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A Model-Based Approach to Trade-Space Evaluation Coupling Design-Manufacturing-Supply Chain in the Early Stages of Aircraft Development

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Product design and supply chain management are two research domains extensively explored in literature. In the last decades, many studies have highlighted that the integration of these domains is important to increase the profitability and efficiency of companies. However, most of these studies aims at optimizing the supply chain after freezing the design of the product, and hence addressing the supply chain as the following step in product development. This paper presents a value-driven model-based approach that concurrently links product design, manufacturing and supply chain in the frame of aerospace system design. Thus, the challenge is to expand the early design phase of an aircraft to account both for manufacturing choices (e.g. raw materials, manufacturing and assembly processes) and supply chain management (e.g. suppliers' location, production cost per supplier). Three domains – manufacturing, supply chain, overall aircraft design – are selected to investigate all the aspects related to the entire aircraft development, from the initial design to the manufacturing and the assembly, through the aeronautical supply chain. The modelling of

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these domains and the information flow exchanged among them, is addressed in this paper. The concurrently coupling of these domains results into an enlargement of the alternatives populating the final solutions tradespace, from which decision makers select a solution. The value-based approach is proposed to quantify the multiple-choice criteria and support decision makers in selecting the best alternative, simultaneously considering the aircraft design variables with those of manufacturing and supply chain. Thus, the objective of the value driven model-based approach introduced in this paper, is to provide a quantitative supportive framework that decision makers could use during the early phases of aircraft development, when strategic decisions have to be taken. Concluding, three application cases described in this paper, demonstrate the strengths of this methodology and the possible future improvements.

Nomenclature

CPACS	=	Common Parametric Aircraft Configuration Schema
HTP	=	Horizontal Tail Plane
MAUT	=	Multi Attribute Utility Theory
MBSE	=	Model Based Systems Engineering
MDAO	=	Multidisciplinary Design Analysis Optimization
MfG	=	Manufacturing
OAD	=	Overall Aircraft Design
OEM	=	Original Equipment Manufacturer
PIDO	=	Process Integration Design Optimization
SC	=	Supply Chain
TLAR	=	Top Level Aircraft Requirement
XDSM	=	eXtended Design Structure Matrix

I. Introduction

The design of a modern aerospace systems is continuously increasing in complexity due to more stringent environment and safety requirements, the demand for better performance, as well for integrating more functionalities. As the complexity of the aeronautical systems increases, enhanced design methodologies are needed to evaluate and optimize the systems' performance. Within the AGILE project [1], funded by the European Commission and led by the DLR, a novel approach called AGILE Paradigm [2] has been developed to streamlines the setup, deployment and operations of collaborative multidisciplinary design analysis optimization (MDAO) systems, in order to accelerate the development of complex aeronautical products [3] in a collaborative, multi-national and cross-organizational environment. On the other hand, the globalization and the extreme competitiveness of the today´s market has induced industrial organizations to search for solutions with lower production cost in order to be commercially viable. A literature review highlights the considerably increasing number of studies addressing the supply chain since the early 1990s [4]. The transformation of the aerospace industry in multinational operations distributed in several stages (including production, after sales, maintenance, repairing and reconditioning) has made today´s aircraft supply chain a multi-period, multi-scenarios, multi-countries, multi-facilities network. This requires a very complex supply chain management. Major aerospace organizations such as Boeing and Airbus have experienced - in their newest B787 and A380 programs [5] – the challenges in supply chain management [6].

Aircraft design and supply chain are two major research domains widely investigated in literature [7], [8], [9], [10]. However, in most of the studies, the supply chain is addressed after freezing the product design. In other words, the two domains are still treated as distinct and sequential, and the supply chain definition is in a later step of the product design process [11]. Few works have recently addressed to incorporate the supply chain decisions during the product design [12]. As reported in [13], over 80% of product cost is determined in the design phase. When the design of the product is fixed and production starts, the cost to change product design drastically rises [14]. It is also demonstrated that a reduction of 7% in manufacturing costs, 12% in time-to-value, and 20% in development costs can be achieved for average manufacturers thanks to the collaboration with their supply chain partners in the design process of new products [15], [16]. Given the importance of the product design and its influence on the supply chain performance, more and more research efforts are aiming to combine product and supply chain decisions during the design phase [17]. The European funded H2020 project AGILE 4.0 [18], follow-up of the AGILE project, and also led by DLR, aims to include all the main pillars of the aeronautical supply-chain (production, certification and manufacturing) during the early stages of aircraft design, with the objective to address innovative trade-offs, never performed before. The project leverages MDAO and Model Based Systems Engineering (MBSE) principles, in order to create a digital representation of the production systems and supply chain throughout the entire life-cycle of the product under design [19].

This paper introduces one of the AGILE4.0 application cases, in which a model-based approach, is developed with the main objective to concurrently combine product design, manufacturing and supply chain in the frame of aircraft design. During the aircraft conceptual design phase, the external aircraft geometry, the engine, the internal structures and the materials of the main aircraft components, and the dimension of the main systems needed for the aircraft flights, are defined and evaluated. The challenge of the proposed approach is to expand the early design phase of an aircraft to account for production concerns, including, manufacturing and assembly processes, transportation, quality, quantity, resources capacity, production schedule, material availability, production technologies, production regulations, laws and so on. On another hand, this translates into expanding the aircraft design variables with those of manufacturing and production, resulting into an enlargement of the alternatives populating the final solutions tradespace from which decision makers selects a solution.

In the study here presented, a value-based approach is adopted to formalize the multiple-choice criteria that the decision maker considers of fundamental importance in identifying the best alternative in the tradespace of proposed solutions. Therefore, the objective of the value driven model-based approach here introduced, is to provide a quantitative supportive framework that an organization could use during the early phases of aircraft development, when strategic decisions have to be taken.

Section II introduces the individual domains addressed by this study, as well as the envisioned couplings. Section III focuses on the value model theory and on its use for this cross-domain multi-disciplinary analysis. Afterwards, the details regarding the implementation of the main competences composing the MDAO problem are provided in Section IV. Finally, an application example is shown in Section V. The application case addresses the production of a horizontal tail plane (HTP) for a commercial aircraft. Conclusions and possible future developments are provided in Section VI.

II. Manufacturing, Supply Chain and Overall Aircraft Design Domains overview and identification of the respective links

The manufacturing (MfG), the supply chain (SC) and the overall aircraft design (OAD) have been identified as main domains to concurrently combine the product performance and the production performance parameters in the early stage of aircraft design. The complexity of the proposed approach relays in the management of a huge number of design choices characterizing each domain (might be hundreds for increasingly complex problems). The first challenge is to streamline and model information across these domains. The second challenge is to support decision makers in finding the best solution in a huge tradespace of proposed solutions. Figure 1 shows a schematic representation of the information flow exchanged between the manufacturing, supply chain and overall aircraft design domains.

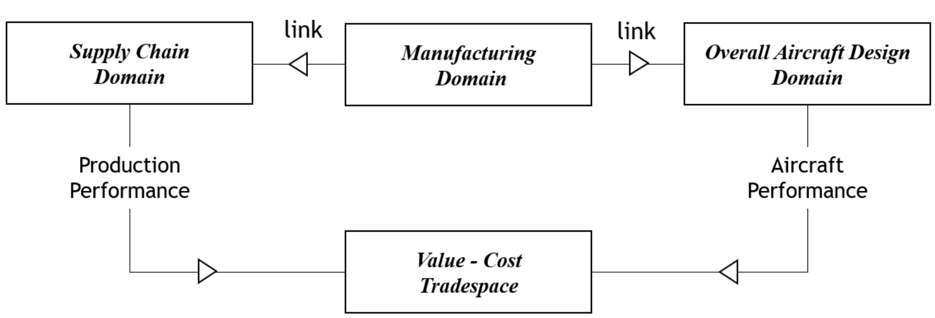


Figure 1 – Schematic representation of the information flow exchanged between the manufacturing, supply chain and overall aircraft design domains, to concurrently combine product design and supply chain in the early stage of aircraft development

The alignment of the three domains highlights the concurrently coupling of the same. The arrows are indicative of the information flow direction exchanged between domains. A direct link between the manufacturing and the two domains of supply chain and overall aircraft design appears evident. Instead, the link between the SC and OAD is implicit. A detailed description of each individual domain is addressed below. It allows to reach the full understanding of the links existing between these three domains, explained in the subsection D.

A. Manufacturing Domain

Manufacturing is the production of goods through the use of labor, machines, tools, and chemical or biological processing or formulation. This word is mostly applied to industrial design in which raw materials are transformed into finished goods on a large scale. The steps through which raw materials are transformed into a final product represent the manufacturing engineering, or the manufacturing process. The product granularity also plays a key role in the manufacturing domain. The steps through which single components are aggregated into final product are here identified as assembly processes. In this approach, the manufacturing domain ranges from the choice of raw materials that can be used for the production of each level of aircraft component, to the assembly processes needed to combine all the aircraft components within the whole aircraft. The flowchart characterizing the manufacturing domain, is shown in Figure 2 and described below in details.

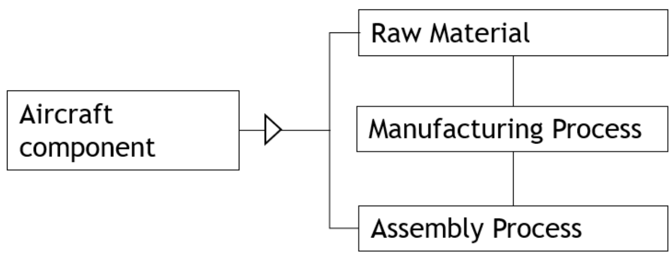


Figure 2 – Product Manufacturing Domain Flowchart; the selection of raw materials, manufacturing and assembly processes for the aircraft components characterize the MfG Domain

Raw Materials. The choice of raw materials depends on the product to be made. The physical properties of a specific material make its use more or less appropriate for the product under design. Clearly different materials can be used for the same product.

Manufacturing Process. The selection of raw materials for a specific product implies, at the same time, the decision of which manufacturing process utilize. For instance, machining, stretch formed and pressed form are some manufacturing processes that can be applied to aluminum.

Assembly Process. Complex products like the aircraft, are made up of several components. Each one can in turn be consisting of many other sub-components, and so on. The choice of raw materials as well as the choice of the manufacturing process can be applied for each level of product component. Then, assembly processes must be considered to realize the final product starting from the single components. There are several assembly processes that can be used to combine components. The choice of the assembly process depends on the materials and the manufacturing processes characterizing the components to be assembled. Different assembly processes can be selected for each combination of material and manufacturing process.

Concluding, the main aspects characterizing the manufacturing domain are the following:

- the choice of raw materials for each level of aircraft component;
- the choice of the manufacturing process depending on the raw materials;
- the choice of the assembly process needed to integrate aircraft components within the whole aircraft; depending on the selected raw materials and manufacturing process.

B. Supply Chain Domain

The supply chain is defined by the non-profit organization Supply Chain Council as "every effort involved in producing and delivering a final product or service, from the supplier's supplier to the customer's customer" [20]. The supply chain domain encompasses all the aspects related to the production of an aircraft (or its components). Production cost, time, quality and risk have been defined as main production performance. The assessment of these four production parameters, is needed since they have been established as key criteria for the choice of the best supply chain (Section IIIA). The supply chain domain flowchart is shown in Figure 3. This clearly shows how the estimation of production performance parameters at the supply chain level, depends on that of suppliers. For this reason, more details are provided below on both the suppliers and supply chain.

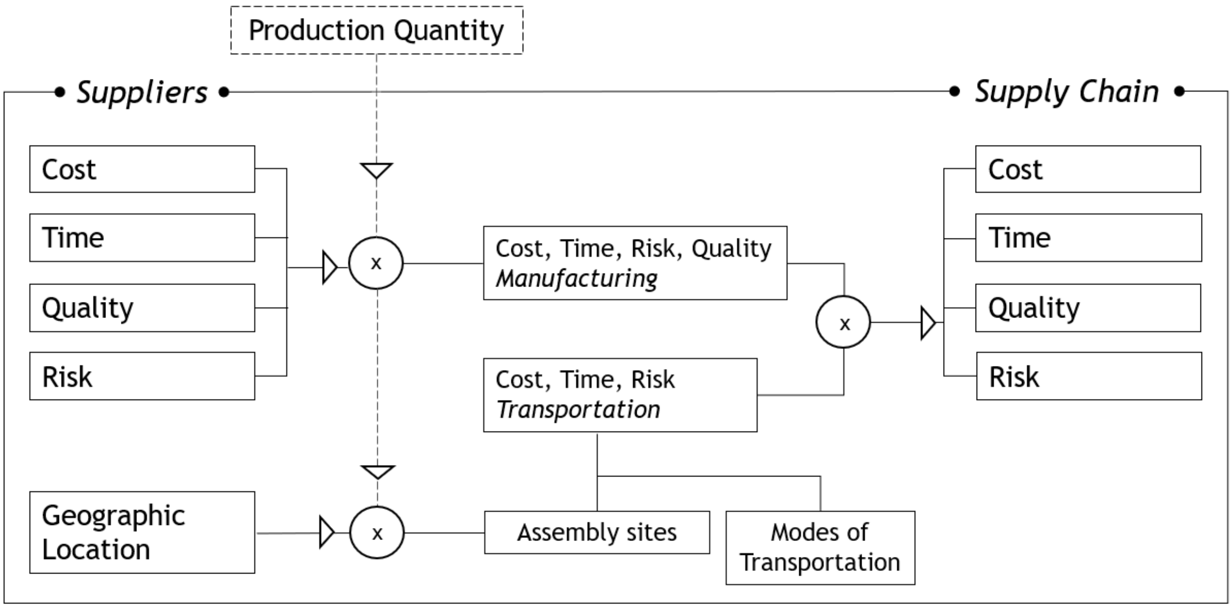


Figure 3 – Supply Chain Domain Flowchart; the estimation of the supply chain production performance parameters of cost, time, quality, risk is the main content of the supply chain domain

Suppliers. Suppliers can be hierarchically classified according to the activities they perform and the components they produce. The aircraft supply pyramid is structured in the following way:

- The Original Equipment Manufacturers (**OEM**): companies that design/develop/manufacture/assemble large aircraft components and provide final product to customers;
- First-tier suppliers (**Tier-I):** direct OEM suppliers who manufacture/assemble major aircraft components;
- Second-tier suppliers (**Tier-II**): key suppliers of Tier I who deliver items obtained from their own production or from a variety of other external providers (Tier III).

The supply pyramid hierarchy can be extended up to tier-n suppliers. For simplicity, in this approach the focus is on the first three level of the supply pyramid (OEM, Tier I and Tier II suppliers).
Each supplier or OEM site is characterized by a production cost, time, level of risk and quality. These performance parameters depend on multiple aspects. The competence of the producers is certainly one of them. The experience of a company in the manufacturing of materials, the availability of machines and human resources, the financial condition of a company, the energy costs and taxes dictated by the place where a company resides, also greatly affect the supplier cost, time, quality, risk. On the basis of these and many other parameters, the overall values of production cost, time, quality and risk for each OEM and suppliers' site have been considered for the model evaluation. For simplicity, hereafter in the paper, suppliers will refer both to OEM and suppliers, except when a clear distinction is needed.

Supply Chain. Considering the supply chain as combination of suppliers, three main production scenarios can be identified:

- **100%InHouse.** The manufacturing and assembly processes are 100% performed in-house.

- **InHouse&Outsource.** The manufacturing and assembly processes are partially performed in-house, partially performed by suppliers.
- **100%Outsource.** The manufacturing and assembly processes are 100% performed by suppliers.

Starting from the production cost, time, quality and risk of each supplier, the evaluation of the same production performance parameters at the supply chain level is performed. The estimation of the supply chain performance characterizes the supply chain domain.

C. Overall Aircraft Design Domain

The aircraft design phase is usually divided in three phases: the conceptual design, the preliminary design, and the detail design. During the conceptual design phases, numerous alternatives design configurations are compared to define the aircraft design that best meets the design requirements. Wind-tunnel testing or computational fluid dynamic calculations are conducted during preliminary design, while in the detail design phase, the selected design is translated in the engineering data need for the production activities. As already specified in the previous sections, the presented approach is framed in the context of the early stage of aircraft development, i.e. the aircraft conceptual design. Thus, the aircraft performance analysis is carried out through low/high fidelity tools. Particularly, the overall aircraft design domain aims, in this approach, at evaluating the aircraft performance on the basis of different design configurations of its components. The flowchart representative of this domain is shown in Figure 4.

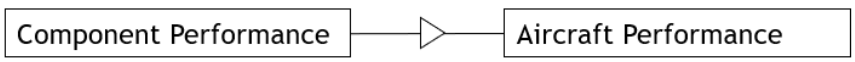


Figure 4 – Overall Aircraft Design Domain Flowchart; the evaluation of the aircraft performance with respect to the different design configurations of its components characterize the OAD domain

D. Domains Coupling

In the previous subsections (A, B, C), the contents of the Manufacturing, Supply Chain and Overall Aircraft Design domains have been identified. The detailed description of the main aspects of each domain, simplifies the identification of the links between them, which are shown in Figure 1.

Manufacturing & Supply Chain Domains. The machining of raw materials, the assembly of aircraft components require suppliers capable of performing these manufacturing activities. Thus, the choice of raw materials, manufacturing and assembly processes impact the supply chain domain in the selection of the OEM sites and suppliers, able to handle the specific requests of the manufacturing domain. The percentage of manufacturing/assembly processes (ProductionQuantity) needed to produce an aircraft component is the link between the manufacturing and the supply chain domains. Obviously, each company produces according to its own capacity, i.e. the maximum amount of work that a company can perform.

Manufacturing & Overall Aircraft Design Domains. The choice of materials, manufacturing and assembly processes for a component directly influence the aircraft performance. In this approach, a technology factor (TF) represents the link between the manufacturing and the overall aircraft design domains. The technology factor is defined as a dimensionless number ranging from 0 to 1. It quantifies the impact that the use of materials, manufacturing and assembly processes has on the weight and on the drag of the aircraft component under design.

Supply Chain & Overall Aircraft Design Domains. Figure 1 reveals a non-direct link between the supply chain and the overall aircraft design domains. However, these two domains are implicitly influenced through the manufacturing domain. The demand for an increasingly performing aircraft (OAD domain), could require the use of new materials and manufacturing process (MfG domain) and therefore, the use of those supply chains capable of handling these new processes (SC domain).

III. Value Model for the quantitative evaluation of trade-spaces coupling product design-manufacturing and supply chain

Several design variables influence the choice of a decision maker in the early stages of aircraft design. In the approach proposed in this paper, the criteria used from the decision making in the choice of the best alternative are related to different domains. Therefore, the so-called *value* has been introduced as a way to reflect the "satisfaction" of a decision maker with respect to these decision variables. *Value* can be used to quantify the criteria used by the decision maker in the choice of the best solution. Several decision-making techniques can be used to support decision makers in formalizing their own value structure [21]. It´s a good practice to use the Multi Attribute Utility (MAU) value model when the number of measures used to evaluate the alternatives are more than three. The Multi-Attribute Utility value model generates an aggregate measure across multiple criteria (called attributes). In the hypothesis that attributes are mutually preferentially independent, the following additive value function can be applied [22],.

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

In which:

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

The *value* is a dimensionless quantity, usually variable between 0 and 1. The higher the MAU, the greater is the satisfaction of the decision maker, thus better is the solution. As consequence, the alternative with the highest MAU is judged as best solution.

A. Attributes

An attribute is a decision-maker perceived metric that measures how well a decision maker-defined objective is met [23]. The choice of the attributes depends on the problem being treated. In this approach, attributes have been defined both for the supply chain and the overall aircraft design domains.

The production performance parameters of ***time***, ***quality*** and ***risk***, for each supply chain, are identified as the three main attributes of the supply chain domain. Production time refers to the time required for the manufacturing, transportation and assembly of aircraft components. The risks associated with these fields are instead estimated in the production risk. The quality of the product manufacturing and process execution is quantified in the production quality. The choice of these parameters as attributes, lies in the key role they play when a decision maker has to decide about which supply chain to choose for goods production [24].

The ***fuel consumption*** for a fixed flight condition (e.g. cruise) represents the attribute characterizing the overall aircraft design domain. The definition of this attribute for the OAD domain is needed to classify the different aircraft designs according to their performance. Obviously, multiple parameters could be used in this case. However, the fuel consumption is chosen as particularly influential in the selection of commercial aircraft.

The overview of the attributes defined for all the domains is provided in Table 1.

Table 1 – Supply Chain and Overall Aircraft Design attributes defined for the value model application; three attributes are related to the supply chain domain, one has been identified for the OAD domain

Domain	Attributes		Field
Supply Chain	Production Performance	Time	Manufacturing, Transportation, Assembly
		Quality	Manufacturing, Assembly
		Risk	Manufacturing, Transportation, Assembly
Overall Aircraft Design	Aircraft Performance	Fuel Consumption	Design

B. Single Attribute Utility (Value) Function

The single attribute utility (value) function is a value metric that converts the attributes into a quantified measure of the preference(s) of the decision maker. It is used to express the relative desirability of values of each attribute, answering to the question: “how desirable is a given level of a given attribute [23]?”. Defined as a quantitative, often dimensionless and relative quantity ranging from 0 to 1, the single attribute utility function U (X_i) has to be assigned in the way that:

- U (X_i) = 0 at the least desirable, but still acceptable value of the attribute;
- U (X_i) = 1 at the highest (most desirable) value of the attribute.

The assignment of these extreme quantities, define the attribute values that characterize the final tradespace of proposed solutions. As shown in Figure 5, attribute values lower than the least desirable one are unacceptable and therefore excluded from the final solutions tradespace. The attribute values greater than the most desirable one are instead irrelevant on the final choice of the best alternative, having a utility always equal to the maximum one. Hence, the identification of the last acceptable attribute value and of the most desirable one, influence the size of the final solution tradespace, which is the number of alternatives generated by the acceptable attribute values.

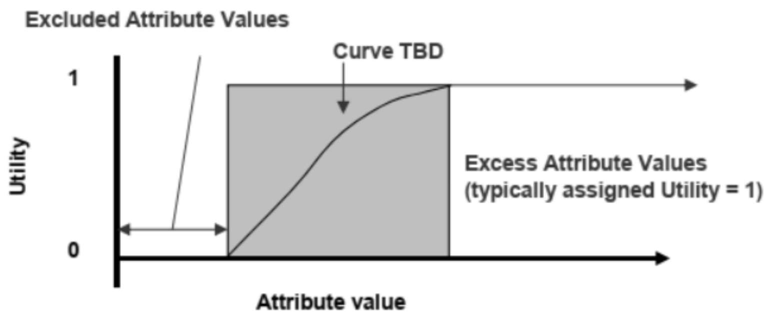


Figure 5 – Attribute Single Utility (Value) Function, adapted from [23]

The single utility curve must be drawn interacting with the decision maker, since it is a quantitative representation of the decision maker´s preference with respect to a specific attribute. Several ways can be used to elicit the single attribute utility curve. A computer-based survey or an oral interview submitted to the decision makers are the common way to define the attribute single utility curve [25]. However, interactive and graphical methods seem to involve the decision maker more, making the utility model closer to the decision makers’ will [21]. The challenge is to model the utility curve fully reflecting what the decision maker has in mind.
For the realization of a simple but functional model, at this stage some simplifications have been made in the assignment of the utility curves for the four attributes, identified in this approach and reported in Table 1. The assumptions include: a linear trend assigned to the utility curves of each attribute; the last acceptable attribute value and the most desirable one matching the minimum or maximum attributes values. In this way, all the solutions are part of the final tradespace.

C. Attributes Weights

For the value additive form (Equation (2)), the weights λ_i to each attribute *i* have to be assigned such that the sum is one, as written in the following equation.

$$0 < \lambda_i < 1 : \sum_{i=1}^{N} \lambda_i = 1 \quad (3)$$

In which:

- N is the number of attributes.

The weights indicate the level of satisfaction when a given attribute is at its best value and other attributes are at their worst level; they can be interpreted also as the relative importance of attributes. Different approaches can be used to identify the weights to be assigned to each attribute [25].
In this approach, the weights have been assigned considering the relative importance of attributes. Obviously, different combinations of weights can be defined for the four identified attributes (Table 1). The assignment of a different weight to an attribute impacts its relative importance. Consequently, multiple combinations can be analyzed to provide

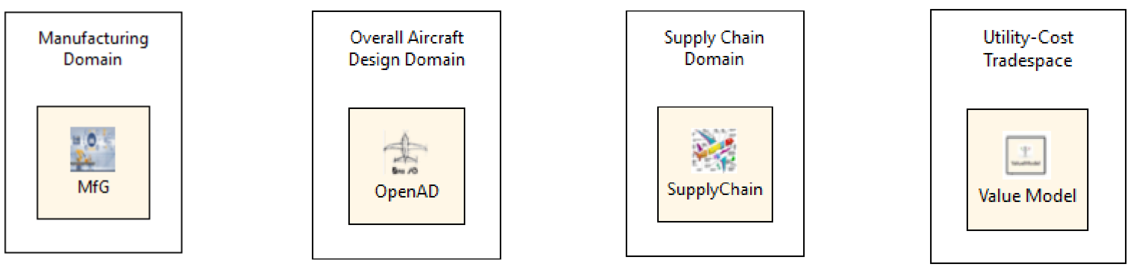
several alternatives of solutions tradespace corresponding to specific strategic needs. As better explained in Section VI, one of the next steps is to perform a Design of Experiment (DOE) in order to consider all the possible solutions tradespace alternatives.

IV. Implementation of a value-driven MDAO problem for coupling manufacturing, supply chain and overall aircraft design domains

The implementation of the approach explained in the previous sections, is realized by implementing each domain as an individual analysis module, which are treated as disciplinary competences. However, the disciplinary competences require a reciprocal exchange of information to perform the analysis and provide results. Therefore, a computational MDAO workflow has been setup to enable the single-domains analyses to exchange information. In sub-section A, a detailed description of the inputs/outputs necessary for the execution of each disciplinary code is provided. The automated workflow generation strategy to set-up the multidisciplinary process and the execution environment is explained in the sub-section IVB.

A. MDAO Disciplinary Competence

Three domains play a key role in this approach, as explained in Section II. The value model is instead used as a mean to choose the best alternative in the tradespace populated by solutions aggregating measures related to multiple domains (Section III). The execution of the cross-domains multi-disciplinary analysis is realized by the implementation of four domain disciplinary analysis codes, shown in Figure 7. The variables accounted from each domain and the outputs generated are explained in the following.



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)

MfG (Manufacturing). For a given aircraft component, the choice of materials, manufacturing and assembly processes characterize the manufacturing domain. The selection of the aircraft component to be produced, is the main input of this disciplinary code. The outputs are represented by the links - ProductionQuantity, TF - between, the manufacturing domain and, respectively, the domains of supply chain and overall aircraft design. The reader can refer to Section IID for more details concerning the domains couplings.

OpenAD. Open AD is 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 TLARs) and evaluate its performance [26]. In this approach, the impact of the use of different materials, manufacturing and assembly processes on an aircraft component, is quantified through the technology factor. OpenAD is used to evaluate the effect that the performance variations of the single component (defined by the TF) have on the whole aircraft.

Supply Chain. The percentage of manufacturing/assembly processes (ProductionQuantity) needed to produce an aircraft component is one of the inputs needed from this disciplinary code. Providing information on the suppliers, the estimation of the supply chain production performance parameters (time, quality, risk, cost) is the main output of this disciplinary competence.

Value Model. The procedure to estimate the *value* (explained in Section III) is implemented in this disciplinary code. The main inputs are: the attributes values, the weights combination and the single utility functions.

B. MDAO Process

The description of the individual competence highlights how the output of one domain competence can be an input for another. For instance, the Technology Factor (TF) provided as output from the MfG competence, is needed from the OAD discipline to run. Therefore, the MDAO process is implemented as an automated execution workflow in which disciplinary competences communicate each other. CPACS is used as the common language to allow the exchange of information between the disciplinary implemented modules. MDAx is used to automatically generate the MDAO problem, which is exported and executed within the PIDO (Process Integration Design Optimization) environment RCE. The framework is shown for a general application in Figure 8, is tailored to support the collaborative MDAO processes between international partners, which own the disciplinary codes, and provide them as a service within the same MDAO problem. For further details, the reader can refer to [2].

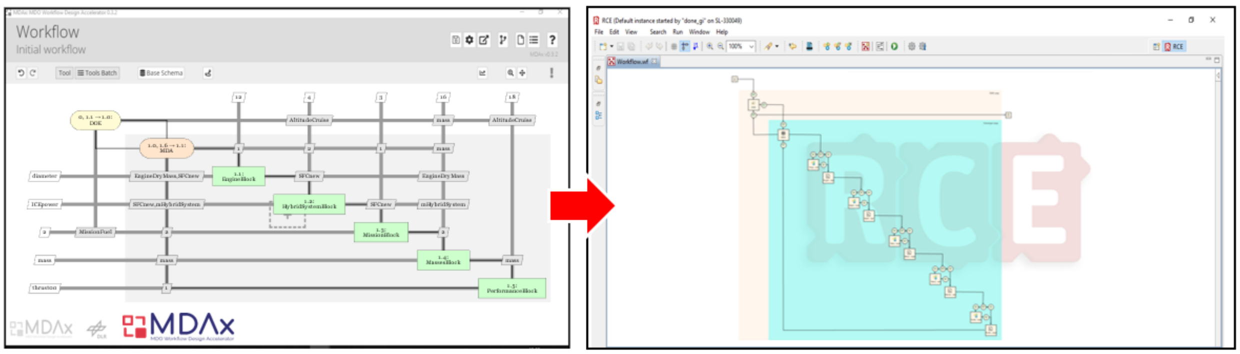


Figure 7 – Disciplinary tools can exchange information using CPACS as common language [27]; the MDAO process coupling disciplinary competences is then automatically generated using MDAx [28]; the workflow is finally exported and executed in the PIDO RCE [29].

CPACS as common language. CPACS (Common Parametric Aircraft Configuration Schema) is used to automate the exchange of information between disciplinary codes [27]. CPACS has been developed by the German Aerospace Center (DLR) located in Hamburg, to support the collaboration among different experts. It is an xml file serving as a central description of the aircraft, in terms of properties and geometry. Information not yet modeled in CPACS, can be stored in CPACS tool specifics. A disciplinary code is CPACS-compliant when it is able to extracts the inputs needed for the analysis from the CPACS file and, after the run, upload the outputs in the same file. These CPACS-ized tools can be connected together in a simple design process, since able to communicate in the same language.

MDAx to set-up the MDAO process. The MDAO process coupling the disciplinary codes in a single workflow, is automatically generated by the MDAO Workflow Design Accelerator, short MDAx [28]. MDAx, developed by the DLR, enables workflow integrator and disciplinary experts to model, inspect, and explore workflow components and their relationships. It provides an intuitive workflow modeling environment using an expansion of the XDSM format with additional design rules. Referring to Figure 7, the disciplinary codes are placed on the main diagonal, the inputs of each tool are represented vertically, the outputs horizontally. The outputs of one discipline required as input by another are defined as "coupling variables". Furthermore, various functionalities to automate repetitive design tasks, to resolve ambiguities and inconsistencies in complex workflow are provided. Finally, it allows the export of the workflow configuration for the execution on integration platform.

RCE to execute the MDAO process. The MDAO workflow, set-up with MDAx, is executed within the PIDO Remote Component Environment (RCE). RCE is an engineering framework software, developed by the German Aerospace Center DLR for the management of the development process and optimization [29].

V. Application to the design-manufacturing-supply chain of horizontal tail planes

The value-driven model-based approach described in this paper has been applied to the horizontal tail plane of an aircraft. The horizontal tail plane of the DC-2 is used as reference for the aircraft performance analysis. The DC-2 is a short-medium range regional jet of 90 passengers, whose Top-Level Aircraft Requirements (TLARs) are reported in Table 2 [30].

Table 2 – Top-Level Aircraft Requirements of the reference aircraft DC-2 [30]

Parameter	Value	
Long-range cruise Mach, ISA, WTO	0.78	-
Design payload (n Pax)	90	-
Design range	3500	km
Fuselage length	34	m
Take-Off field length	1500	m
Landing field length	1400	m
Initial cruise altitude	10972	m

The following sub-section A briefly describes the application of the MBSE principles for the modeling of stakeholders, needs and requirements from which several HTP design configurations and supply chain options have been extracted. However, not too many details are provided on that, since this topic is not the focus of this paper. In section B, the three domains of manufacturing, supply chain and overall aircraft design, have been characterized for the design, manufacturing and production of the main HTP components, depicted in Figure 8. The case studies performed using this approach, and the preliminary results are finally reported in sub-section C.

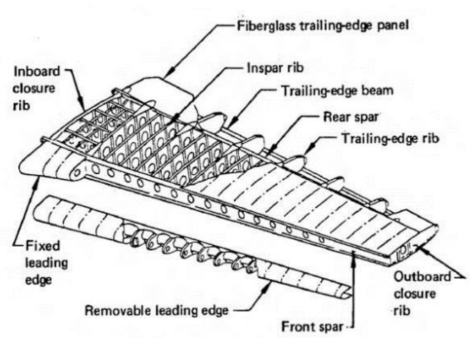


Figure 8 – Horizontal tail plane structure breakdown [31]

A. MBSE principles for modelling stakeholders, needs and requirements concerning the design, manufacturing, production of an HTP

The different HTP design configurations and supply chain options analyzed in this section, are the results of the needs identified by the stakeholders. MBSE approach and methods developed in AGILE 4.0 project have been adopted for the identification and modeling of the stakeholders and their respective needs and requirements, as explained in [32]. Several stakeholders are involved in the design, manufacturing and production of an aircraft. However, in Figure 9 only those of interest for this specific application case are highlighted.

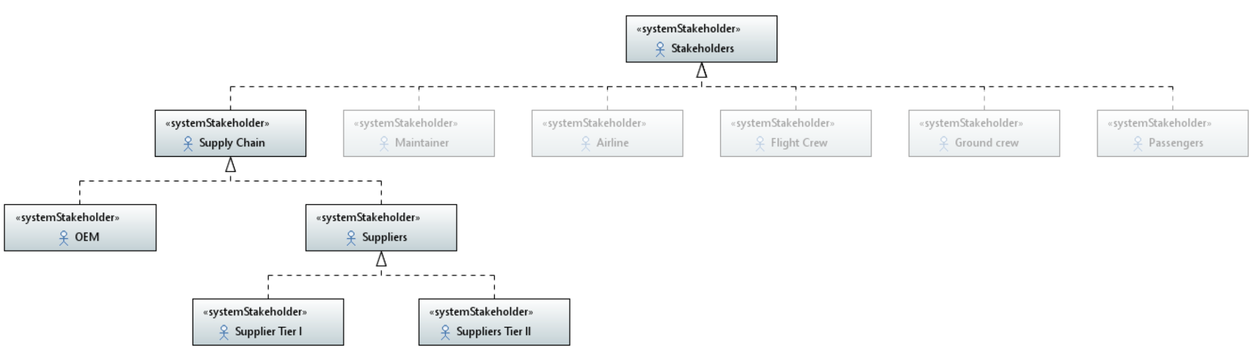


Figure 9 – Model of the Stakeholders involved in the design, manufacturing and production of the horizontal tail plane modelled using the new *AGILE4Profile*, [32]

The supply chain is a combination of OEM sites and suppliers, and itself is a key stakeholder for the definition of the several HTP configurations and supply chain options. Therefore, for each stakeholder the needs are identified and explicitly modeled, as shown in Figure 10. For instance, the need to *sell a large volume* of aircraft (N24) influences the production choices, and consequently the alternatives of the supply chain to be used for the aircraft (or HTP) production. On the other hand, the need to *have a well-designed HTP* (N52) influences the design and manufacturing variables that generate the different HTP design configurations. These generic needs, are converted into requirements following specific modeling rules and patterns. The shift from needs to requirements eliminates any ambiguity of interpretation. From each requirement, it is then possible to derive others, as visible in Figure 10. A "responsible stakeholder" is in charge of the effective application of these requirements to the product. Several consequences occur in case of non-compliance of the product with the requirements. In the case of interest, the HTP non-compliance with the requirements of design, manufacturing and production implies, for instance, a loss of competitiveness in the market, due to lower aircraft performance or production issues. This consequence is also modelled in Figure 10. Obviously, the model is much more complex than the simplified one reported in Figure 10. This representation has been reported in this section, only to provide the reader an example of the application of the MBSE principles in the AGILE framework to the design, manufacturing and production of a horizontal tail plane.

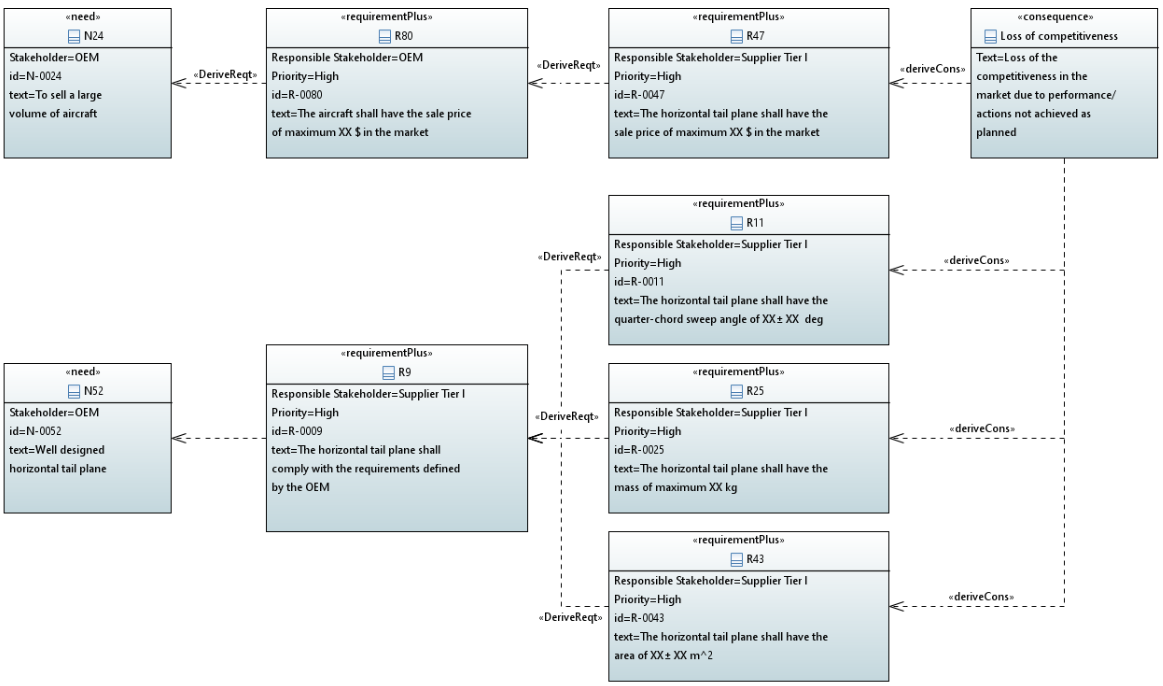


Figure 10 – OEM´ needs and requirements concerning the supply chain domain (N24) and the manufacturing and design domains (N52) modelled using the new *AGILE4Profile*, [32]

B. Identification of the tradespace alternatives based on the HTP manufacturing-design-supply chain variables

This subsection focuses on the different HTP design configurations and supply chain options that populate the final solutions tradespace. The materials, the manufacturing and the assembly processes are identified for the main components of the horizontal tail plane: skins, stringers, ribs and spars. Two material options are selected for the production of the HTP components: aluminum and composite. In this application, four HTP design alternatives have been considered, two mainly made in aluminum, two in composite. The HTP configurations that are characterized by the same material, differ in the manufacturing and assembly processes selected. The choice of materials and processes needed for the HTP components production, determines the selection of suppliers able to perform these activities. The supply chain options, combination of suppliers, are clustered according to the three production scenarios identified in Section IIB. The number of supply chain options belonging to each scenario, as well as the total number of supply chains available for the production of each HTP configuration, are specified in Table 3. The four HTP design configurations resulting from the manufacturing domain, affect the aircraft performance in a different way. The HTP

of the DC2 is used as reference. Thus, the mass and the drag of the other HTP configurations have been scaled (reduced or increased) with respect to the DC2-HTP design configuration through the TFs. In this application, the value model theory has been applied fixing the attributes weights combination and the single attribute utility function.
Thus, the size of the solutions tradespace is set by the different HTP design configurations and the multiple supply chain options identified for each of them. Table 3 schematically summarizes the alternatives populating the tradespace of this application. Instead, the application approach to the HTP is shown in Figure 11, in which not all the alternatives of the manufacturing and assembly processes are shown for readability reasons.

Table 3: Design variables characterizing the solutions tradespace for the horizontal tail plane application. For each HTP configuration, several supply chain options are considered and clustered according to the three main production scenarios: A) 100%InHouse, B) InHouse&Outsource, C)100%Outsource. The third column indicate the total number of supply chain options analyzed for each HTP configuration, and the number of supply chain alternatives belonging to each production scenario.

HTP_ID	*HTP Configuration*	*Supply Chain Options*	*Owner*
1	Mainly Aluminum	15 (A=4, B =5, C = 6)	Embraer (E)
2	Mainly Composite	12 (A=3, B =5, C = 4)	Embraer (E)
3	Mainly Aluminum	6 (A=2, B =2, C = 2)	GKN/Fokker (F)
4	Mainly Composite	6 (A=2, B =2, C = 2)	GKN/Fokker (F)

C. Studies Performed & Preliminary Results

The execution of the previously described approach allows to perform different studies by coupling domains one step at time. The flexibility of this approach allows to investigate several trade-off analyses depending on the combined domains. The alternatives proposed in the tradespace of each study here performed, refer to those reported in Table 3 and explained in Section VB. The cost characterizing the value-cost tradespace, are normalized because of intellectual proprieties of industrial partners. Furthermore, it is assumed that the measures necessary for the *value* generation (weight and single attribute utility) are fixed.

Manufacturing and Supply Chain Domains. Each solution of the value-cost tradespace accounts only for attributes characterizing the supply chain domain. MDAx has been used to set-up the workflow of this MDAO process. The XDSM workflow, the executable workflow and the preliminary results of this study, are shown in Figure 12. The trade-off studies, that can be performed coupling these two domains are hereafter described.

Make or Buy. For each HTP design configuration, the decision maker can identify the best supply chain option considering the production performance parameters of time, quality and risk, aggregated in the *value*. The best alternative of supply chain is the one with the highest *value*. A larger tradespace can be generated considering all the supply chain options for all the HTP configurations, at the same time. In this case, the decision maker can make some initial considerations looking at the production performance (cost, risk, quality, time) needed to produce different HTP configurations. For instance, Figure 13 highlights - circled – that the best supply chain option is relating to the second HTP configuration, mainly made by composite. However, other solutions can be considered as alternatives to the best one, giving up the higher *value* but having 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 13, the highest value is associate to the supply chain 1A - circled - belonging to the 100%InHouse scenario. A lower cost supply chain alternative with a lower *value*, for the same HTP configuration, is provided by the solution 5B (circled). The reduction in cost is related to a production partially made in house, partially outsourced to suppliers. The lower *value* can be related to the estimated time, quality, risk for this supply chain. In practice, the decision maker can also look into the details of each solution and therefore into the measures that have determined that *value*. This allows to identify the weaknesses and/or the strengths of each supply chain, giving the decision maker the opportunity to take decisions in the full awareness of every detail.

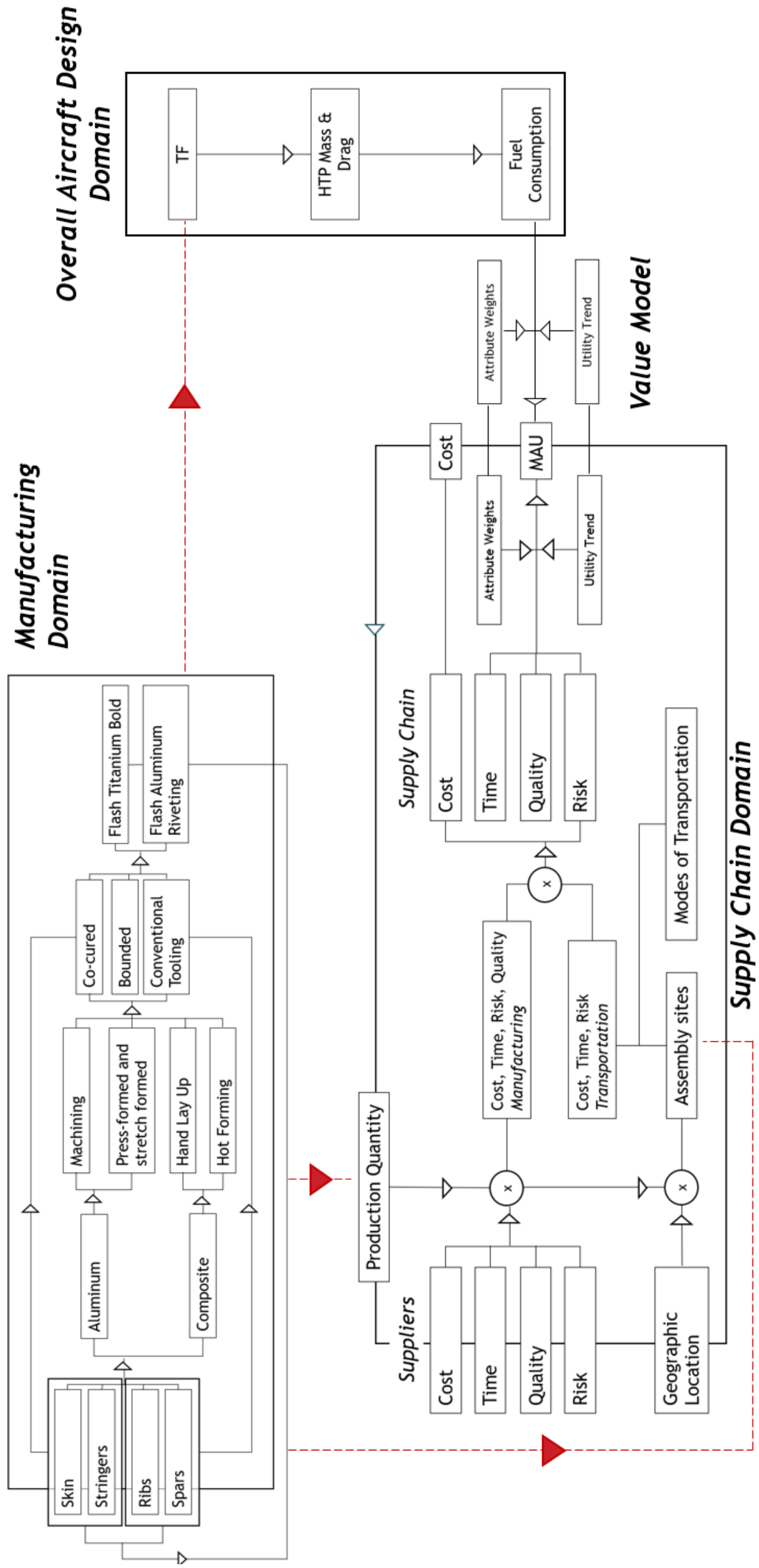
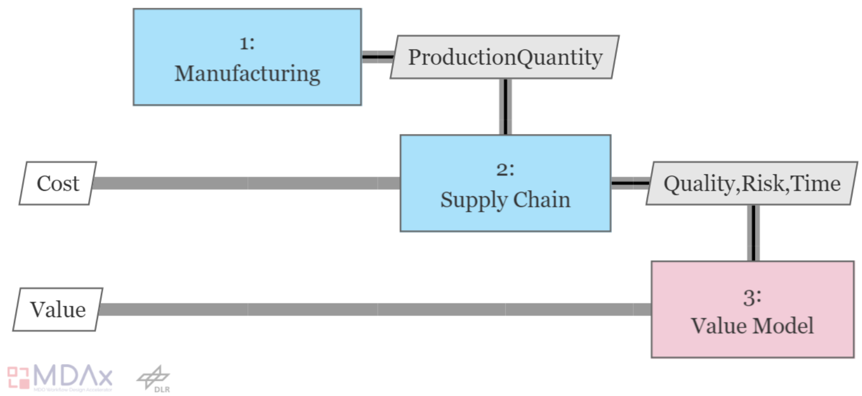
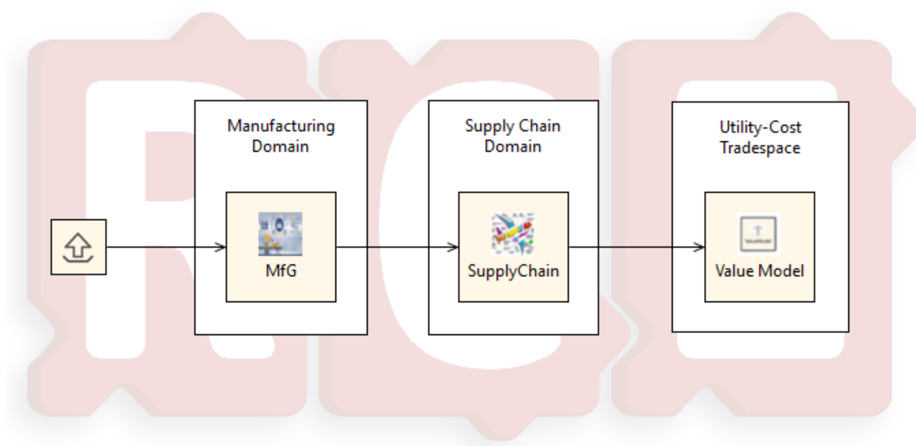


Figure 11 – Value-driven model-based approach for the Horizontal Tail Plane application

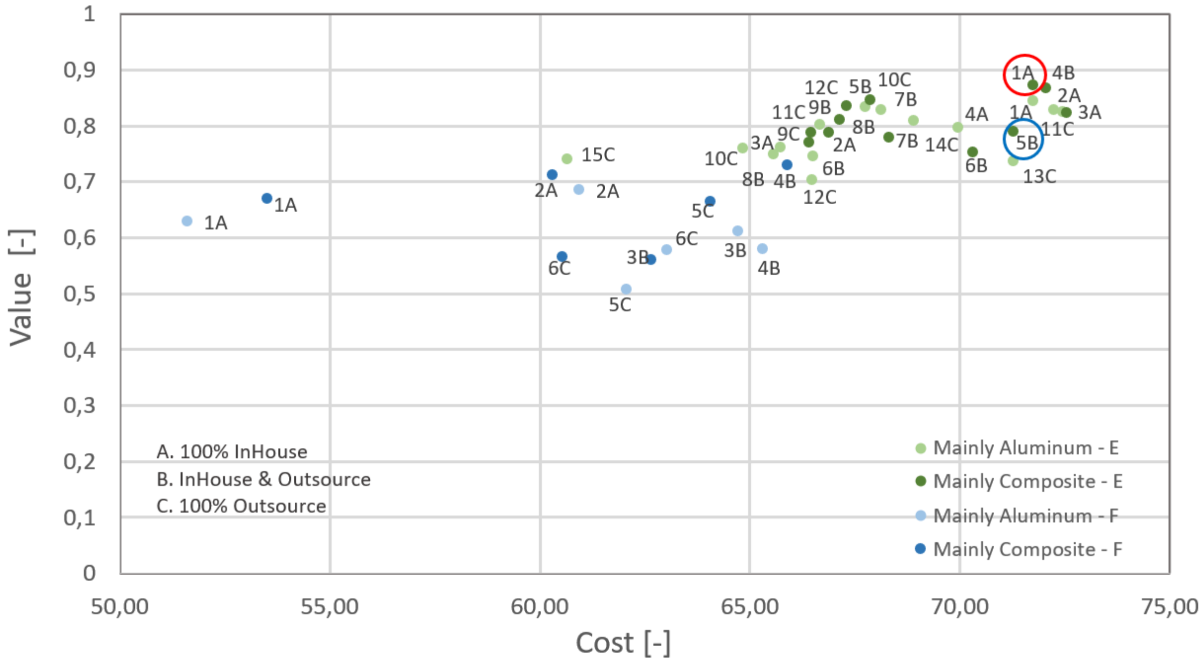
Risk/Quality/Time vs. Production Cost. The *value* is used when several measures (decision variables) define the choice of an alternative. In this approach, the value model can be used also to execute two-variables trade-off studies. By assigning a non-null weight only to one attribute, it is possible to coincide the *value* with this attribute, thus defining a classical bi-dimensional pareto-front. As consequence, the value-cost tradespace can be read as a risk/quality/time – cost tradespace assigning a non-null weight respectively to risk, quality and time. In this case, the decision maker can make his/her choice by looking at a specific attribute of interest.



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



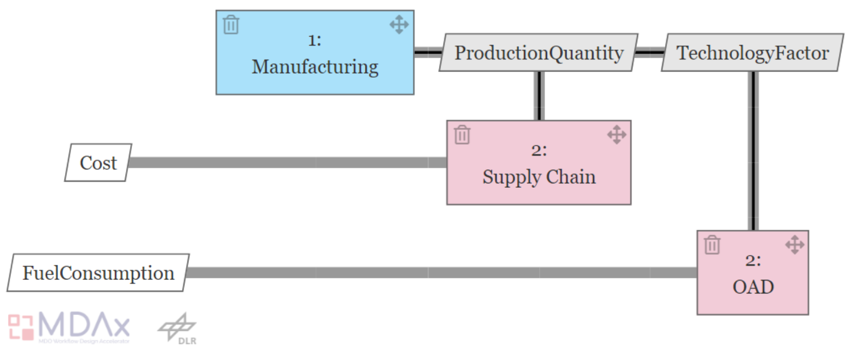
II. Executable Workflow, run in RCE, coupling MfG Domain and SC Domain



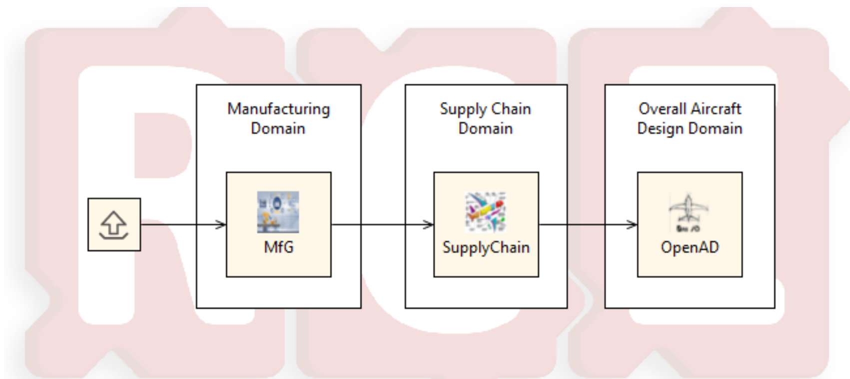
III. Solutions Tradespace coupling MfG Domain and SC Domain

Figure 12 –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)

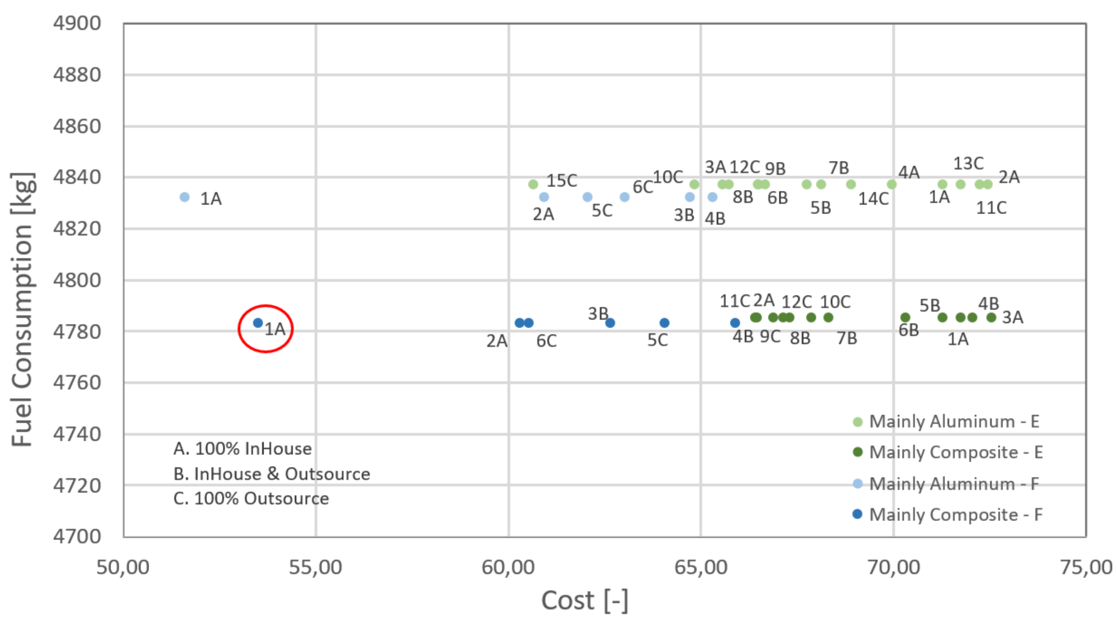
Manufacturing and OAD Domains. The four horizontal tail plane configurations can be compared in terms of aircraft performance, specifically fuel consumption. Doing so, a trade-off study between the manufacturing characteristics (choice of materials, manufacturing, assembly processes) and the aircraft performance is possible to carry 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 configuration. 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 of this more complex MDAO problem is shown in Figure 13. It highlights the coupling variables between domains. This workflow has been exported from MDAx and run in RCE. The preliminary results are also reported in Figure 13. It is immediately evident from this figure, how the use of the aluminum for the production of the horizontal tail plane has a greater impact on the fuel consumption than the composite. The properties of the composite, used for the realization of the HTP, imply a lower fuel consumption at the aircraft level, for the same flight condition (cruise). From the analysis of the results, the decision maker can also identify the supply chain alternative, capable of producing the same product (HTP) with lowest cost. Referring to Figure 13, 1A – circled - is the supply chain alternative producing the composite tail plane at the lowest cost. This supply chain belongs to the first production scenario (100%InHouse). Compared to the previous study, here the decision maker bases this choice only on the production cost associated to each supply chain. The focus is on the aircraft performance and manufacturing proprieties; therefore, it is not possible to make choice also considering the production time, risk and quality.



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



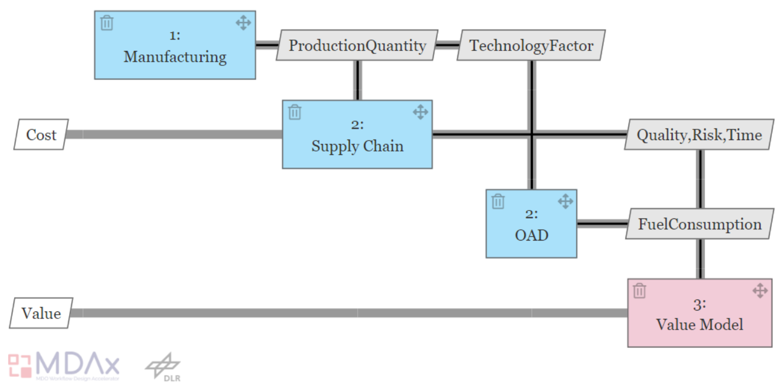
II. Executable Workflow, run in RCE, coupling MfG Domain and OAD Domain



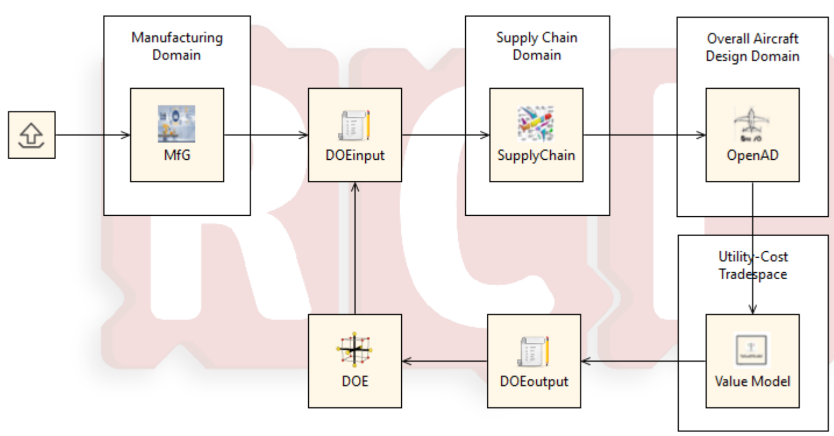
III. Solutions Tradespace coupling MfG Domain and OAD Domain

Figure 13 – 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)

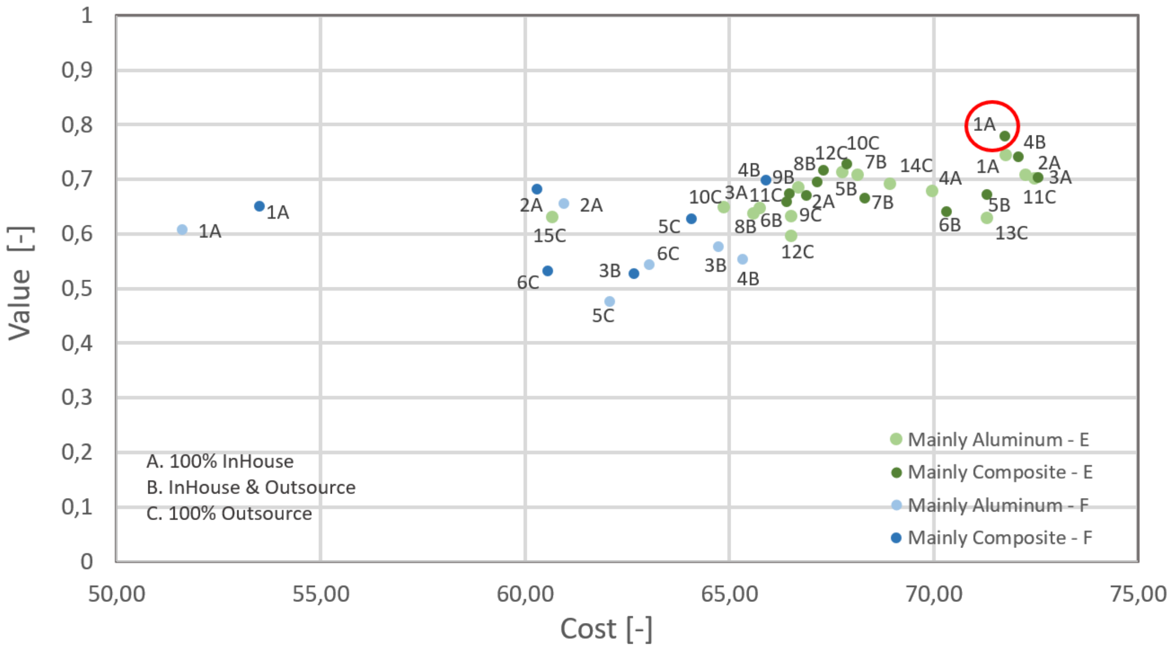
Manufacturing, Overall Aircraft Design and Supply Chain Domains. Each solution of the value-cost tradespace accounts for attributes characterizing both the supply chain (production performance parameters) and the overall aircraft design domain (aircraft performance). Horizontal tail plane configurations made by different manufacturing proprieties, influencing differently the aircraft performance, produced by several supply chain options, populate the tradespace. As consequence, the solutions tradespace offers a range of alternatives in which the decision maker can choose simultaneously considering a large number of measures of interest. At this step, the entire approach applied to the HTP, Figure 11, is executed. The MDAO process of the full study, has been set-up using MDAx. The XDSM workflow, reported in Figure 14, includes all the MDAO competences described in Section IVA. The same figure also shows the preliminary results of this analysis, obtained by running the workflow in RCE. In the tradespace of proposed solutions, the one with highest value – circled – is 1A. This solution relates to the HTP configuration mainly made of composite. But, from the tradespace, it is also possible to extrapolate the production cost and *value* associate with this solution. The *value*, particularly, shows that this alternative is the best one in terms of production performance parameters (time, risk, quality) and aircraft performance (fuel consumption). In fact, all these attributes, are aggregated, with a weight, in the *value*. This is the main difference with the first study (Manufacturing and SC domains), in which the *value* aggregates attributes characterizing only the supply chain. Therefore, this solution represents, in the complete study, the best compromise across multiple domains. A further information can be extracted from the same tradespace, that is the production scenario which the solution belongs to. Therefore, the decision maker can carry out, at the same time, the make or buy investigation and consider valid all the observations already made in the "Manufacturing and Supply Chain Domains" study. The analysis of the solutions tradespace of the complete study can represent a powerful means of support for the decision maker, who can take decisions based on measures belonging to different domains, entering in the details of each solution.



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 14 – 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)

VI. Conclusions and Outlook

The value-driven model-based approach presented in this paper has as its main objective to simultaneously coupling three domains of manufacturing, supply chain and overall aircraft design at the early stage of aircraft developments. In Section II, the main contents of the three domains and the information exchanged between them are widely described. Instead, Section IV shows the disciplinary codes implemented to make possible the execution of this approach. Semi-empirical methods have been used for the analysis of the single domains. The priority was to create a simple model able to execute this cross-domains multi-disciplinary analysis. Assessed the methodology, one of the next steps is to use ever more precise and detailed models for the analysis of the single domains.

The value model is used to support the decision maker in the choice of an alternative influenced by measures (decision variables) related to different domains. The attributes (Table 1, Section IIIA) considered indispensable in the choice of the best solution, are related both to the supply chain and the overall aircraft design domains. The single utility functions (Section IIIB) can have a completely different trend from the linear one, assumed now. A simplified model of single utility functions has been exploited for the attributes, to demonstrate the applicability of the value model to this methodology. The next challenge is to formalize the attributes utility curves to reflect the decision makers´ levels of desirability of each attribute. The *value* estimation also passes through the assignment of weights to the attributes (Section IIIC). The combination of weights is assigned according to the relative importance of the proposed attributes. Addressing a different weight to each attribute, means follow a specific industrial strategy. Prioritize risk while neglecting time, promote quality instead of risk, prefer time, are just some of the possible strategy alternatives to pursue, especially during the early stage of aircraft design. Thus, the weights combination can be set according to the needs of the decision maker. However, a DOE to analyze all the possible weights combinations, is something that will be addressed in the near future. The preliminary results reported in this paper, have been obtained for a fixed weight combination.

The execution of the multiple studies that can be performed through this approach, are shown in Section V. The possibility of being able to carry out various trade-off investigations, demonstrates the flexibility of this approach.

Robust optimization algorithms will be applied to this cross domain multi-disciplinary analysis to identify the global optimum. Such algorithms will consider the uncertainties modeling. In fact, uncertainties play a key role in taking

decisions. The use of artificial intelligence algorithms for the generation of the HTP configurations or supply chain options, is another interesting aspect that will characterize this approach in the future.
Concluding, the possible activities that can be undertaken on this approach are many, given the multiplicity of different aspects involved in it. Effectively, the management of such a wide flow of information, with all the uncertainties associated with its modeling, is the strength but also the weak point of this approach. However, its potential use has been recognized by industrial partners, who have defined this approach as a support means that aerospace companies might use in the early stages of aircraft design when strategic decisions have to be taken.

VII. Acknowledgments

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