒	☒	☒	☒	☒	☑	☒	☒	☒	☒	☒	☑	☑
Rib_Aluminum_Z-extrusion	2.4.5	☒	☑	☒	☒	☑	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
Rib_Thermoplastic_Thermoforming	2.4.2	☒	☒	☒	☒	☒	☒	☑	☒	☒	☒	☒	☑	✓	☒	☑	☒	☒
Rib_Thermoset_Hand_Lay_up	2.4.3	☒	☒	☒	☒	☒	☒	☒	☑	☒	☒	☒	☒	☒	☑	☒	☒	☒
Rib_Titanium_machining	2.4.4	☒	☒	✓	☒	☒	☑	☒	☒	☑	☒	☑	☒	☒	☒	☒	☒	☒
Skin_Processes	2.1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Skin_Aluminum_Machining	2.1.6	☑	☑	☑	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
Skin_Aluminum_Stretch_Formed_an...	2.1.2	☒	☒	☒	☑	☑	☑	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
Skin_Thermoset_Automated_Tape_La...	2.1.4	☒	☒	☒	☒	☒	☒	☒	☒	☒	☑	☑	☑	☒	☒	☒	☒	☒
Skin_Thermoset_Fiber_Placement	2.1.1	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☑	☑
Skin_Thermoset_Hand_Lay_up	2.1.3	☒	☒	☒	☒	☒	☒	☑	☑	☑	☒	☒	☒	☒	☒	☒	☒	☒
Skin_Thermoset_Infusion	2.1.5	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☑	☑	☑	☒	☒
Spar_Processes	2.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Spar_Aluminum_Machining	2.3.1	✓	✓	✓	✓	✓	✓	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
Spar_Thermoplastic_Thermoforming	2.3.2	☒	☒	☒	☒	☒	☒	☑	☒	☒	☒	☑	☒	☒	☒	☑	☒	☒
Spar_Thermoset_Fiber_Placement	2.3.3	☒	☒	☒	☒	☒	☒	☒	☒	☒	☑	☒	☒	☑	☒	☒	☒	☑
Spar_Thermoset_Hand_Lay_up	2.3.5	☒	☒	☒	☒	☒	☒	☒	☑	☒	☒	☒	☒	☒	☒	☒	☑	☒
Spar_Thermoset_Infusion	2.3.4	☒	☒	☒	☒	☒	☒	☒	☒	☑	☒	☒	☑	☒	☑	☒	☒	☒
Stringer_Processes	2.2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Stringer_Aluminum_Machining	2.2.1	☑	☑	☑	☑	☒	☒	☒	☒	☒	☑	☒	☒	☑	☒	☒	☑	☒
Stringer_Aluminum_Z_extrusion	2.2.3	☒	☒	☒	☒	☑	☑	☑	☒	☒	☒	☒	☒	☒	☒	☒	☒	☒
Stringer_Thermoplastic_Additive_Ma...	2.2.2	☒	☒	☒	☒	☒	☒	☒	☒	☑	☒	☒	☑	☒	☒	☑	☒	☑

Figure 9 – Variants of the product line and features selected in *pure::variants*

Step 4 – Derive Member Product Assets: This means deriving 100% models from the 150% models created in step 2. So once the member product variants are defined through the selection of features from the features model (previous step), all the assets charactering each individual member are collected. These assets can for example include the 100% requirements model and the related (co)architectural model. The requirements and the (co)architectural model shown in Figure 10 are related with a specific (co)architecture: the HTP4, characterized by a specific number of stringers and ribs, made by aluminum, outsourced to suppliers TierI_1.

ID	Name	Statement	Links:
RQ-10	Span	The htp shall have the span of maximum TBD m	HTP_4 HTP_3 HTP_1 HTP_2
RQ-19	Production Duration	The htp supply chain shall have the production time of maximum TBD h	HTP_4 HTP_1 HTP_2 HTP_3
RQ-6	Production Risk	The htp supply chain shall have the production risk of maximum TBD	HTP_4 HTP_1 HTP_2 HTP_3
RQ-12	Mass HTP4	The htp shall have the mass of maximum 412 kg	HTP_4
RQ-16	Material Aluminum	The htp shall have material of aluminum	HTP_4 HTP_2
RQ-18	Production Cost	The htp supply chain shall have the production cost of maximum TBD $	HTP_4 HTP_1 HTP_2 HTP_3
RQ-20	Production Quality	The htp supply chain shall have the production quality of PERFORMANCE	HTP_1 HTP_3 HTP_4 HTP_2

a) 100% requirements model



b) 100% (co)architectural model

Figure 10 – 100% requirements (a) and (co)architectural model (b) of one of the (co)architecture among the 28 members product variants of the investigated product line

Step 5 – Explore and Assess Member Products: all the member products, so all the variants generated in the previous step, are traded and assessed considering stakeholders' expectations by leveraging the value model theory. In this application case, five main attributes are considered: the fuel consumption mass as key performance indicator of the aircraft performance and the production

time, quality, risk and cost as key performance indicator of the industrial systems (supply chain and manufacturing). To estimate the value, first, the same weight is assigned to all the attributes meaning that there is no prioritization of all of them. Then, two other weight combinations are analysed: the first one in which more importance is given to the aircraft performance, thus to the fuel consumption mass; the second one in which the production risk is prioritized. Linear utility functions for all the attributes are used to estimate the value. The analysed cases are summarized in Table 3. The production cost is not included as attributes since used as other independent variable.

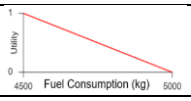
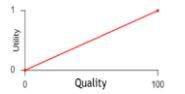
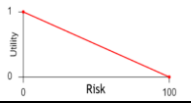
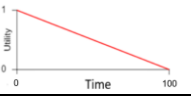
Attribute	Weight Combination I	Weight Combination II	Weight Combination III	Utility Function
Fuel Consumption Mass (Kg)	0.25	0.7	0.1	
Production Quality (-)	0.25	0.1	0.1	
Production Risk (-)	0.25	0.1	0.7	
Production Time (-)	0.25	0.1	0.1	

Table 3 – Weight Combinations and Utility Functions

The value-cost tradespace related with the weight combination I is reported in Figure 11.

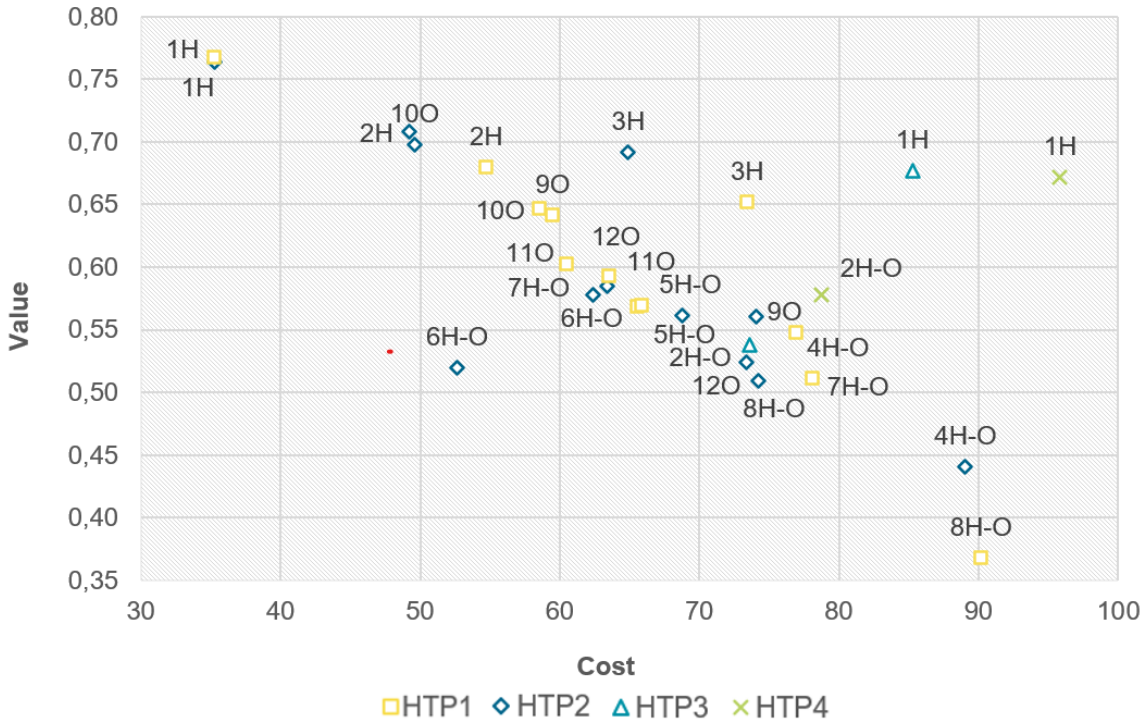
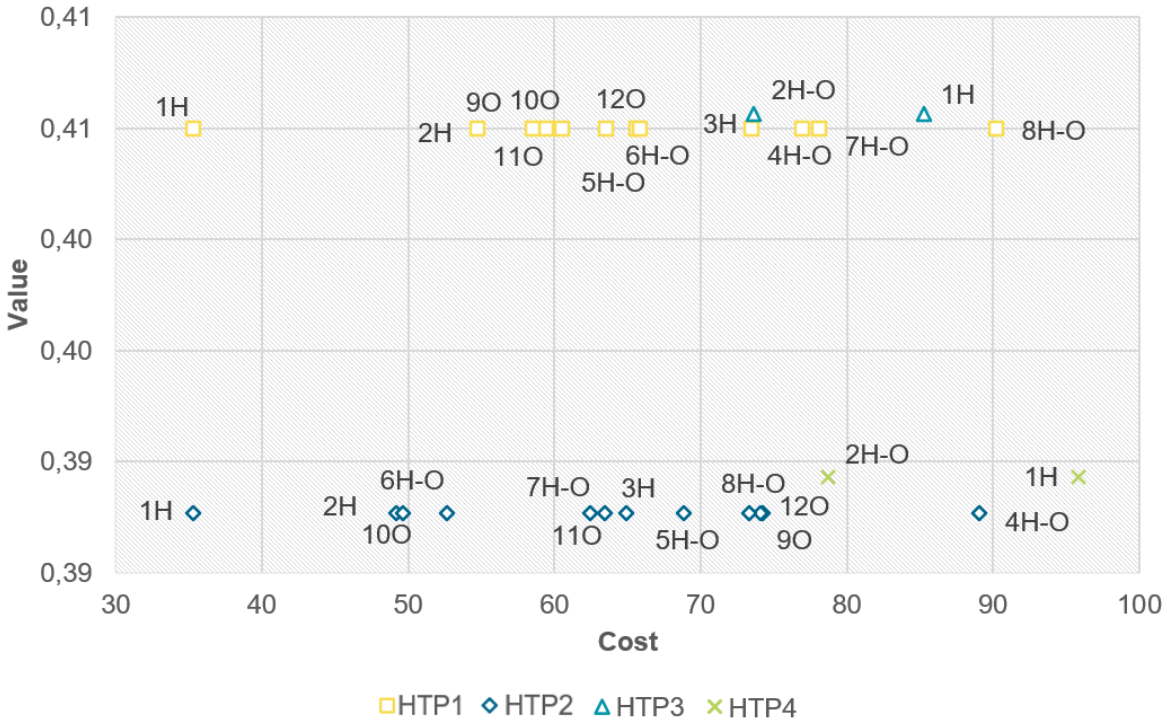
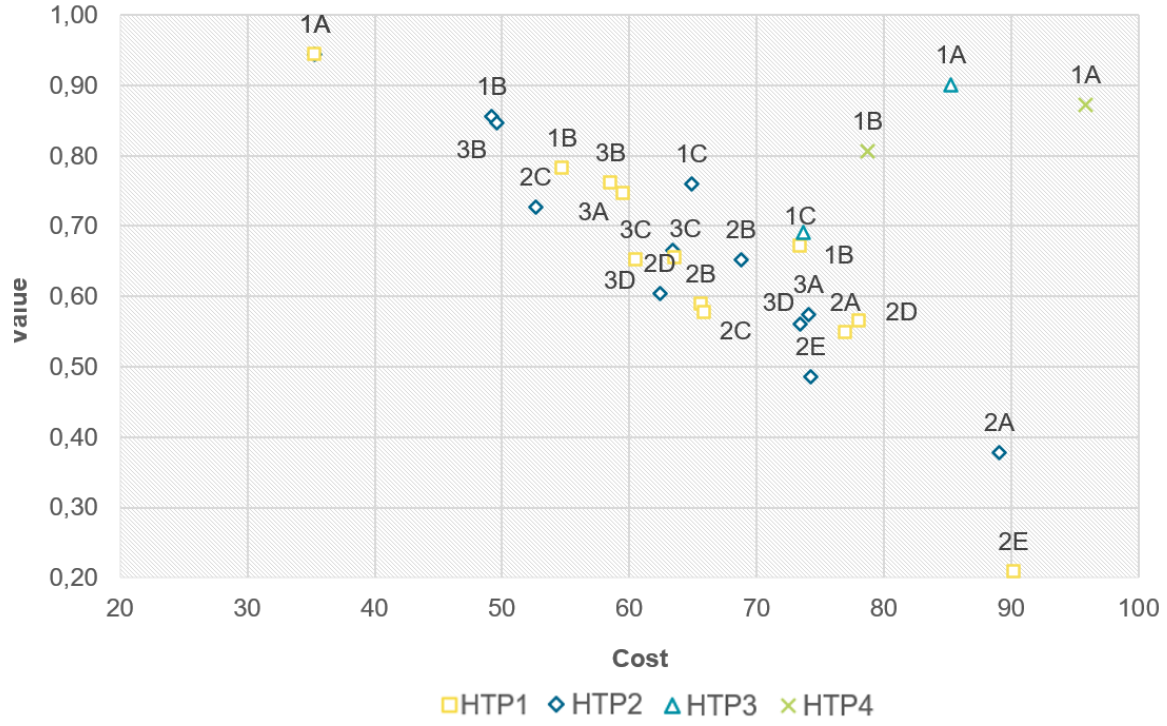


Figure 11 – Value-cost tradespace: linear utility functions and same weight

It shows how the best (co)architecture is the solution related with the HTP2 (yellow square), produced in house (H). Even do the HTP architecture characterizing this variant is not the one minimizing the fuel consumption (HTP3), the best production performance make this solution being the one with the highest value. The value-cost tradespaces of the other weight combinations are instead reported in Figure 12.



a) Weight Combination II: Fuel Consumption Mass Prioritization



b) Weight Combination III: Production Risk Prioritization

Figure 12 – Value-cost tradespace: linear utility functions, weight combination II and III

The tradespace in Figure 12a is the one in which the fuel consumption mass is prioritized. As expected, the best (co)architecture, highest value, is the one related with the HTP3, architecture minimizing the fuel consumption. In this case, the impact of the supply chain performance on the value is almost negligible. The tradespace simply shows that the HTP1 and HTP3, mainly made by aluminum, have lower fuel consumption (and therefore high value) than the HTP2 and HTP4, mainly made by composite. Instead, the tradespace in Figure 12b is the one in which the production risk is prioritized and therefore considerations on the aircraft performance cannot be addressed. The best (co)architecture, in this case, is the HTP1 in which the production and assembly of all the HTP components are performed at the same site, so fully produced in house. Enterprises involved in this

supply chain have higher competences than enterprises selected for the production of other HTP architectures and consequently, lower production time and risk and thus higher value.

These results are fully aligned with those obtained in [16], where a different methodology has been used to achieve such results, validating the proposed tailored MBPLE approach and showing the main advantages of using it. One of its main strengths is the ability to provide a comprehensive perspective on variability. By formally capturing product characteristics, constraints, and interdependencies within models, such tailored MBPLE approach enables stakeholders (e.g. engineers, managers) to assess trade-off studies across the full range of possible configurations rather than focusing on individual architectures.

4. Conclusion

A tailored Model Based Product Line Engineering approach which includes the application of the value model theory is proposed in this research activity. The aim is to demonstrate how an MBPLE approach can support the system of interest and industrial systems co-architecting for the identification of the best solution for stakeholders. Create (co)architectures that including design and production choices at the same time can reduce the possibility of identifying design errors during the production stage, when the mitigation actions would have negative impact on the lead time and cost of the member products. However, the co-architecting of this multiple systems would create a huge quantity of data, that can be effectively managed through the proposed tailored MBPLE approach. Such developed approach has been applied to the horizontal tail plane and it industrial systems, manufacturing and supply chain. Some assumptions have been made during the investigation. These assumptions do not limit the quality of the work, but they simplify it giving the chance to validate the proposed approach and show the advantages of leveraging it. More complex application cases might be addressed in the future by considering, for instance, the possibility to split the number of components to be produced among enterprises (OEM sites or suppliers). In addition, further investigation can be done in the direction of software development to understand how to automatize all the presented steps – even using different technologies. Concluding, the proposed tailored MBPLE approach enables effective management of the complexity and data generated in the system of interest and industrial systems co-architecting. By formally representing product features, constraints, and dependencies, it provides a holistic view of variability and supports trade-off analysis across the entire design space from early development stages.

5. Acknowledgment

Authors would like to thank Gabriele Allegra for the activities addressed during his master thesis, investigating the same topic but with a different application case.

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