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A VALUE-DRIVEN QUANTITATIVE FRAMEWORK COUPLING AIRCRAFT DESIGN, MANUFACTURING AND SUPPLY CHAIN BY LEVERAGING THE AGILE 4.0 MBSE-MDO FRAMEWORK

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Abstract

The design of future innovative, sustainable and circular aircraft configurations arises 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. In this frame, within the EU-funded H2020 AGILE 4.0 project, the concurrent coupling of the three domains of product design, manufacturing and supply chain has been addressed by levering Model-Based Systems Engineering (MBSE) and Multidisciplinary Design and Optimization (MDO) technologies The MBSE models and the MDO preliminary results related to the three-dimensional approach applied to a specific aircraft component, that is the horizontal tail plane, are addressed in this research activity and presented in the paper.

Keywords: MBSE, MDO, manufacturing, supply chain, value model

1. Introduction

In the last decade, the European Commission introduced the Flightpath 2050, defining new challenges for the design of the future innovative, sustainable and circular aircraft configurations [1]. 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. 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. In this context, the DLR Institute of System Architectures in Aeronautics is developing methods and technologies enabling the concurrent coupling of multiple domains in the early development phase. This allows the decision makers to take strategic decisions that would optimize the system life-cycle. The research activity presented in this paper introduces a simultaneous coupling of the three domains of product design, manufacturing and supply chain, applied to an aeronautical system. In details, the overall aircraft design (OAD) domain deals with the aircraft specification and determination of its technical performance; the manufacturing (MfG) domain includes all the processes through which raw materials are transformed in the final product; the supply chain (SC) domain characterizes the enterprises involved in the product development encompassing all the logistic and management aspects. A schematic representation of the proposed value-driven three-dimensional methodology is showed in Figure 1. The alignment of the domains highlights the concurrent coupling of the same, the arrows instead indicate the direction of the information flow exchanged between domains. Particularly, a technology factor, i.e. a number ranging from zero to one, is proposed as the link between the manufacturing and overall aircraft design domains. It indicates the impact that the use of different materials, manufacturing and assembly processes has on the aircraft performance. On the other side, the production quantity that each enterprise has to perform to realize the final product is identified as the link between the manufacturing and supply chain domains. The parameter *value*, estimated using the Multi Attribute Utility theory [2], is then adopted to aggregate multiple criteria charactering different domains in a single measure, hence enabling the simultaneous coupling of multiple domains. Expanding the aircraft design variables with those of manufacturing and production complicates the design problem, due to an enlargement of the alternatives populating the final solutions tradespace [3]. However, the generated value-cost tradespace supports the decision making while taking strategic decisions in the early stage of aircraft development. In fact, considering all requirements of design, manufacturing, and supply chain, provides a great chance of giving responsiveness, agility, variety, quality, and competitive advantages to win the market.

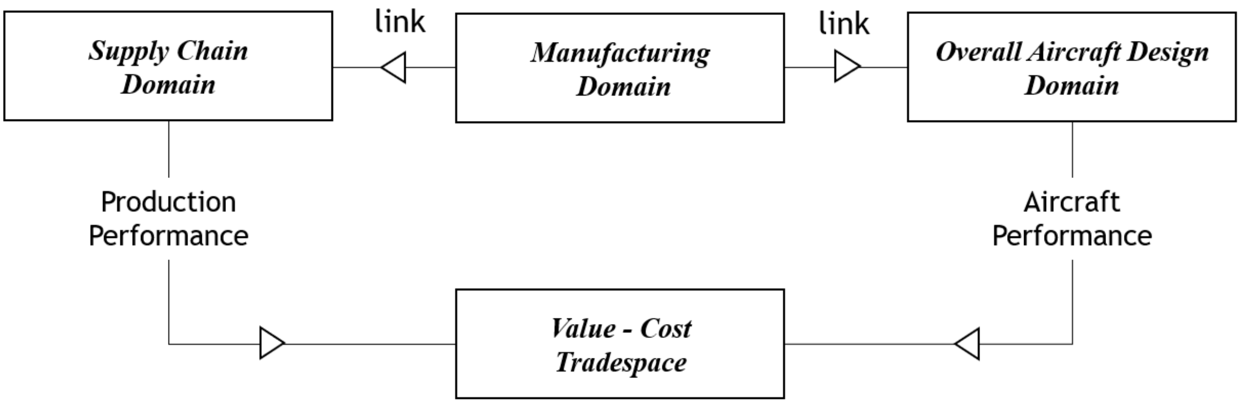


Figure 1 – Schematic representation of three-dimensional methodology concurrent coupling product design, manufacturing and supply chain in the early development stage [4]

The concurrent coupling of the three domains is being addressed within the European project AGILE4.0 [5], by levering Model-Based Systems Engineering (MBSE) and Multidisciplinary Design and Optimization (MDO) technologies. Thus, the AGILE 4.0 MBSE and MDO framework, showed in Figure 2, is adopted for the modelling of the upstream and downstream activities, including stakeholders, needs and requirements identification, system architecting and design and optimization exploration. The models and the preliminary results of the MBSE and MDO framework applied to the concurrent coupling of the horizontal tail plane (HTP), manufacturing and supply chain systems are presented in this paper.

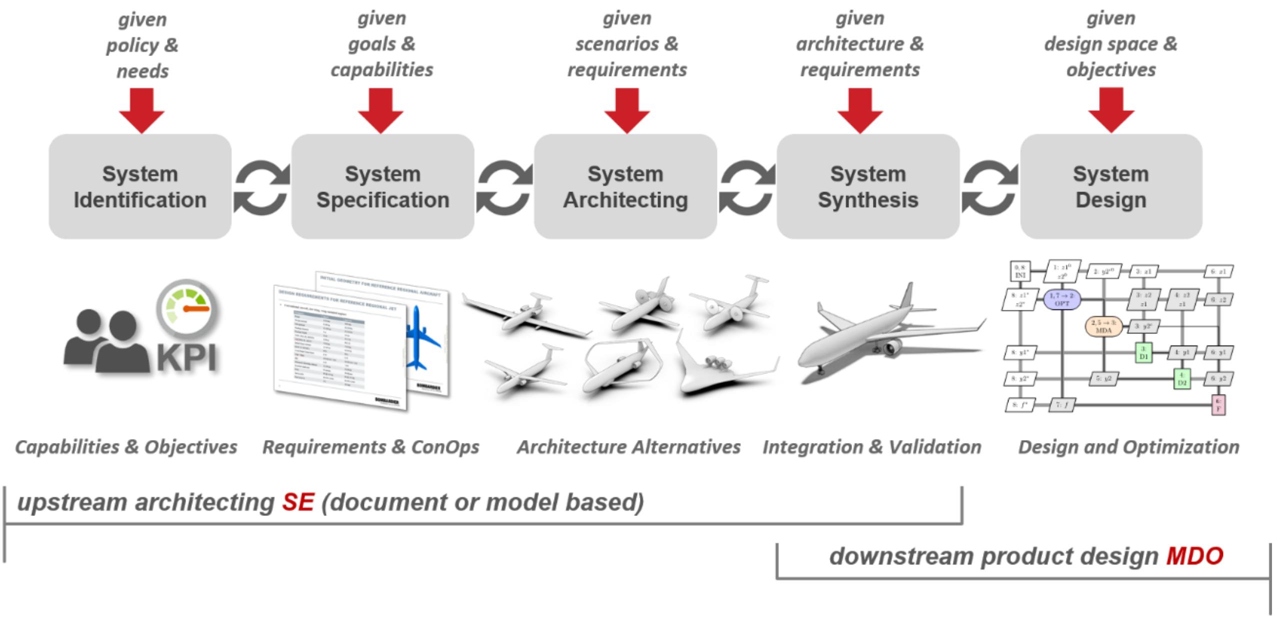


Figure 2 – The AGILE 4.0 MBSE-MDO Development Framework: “upstream architecting SE” and “downstream product design MDO” phases [6].

Thus, the system identification and specification activities are addressed in Section II. The system architecting details are provided in Section III, while the MDO process technologies, the design studies and the MDO preliminary results are shown in Section IV. Conclusions and future activities are described in Section V.

2. System definition and specification: stakeholders, needs and requirements modelling

The system identification and specification, first activities addressed with the AGILE 4.0 MBSE and MDO framework shown in Figure 2, include the modeling of stakeholders, their respective needs and requirements. Different MBSE technologies are developed and used in the AGILE 4.0 project for the stakeholders, needs and requirements modelling [8]. Few examples of stakeholder, need and requirement models are described hereafter.

Starting from stakeholders, a view of the Papyrus model is reported in Figure 3. As shown in the SysML diagram in the figure, several stakeholders are involved in the design, manufacturing and production of an horizontal tail plane. However, since the horizontal tail plane is integrated in the aircraft, also stakeholders related to the aircraft design and production are accounted. Thus, stakeholders vary from the certification authorities, airlines, flight crew to the passengers, maintainers, manufacturers. The focus, in Figure 3, is on the supply chain stakeholder, thus on the enterprises involved in the production of the HTP. Particularly, the Original Equipment Manufacturer (OEM), the supplier tier I and the supplier tier II are supposed to be involved in the supply chain. The OEM is responsible for the production and assembly of the entire aircraft; the supplier tier I for the production and assembly of aircraft components (e.g. the horizontal tail plane); while minor parts are assigned to supplier tier II.

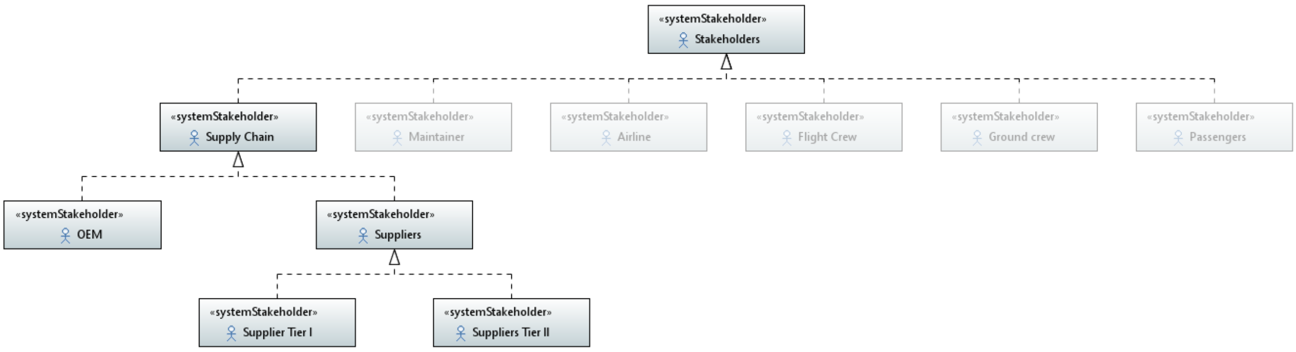


Figure 3 – Model of the stakeholders involved in the design, manufacturing and production of the horizontal tail plane modelled using the AGILE 4.0 Framework, [6]

Depending on the role they play in the aircraft production, each enterprise has different needs. For instance, the OEM, which delivers the final product (aircraft) to the airlines, has interest in selling a large volume of aircraft but also in having a well-produced HTP, especially if outsourced to suppliers. The model of these OEM´s needs is showed in Figure 4. These stakeholders´ needs are then converted into requirements, which follow specific modelling rules and patterns, to eliminate any ambiguity of interpretation. So, the OEM´s need about selling a large volume of aircraft (N24) is translated into a requirement related to the sale price of the aircraft (R80). From this requirement, others can be derived. For instance, the requirement on the sale price of the aircraft impacts the sale price of the aircraft components, thus the sell price of the horizontal tail plane. A requirement on the sale price of the HTP (R47) is derived from the one related to the aircraft. On the other hand, the OEM´s need about a well-designed HTP (N52) leads to technical HTP requirements related to the design and manufacturing variables, for instance to the quarter-chord sweep angle, HTP mass and reference area (respectively R11, R25, R43). The HTP must be therefore compliant with these requirements. In the example of Figure 4, in which the HTP is outsourced, the supplier tier I is the "responsible stakeholder" in charge of the effective application of these requirements to the product. In case of non-compliance of the HTP with the requirements, several consequences occur. For instance, the HTP non-compliance with the requirements of design, manufacturing and production implies a loss of competitiveness in the market, due to lower aircraft performance or production issues. The consequences are also included in the Papyrus model, as shown in Figure 4.

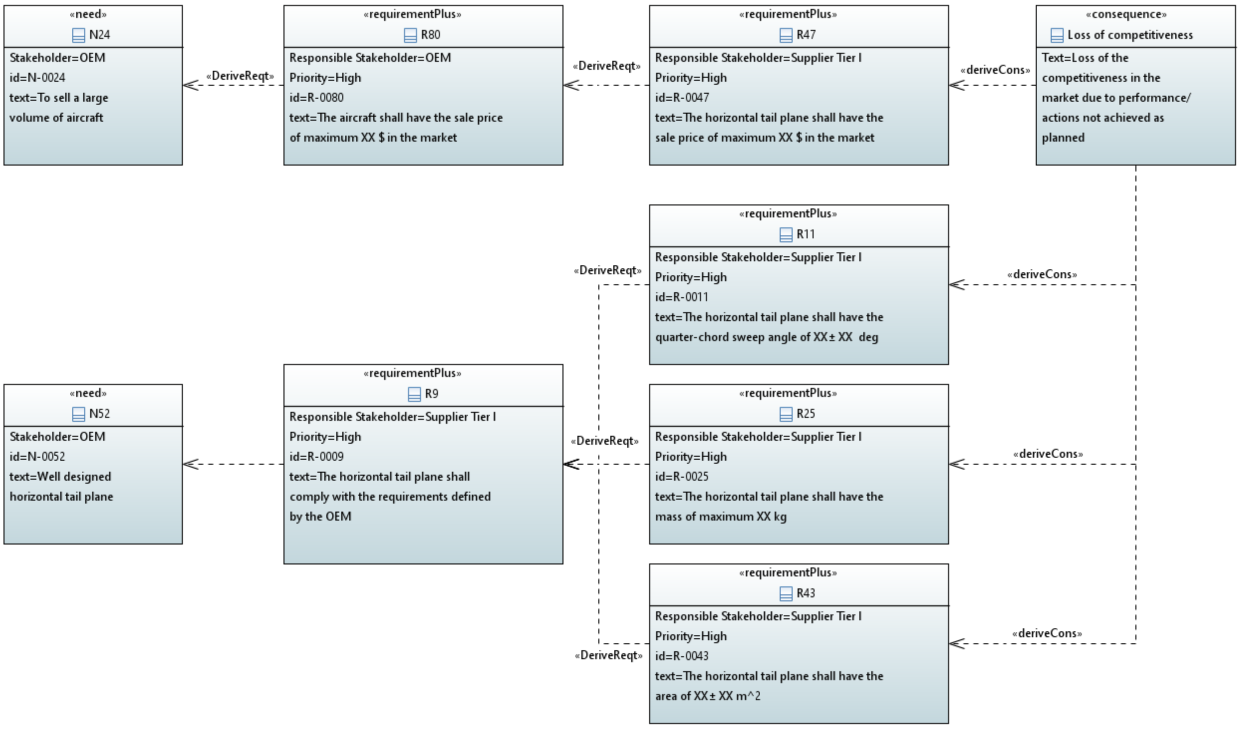


Figure 4 – OEM´ needs and requirements concerning the supply chain domain (N24) and the manufacturing and design domains (N52) modelled using the AGILE4.0 Framework, [6]

The examples addressed in this section are representative of the stakeholders, needs and requirements models that can be generated by using the MBSE technologies developed for the system identification and specification activities, first steps of the MBSE-MDO framework. Once assessed these stages, the system architecure can be generated starting from requirements, as explained in the next section.

3. System architecting: from MBSE upstream activities to MDO design exploration

The previous section has shown how to leverage the MBSE-MDO framework for the modelling of stakeholders, needs and requirements with respect to the HTP, manufacturing and supply chain systems. Hereafter, instead, the focus is on the system architecting, which starts with the collection of boundary functions defined from requirements. In details, the system architecting is based on the allocation of functions to form (e.g. system, component) and relationships among the elements of this form [9]. The architecture modelling has been realized by using ADORE, the DLR tool supporting the MBSE framework in the system architecting [10].
A simplified but representative system architecting coupling the three systems of HTP, manufacturing and supply chain is shown in Figure 5. In this figure, it is possible to recognize the boundary functions, defined from requirements, associated to each system. Thus, the horizontal tail plan system has to *handle the longitudinal flight*, the manufacturing system has to *manufacture the horizontal tail plane*, while the supply chain system has *to perform manufacturing processes*. The key aspect of this multi-systems architecture modelling is the translation of an induced function of a system in the boundary function of the other one. For example, the HTP system has to handle the longitudinal flight (boundary function of HTP system), but it needs to be manufactured (induced function of HTP system translated in the boundary function of manufacturing system). Same applies for manufacturing and supply chain systems.

At the systems components, the same relationship between function-component can be identified. Thus, the HTP components, i.e. spars, stringers, ribs and skins perform other functions to assure that the HTP fulfill its boundary function. For instance, the skins maintain the aerodynamic shape to produce the lift needed to handle the longitudinal flight. Instead, the manufacturing and assembly processes have been identified as main components of the manufacturing system. Thus, the machining, the hand-lay-up, the riveting can be used to manufacture and assembly the HTP components. These manufacturing processes are then performed by multiple enterprises (OEM and suppliers), defined as main components of the supply chain system.

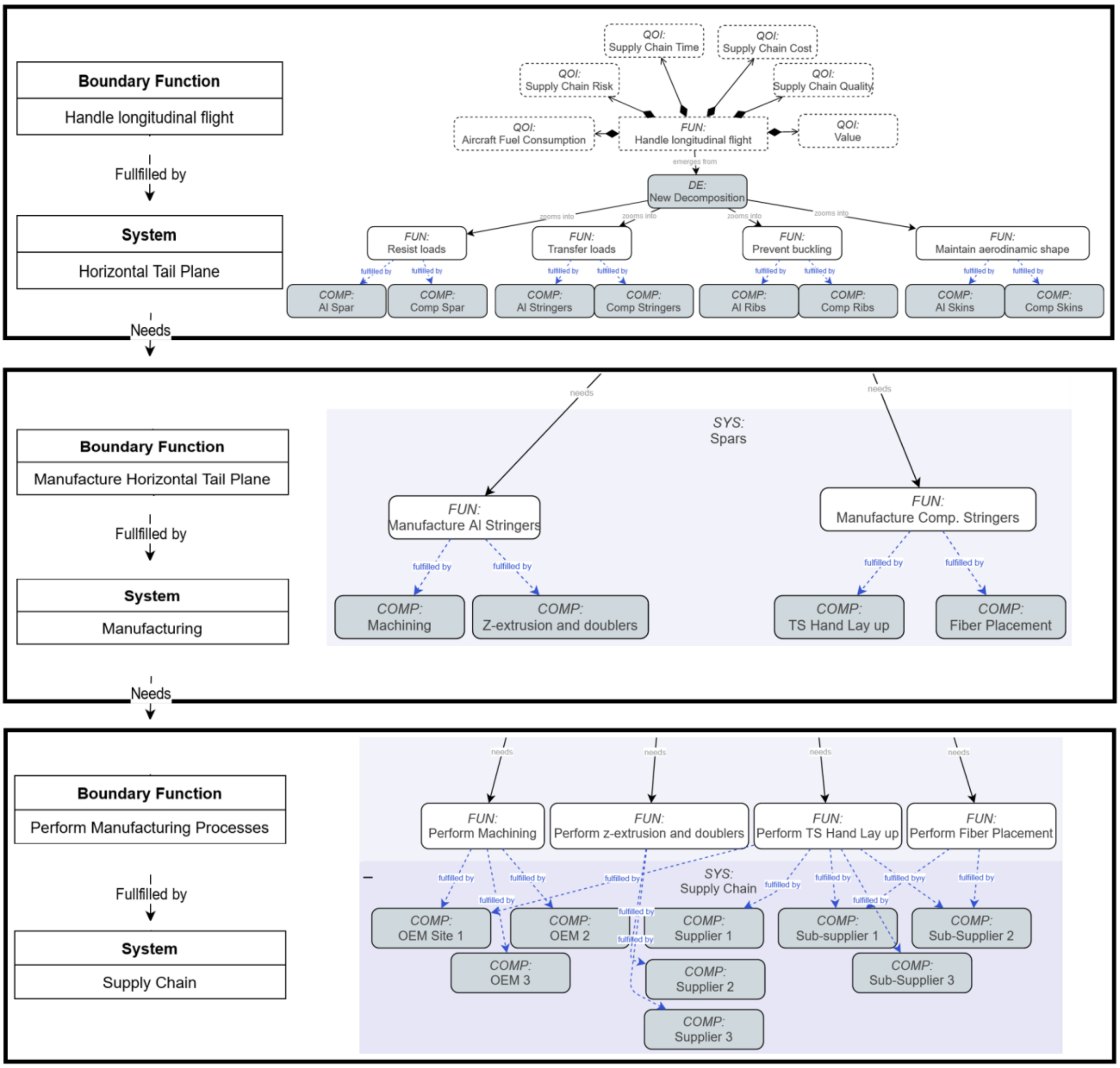


Figure 5 – Multi-systems architecture modelling in ADORE coupling the horizontal tail plane, manufacturing and supply chain systems, [7]

From the modelling showed in Figure 5, multiple architectures can be generated based on:

- The materials for each HTP component
- The manufacturing and assembly processes for each material (and so for each HTP component)
- The production quantity performed by each OEM and supplier site
- The OEM and supplier site performing assembly processes

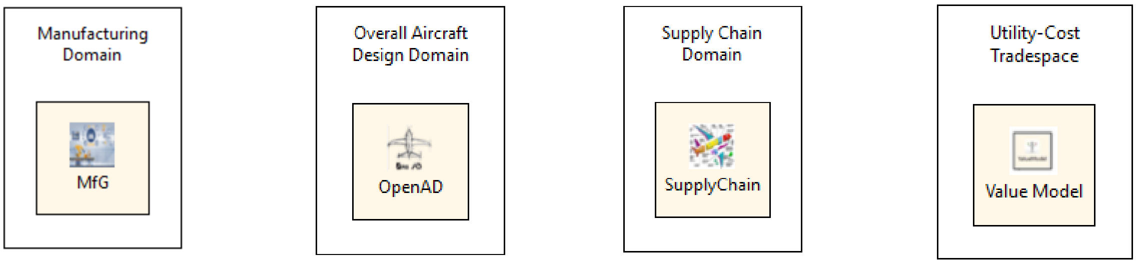
These architectures, generated in ADORE, are linked to the MDO process, last step of the AGILE 4.0 MBSE-MDO framework, through the DLR tool MultiLinQ [12]. Based on the inputs/outputs defined for each disciplinary tool and taking as input the information of the architecture model, MultiLinQ is able to show which tools are used to evaluate which architectural components. Details on the MDO process set-up and implementation are provided in the next section.

4. System Design Exploration and Optimization

The system architecting activitiy, described in the previous section, bridges the upstream MBSE models and the downstream MDO activities, providing from requirements the architecture models to analyze in the MDO process. This section focuses on the technologies used to automatize the MDO process, the achieved preliminary results and the optimization studies performed.

A. Technologies to automatize the MDO process

To automatically explore and optimize the architectures generated by three-dimensional approach in the MDO environment, individual analysis modules, implementing the features characterizing each domain, are developed. The four disciplinary codes (manufacturing, OAD, supply chain and value model) involved in the MDO process and workflow are shown in Figure 6 and briefly described hereafter.



I II III IV

Figure 6 – Disciplinary codes as implementation, respectively, of the manufacturing domain (I), overall aircraft design domain (II), supply chain domain (III), and value model (IV)

The manufacturing tool, related to the manufacturing domain, characterizes an aircraft component in terms of materials, manufacturing and assembly processes. It provides as output a technology factor that quantifies the impact that the selected manufacturing properties have on the aircraft performance and on the production quantity to be performed by each company to produce the selected aircraft component. The technology factor is taken as input by OpenAD, a software tool, in-house developed, for preliminary aircraft design analysis. Based on semi-empirical formulas, it is able to design an aircraft (starting from its top level requirements) and evaluate its performance [13]. The production quantity, expressed in percentage, is instead one of the inputs needed by the supply chain code. Providing information on the suppliers, the supply chain performance (production time, quality, risk, cost) is the main output of this disciplinary tool. The last competence, the value model tool, implements the procedure to estimate the value [6]. These four disciplinary competences require a reciprocal exchange of information to perform their own analysis and provide results. Thus, a computational MDO process, shown in Figure 7, is implemented as an automated execution workflow in which disciplinary competences communicate to each other. For this scope, CPACS is used as the common language to allow the exchange of information between the disciplinary implemented modules [14]. Instead MDAx is used to formulate the MDO problem [15], which is automatically exported into an executable workflow and run within the PIDO (Process Integration Design Optimization) environment RCE [16].

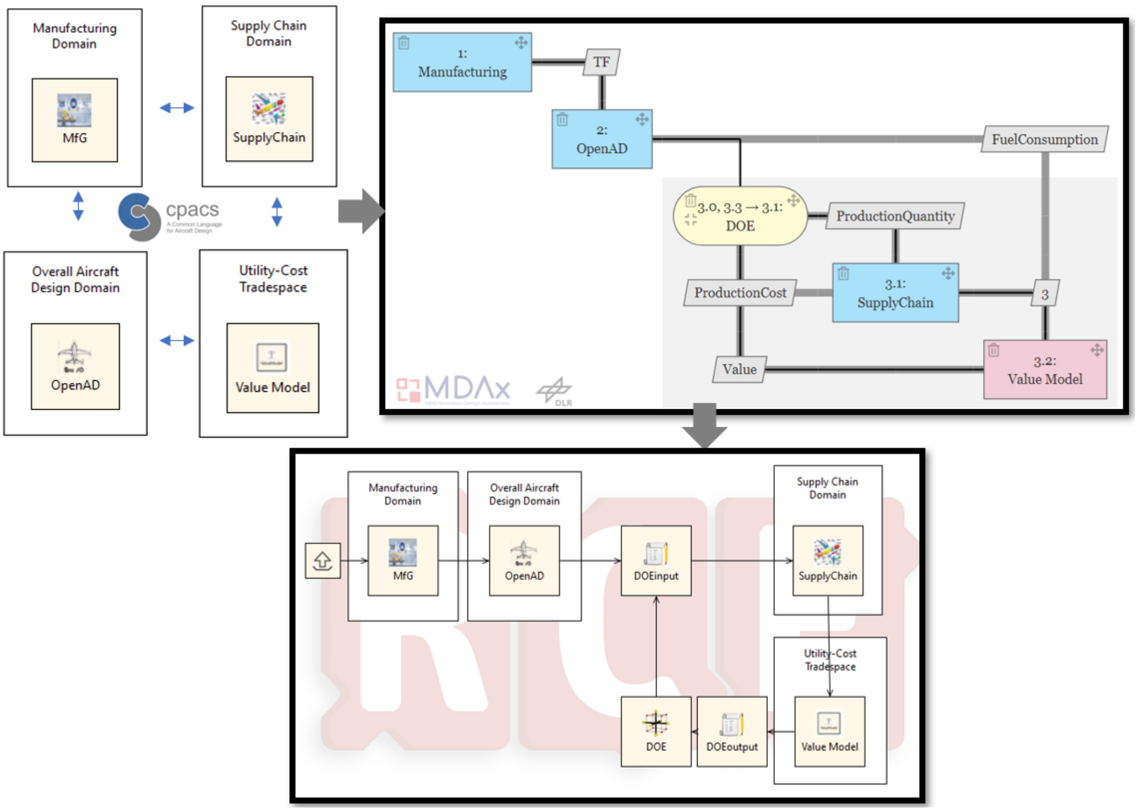


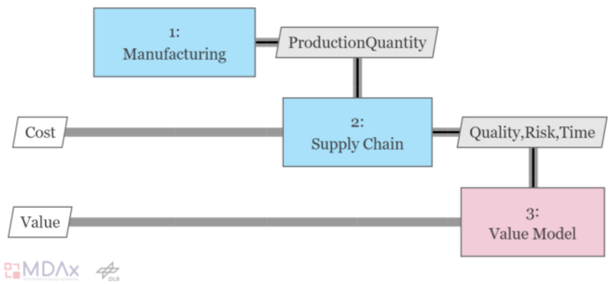
Figure 7 – Models and technologies enabling the automatically execution of the value-driven concurrent methodology coupling manufacturing, overall aircraft design and supply chain domains

These models and technologies provide flexibility to the methodology, which can be executed by coupling domains in different ways, as described in the next sub-section.

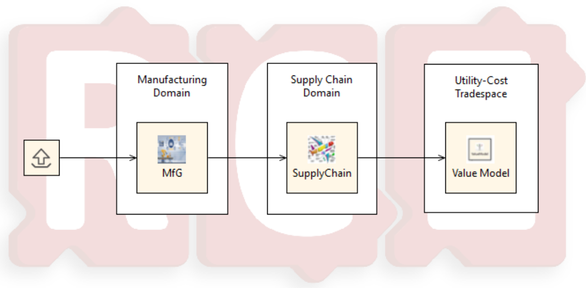
B. Design studies and preliminary results

The flexibility of the proposed methodology allows to investigate several trade-off studies depending on the combined domains. Particularly, three case studies can be executed by differently coupling the disciplinary codes.

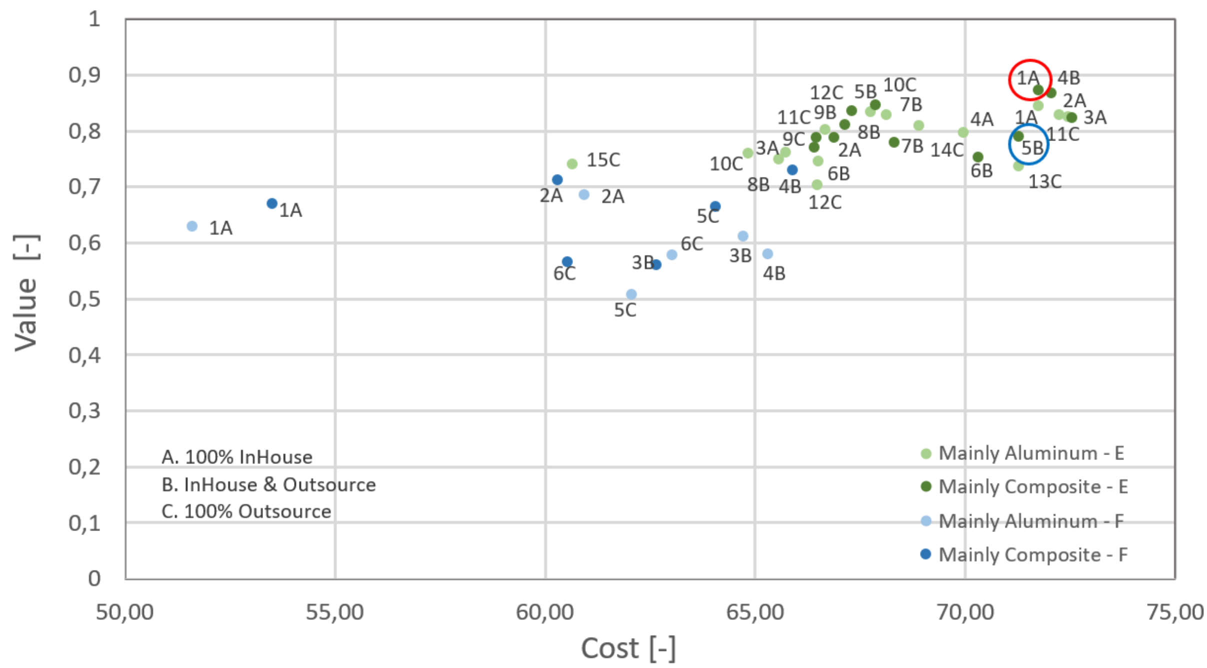
In the first case study, the workflow concurrently coupling the manufacturing and supply chain domains is set-up and executed. The eXtended Design Structure Matrix (XDSM), the executable workflow and the preliminary results of this study are shown in Figure 8. Each solution of the value-cost tradespace accounts only for attributes characterizing the supply chain domain. Thus, for each HTP architecture, the decision maker can identify the best supply chain architecture considering the production time, quality and risk, aggregated in the value. The best alternative of supply chain is the one with the highest value. Figure 8 highlights - circled solution – that the best supply chain architecture is relating to the second HTP architecture, mainly made of composite. However, other solutions can be considered as alternative to the best one, with lower value but having also lower cost. Furthermore, the cluster solutions in three main production scenarios, allows the decision maker also to know which scenario the chosen alternative belongs to. In this way, the decision maker can strategically choose if to produce in-house or outsource to suppliers, performing a make or buy trade-off investigation. In Figure 8, the highest value solution belongs to the 100%InHouse scenario. A lower cost supply chain architecture with a lower value, for the same HTP architecture, is provided by the solution 5B (circled). The reduction in cost is related to a production partially made in house, partially outsourced to suppliers.



I. XDSM Workflow coupling MfG Domain and SC Domain, set-up using MDAx



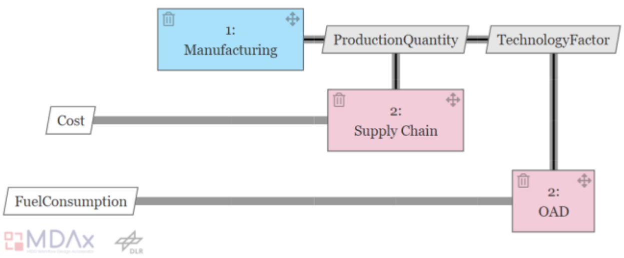
II. Executable Workflow, run in RCE, coupling MfG Domain and SC Domain



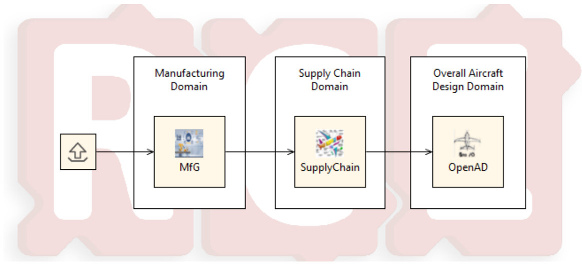
III. Solutions Tradespace coupling MfG Domain and SC Domain

Figure 8 –MfG Domain and SC Domain application for different HTP configurations (circles), supply chain options (specified with a number) and production scenarios (indicated with a letter). The XDSM workflow has been obtained using MDAx (I), RCE has been used to run the executable workflow (II) and achieve the preliminary results (III), [4]

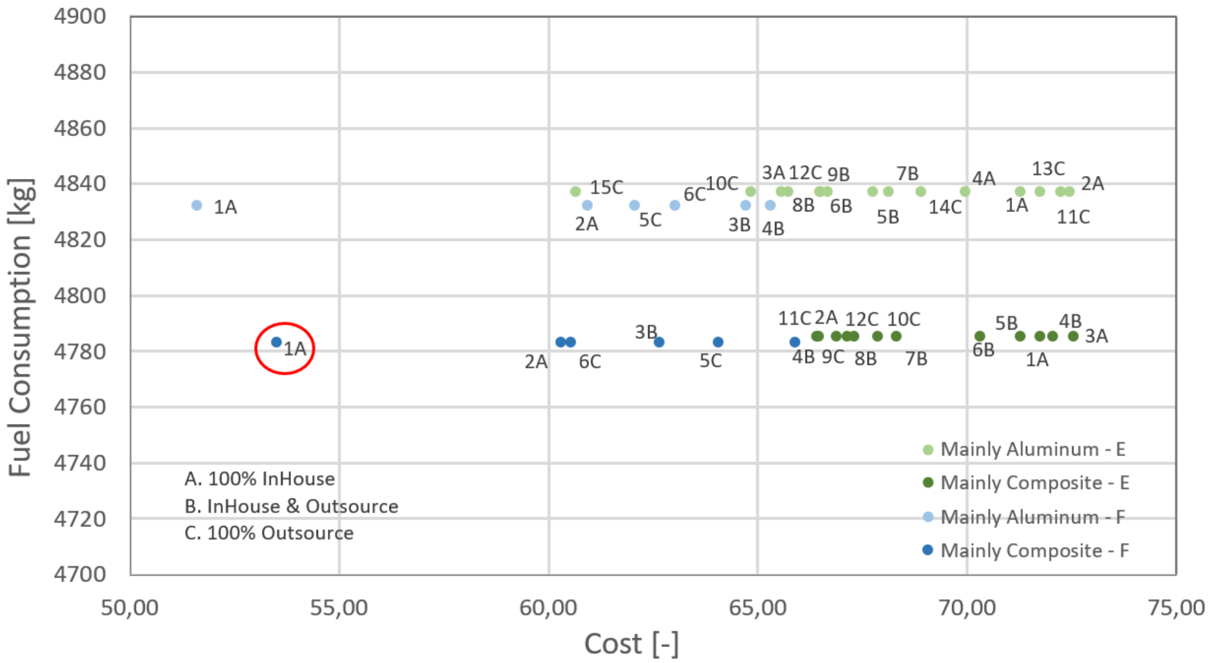
In the second case study, the manufacturing and OAD domains are aggregated. Four horizontal tail plane architectures, based on different materials, manufacturing and assembly processes, are compared in terms of aircraft performance, specifically fuel consumption. Doing so, a trade-off study between the manufacturing characteristics (choice of materials, manufacturing, assembly processes) and the aircraft performance is carried out. In practice, this study can be further expanded, also considering the production cost (output of the supply chain domain) of each supply chain option able to produce a specific HTP architecture. In this way, the decision maker can observe, at the same time, both at the variation of the aircraft performance due to the manufacturing properties and more strategic aspects related to the decision of making in-house or outsource to suppliers. The XDMS workflow, the executable workflow and the preliminary results of this more complex MDO problem is shown in Figure 9. The HTP architectures, made by aluminum, provide a higher fuel consumption then the composite once. In addition, from the analysis of the results, the decision maker can also identify the supply chain architectures producing the same product (HTP) with lowest cost. The solution 1A – circled - is the supply chain architecture producing the composite tail plane configuration at the lowest cost. With respect to the previous study, here the focus is on the aircraft performance and manufacturing properties; therefore, it is not possible to make decisions also considering the production time, risk and quality.



I. XDSM Workflow coupling MfG Domain and OAD Domain set-up usign MDAx



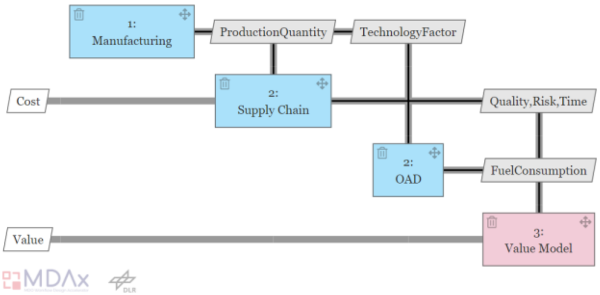
II. Executable Workflow, run in RCE, coupling MfG Domain and OAD Domain



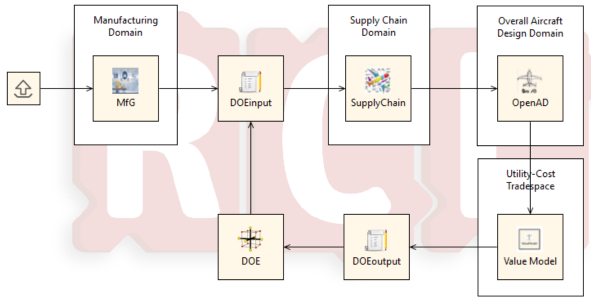
III. Solutions Tradespace coupling MfG Domain and OAD Domain

Figure 9 – MfG Domain and OAD Domain application for different HTP configurations (circles), supply chain options (specified with a number) and production scenarios (indicated with a letter). The XDSM workflow has been obtained using MDAx (I), RCE has been used to run the executable workflow (II) and achieve the preliminary results (III), [4]

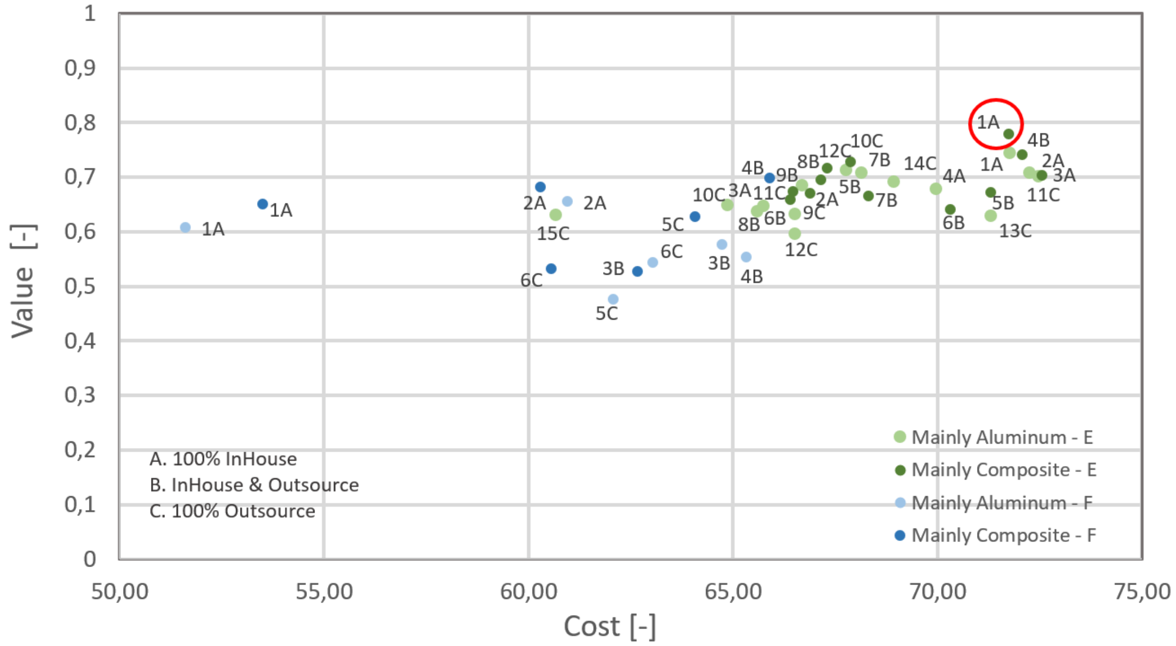
In the third case study, the concurrent coupling of the manufacturing, supply chain and OAD is performed. The XDSM, the executable workflow and the preliminary results of this study are shown in Figure 10. In this case, horizontal tail plane architectures made by different manufacturing proprieties, produced by several supply chain architectures, populate the value-cost solution tradespace. The solution with highest value – circled – represents the best compromise between multiple criteria, i.e. the production time, risk, quality and fuel consumption, aggregated in the value. An additional information can be extracted from the same tradespace, that is the production scenario which the solution belongs to. Therefore, the decision maker can also perform the same trade-off investigations addressed in the first case study. The analysis of the solutions tradespace of the complete study can represent a powerful means for the decision maker, who can take decisions based on measures belonging to different domains.



I. XDSM Workflow coupling MfG Domain, SC Domain and OAD Domain, set-up using MDAx



II. Executable Workflow, run in RCE, coupling MfG Domain, SC Domain and OAD Domain



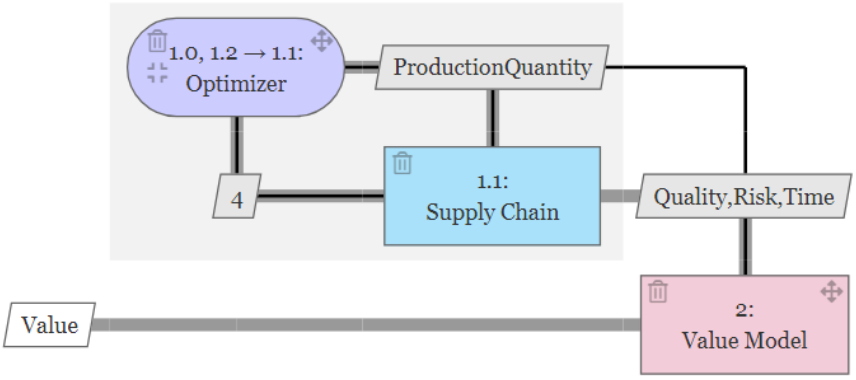
III. Solutions Tradespace coupling MfG Domain, SC Domain and OAD Domain

Figure 10 – MfG, SC Domain and OAD Domain Application for different HTP configurations (circles), supply chain options (specified with a number) and production scenarios (indicated with a letter). The XDSM workflow has been obtained using MDAx (I), RCE has been used to run the executable workflow (II) and achieve the preliminary results (III), [4]

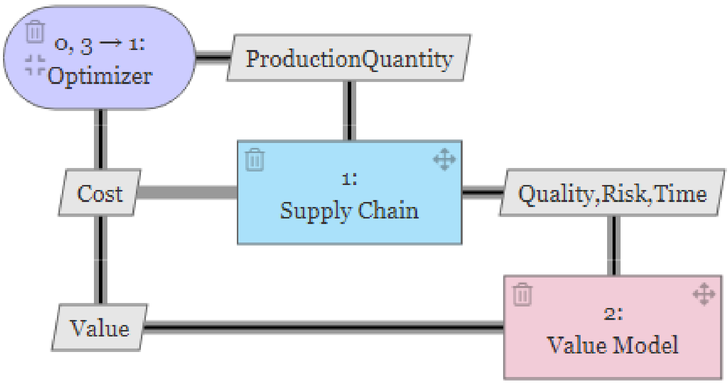
The next challenge is to add the optimization algorithms to these three studies. The objective of the design optimization campaign is to identify the global optimum, simultaneously accounting for horizontal tail plane, manufacturing and supply chain variables. In the next sub-section, only preliminary results related to the first case study, are addressed.

C. MDO workflow and preliminary results

For the first case study, coupling manufacturing and supply chain, a simple MDO problem is run in collaboration with ONERA, which is providing competences related to the optimization algorithms. Adopting the technologies described in sub-section 4A, the MDO workflow is set-up by using MDAx. The XDSM workflows characterizing the MDO problems of interest are reported in Figure 11. Two MDO problems are addressed with the objective to identify the best optimization strategy to use later for the global optimum analysis.



I. First optimization strategy - XDSM 4-objectives MDO workflow



II. Second optimization strategy - XDSM 2-objectives MDO workflow

Figure 11 – XDSM MDO workflows obtained by using MDAx: a) The value is estimated and then the optimization is executed for the value-cost Pareto front investigation; b) The optimization is executed and then the optimized attributes are aggregated in a value for the value-cost Pareto front investigation, [7]

In the first case (Figure 11-I), the supply chain performance (production risk, quality and time, cost) are first optimized and then the attributes (production risk, quality and time) are aggregated in the value for the value-cost Pareto front investigation. In the second MDO problem (Figure 11-II), instead, attributes (production risk, quality and time) are first aggregated in the value and the a bi-objectives value-cost optimization is executed for the value-cost Pareto front investigation.
Both optimization problems are executed considering a specific HTP configuration, whose main characteristics are reported in Table 1.

Table 1 – Components and manufacturing properties of the HTP configuration analyzed in the value-driven MDO problems.

HTP components	**N° Components**	**Materials & Processes**
Skins	2	Sheet Metal Stretch Formed
Stringers	30	Metal by Z-Extrusion
Spars	2	Machined Aluminum

Ribs	20	Machined Aluminum, Sheet Metal Stretch Formed

In addition, in both MDO investigation problems, the design variables are the production quantity of skins and stringers and the location of their assembly sites, as reported in Table 2 and Table 3.

Table 2 – 4-objective optimization problem.

Objective	**Function/variable**	**Quantity**
minimize	Cost	
	Time	
	Risk	
maximize	Quality	
with respect to	Skins Production Quantity	2 * 4 levels
	Stringers Production Quantity	2 * 7 levels
	Assembly Site Location	1 * 4 levels
	Total design variables	26

Table 3 – 2-objective optimization problem

Objective	**Function/variable**	**Quantity**
minimize	Cost	
maximize	Value	
with respect to	Skins Production Quantity	2 * 4 levels
	Stringers Production Quantity	2 * 7 levels
	Assembly Site Location	1 * 4 levels
	Total design variables	26

Preliminary results are reported in Figure 12. They show that the 2-objective Pareto front are contained among the 4-objective Pareto front [7]. This result has also been theoretically demonstrated in [ref].

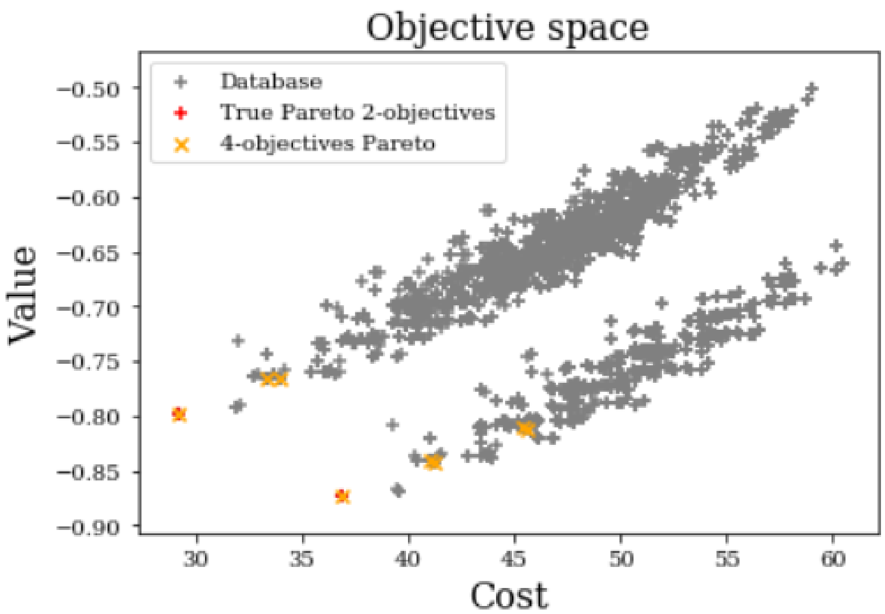


Figure 12 – Comparison between the 2-objectives Pareto front and 4-objectives Pareto front

As preliminary achievement, it has been observed that for the same number of iterations, the 4-objectives is more expensive than the 2-objectives. However, the 4- objectives is executed only once before the value estimation. Instead the 2- objectives, less expensive, has to be executed anytime that the value is estimated, so anytime that the weights and utility functions are changed. Further optimization activities are already planned for the complete supply chain application case, including the production quantity of spars and ribs and the location of the HTP assembly site.

5. Conclusions

A value-driven three-dimensional approach concurrent coupling manufacturing, OAD and supply chain domains has been developed within the European Project AGILE 4.0 by leveraging the MBSE-MDO framework, shown in Figure 2. In this paper, the technologies, the models and the preliminary results characterizing the different steps of the MBSE-MDO framework are addressed, from the stakeholders, needs, requirements to the MDO process, linked by the system architecting activity. Thus, in the first section, details on the stakeholders, needs and requirements models are presented, with the focus on the enterprises characterizing the supply chain, responsible for the HTP production. Starting from requirements, the system architecture is then introduced and described in Section 3. The ADORE model highlights the relationship among the HTP, manufacturing and supply chain systems as well as the link between the components of these systems. The system architecting bridges the upstream MBSE activities with the MDO process exploration. Thus, the generated architectures can be optimized in the MDO workflows. So, Section 4 focuses on the technologies needed to automatize the MDO process, the different case studies that can be analyzed and on the MDO preliminary results achieved by following two different value-driven optimization strategies.
These optimization strategies have been applied to a specific HTP configuration, mainly made by aluminum. The results highlight that a 2-objective Pareto front is contained among the 8-objective Pareto front. Hence, both strategies lead to the same results. However, a 4-objectives MDO problem is more expensive, in terms of computation cost, with respect to the 2-objective MDO problem. But, the 4-objective strategy allows to execute the optimization process only once and then play around with the weights and utility functions needed to estimate the value [17], [18]. Instead, with the 2-objectives strategy the MDO process should be run anytime that the weights and utility functions change. The same MDO problems will be executed for another HTP architecture. However, it is already planned to add new design variables in the future optimization run. The production quantity related to the spars and ribs will be added as well as the assembly site responsible for the assembly of the entire HTP.

6. Acknowledgements

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8. Copyright Statement

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