Università
degli Studi
della Campania
Luigi Vanvitelli

Dipartimento di
Ingegneria

Corso di Laurea Magistrale in
Ingegneria Aerospaziale

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Value-driven optimization campaign addressing manufacturing, supply chain and overall aircraft design domains in the early development stage

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Umberto Merola Matr.A15/208	*Prof.* *Giuseppe Pezzella* *Prof.* *Antonio Viviani*	*Dott.* *Giuseppa* *Donelli*	

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NOMENCLATURE

AGILE	Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
MBSE	Model Based Systems Engineering
MfG	Manufacturing
SC	Supply Chain
OAD	Overall Aircraft Design
PQ	Production Quantity
AQ	Assembly Quantity
TF	Technology Factor
MDAO	Multidisciplinary Design Analysis Optimization
KDE	Product Life Management
PLM	Knowledge Based Engineering
MDO	Multi Design Optimization
OEM	Original Equipment Manufacturer
HTP	Horizontal Tale Plane
RF	Relevance Factor
DOE	Design of Experiment
DLR	Deutsches Zentrum für Luft- und Raumfahrt
PF	Pareto Front
SCCA	Supply Chain Competence Average
SCO	Supply Chain Option
SME	Small and medium-sized enterprises
PP	Production Performance

CHAPTER I

INTRODUCTION

I.1. Context

The top-level aircraft requirements (TLARs) historically lead the early phase of aircraft design with the objective to search for aircraft configurations with optimized performance. In the last decade, however, the European Commission introduced the Flightpath 2050, defining new challenges for the design of 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 of extending the branches of the aeronautical research to the entire aircraft life-cycle, from the design to the production, to the waste disposal after the end of the system activity. The challenge is to account for these new requirements in the early design phase to take strategic decisions that would optimize the entire aircraft life-cycle. In this frame, the European funded H2020 project AGILE 4.0 [2], follow-up of the AGILE project, led by Deutsches Zentrum für Luft- und Raumfahrt (DLR), aims to bring significant reductions in aircraft development costs and time-to-market through the implementation of an integrated cyber-physical aeronautical supply chain, from integrators and high-tiers suppliers to small and medium-sized enterprises (SMEs), leading to innovative and more sustainable aircraft products. In particular, AGILE 4.0 targets the digital transformation of main pillars of the aeronautical supply-chain, including design, production, certification and maintenance. To meet this challenge a Consortium of 18 industry [3], research and academia partners from Europe, Canada, Brazil, and Russia are collaborating. Therefore, in AGILE 4.0 complex product development scenarios are investigated, integrating multiple stakeholders, and covering the complete development life cycle. The composition of the AGILE 4.0 consortium and the available capabilities permit to perform realistic investigations covering all the aspects of the aeronautical supply chain, in order to validate the AGILE 4.0 technologies. A representation of the domains addressed by the project and the Consortium are given in Figure 1.

Figure 1 AGILE4.0: overall concept (right), consortium (left). Focus is on accelerating the development of complex systems, by digital transformation of the aeronautical supply chain [4]

AGILE 4.0 is structured into 7 Application Cases, which consider 7 parallel aircraft application cases investigated during the project. Each one is focuses on a specific aspect of the development life cycle of an aeronautical system, i.e., design manufacturing, assembly, certification and maintenance [4].

I.2. Aim and Structure of the Thesis

As previously described, this master thesis activity is framed within the Application Case 2, which regards the production and the MDO framework implementation [3]. This application case aims at enlarging the early design phase on aircraft by including manufacturing and supply chain properties. Therefore, a methodology, enabling the concurrent coupling of these three domains of manufacturing, supply chain and overall aircraft design domain has been formulated and implemented [5].

The main purpose of this master thesis work is to introduce:

- Manufacturing Competences indicating the enterprise skills in the manufacturing processes involved in the production plan.
- Technology Factor related to the manufacturing processes, which influences the horizontal tale plane (HTP) performance in terms of mass and aerodynamic shape.

- Optimization Campaign aiming at identifying the optimum solution simultaneously accounting for manufacturing, supply chain and overall aircraft design variables.

However, before introducing the innovative aspects of the thesis, it was decided to provide a theoretical background of the whole methodology to allow the reader a complete understanding of the problem. Therefore, the thesis is structured as follows:

- Chapter I focusing on the context in which this master thesis work has been performed with a general overview of the European funded H2020 project AGILE 4.0.
- Chapter II describing the theoretical background of the methodology.
- Chapter III defining the MDO Problems set-up in terms of design variables, objective functions, constraints and adopted methods.
- Chapter IV dealing with the MDO Problems implementation, describing tools and technologies used.
- Chapter V describing the MDO problems results and post-process.
- Chapter VI reporting the conclusions and recommendations for possible future developments.

CHAPTER II

VALUE-DRIVEN METHODOLOGY

In the previous chapter, the AGILE 4.0 Project has been introduced to provide a context in which this research activity is developed.

In this chapter, the theoretical background of the value-driven methodology is firstly provided in II.1. In this paragraph the state of the art related to this methodology is briefly described. Instead, paragraph II.2 highlights the contribution provided by this research activity in enhancing the value-driven methodology.

II.1. Theoretical Background

As already explained in the previous chapter, one of the challenges of the AGILE 4.0 Project is to include the pillars of the aeronautical supply chain in the early phase of aircraft design. For this purpose, a value-driven model-based approach concurrent coupling multiple domains has been developed in one of the AGILE 4.0 application case. Particularly, three domains have been addressed:

- *Overall Aircraft Design (OAD) domain dealing with the estimation of the aircraft performance.*
- *Manufacturing (MfG) domain focusing on the materials, manufacturing and assembly processes feasible for the aircraft components.*
- *Supply Chain (SC) domain estimating the production performance (i.e. cost, time, quality, risk) by characterizing the enterprises involved in the aircraft production and assembly.*

This approach also indicated as three-dimensional approach (since simultaneously coupling three domains) has been applied to an aeronautical system component, which is the horizontal tail plane (HTP), to highlight the advantages of including manufacturing and supply chain decisions in the early design stage. The value model theory has been adopted as key enabler of the concurrent coupling of multi-domains [6]. A value-cost solution trade-space is so generated by the value-driven three-dimensional approach. A schematic representation of this approach is shown in Figure 2, instead below more details on the links identified between domains are provided.

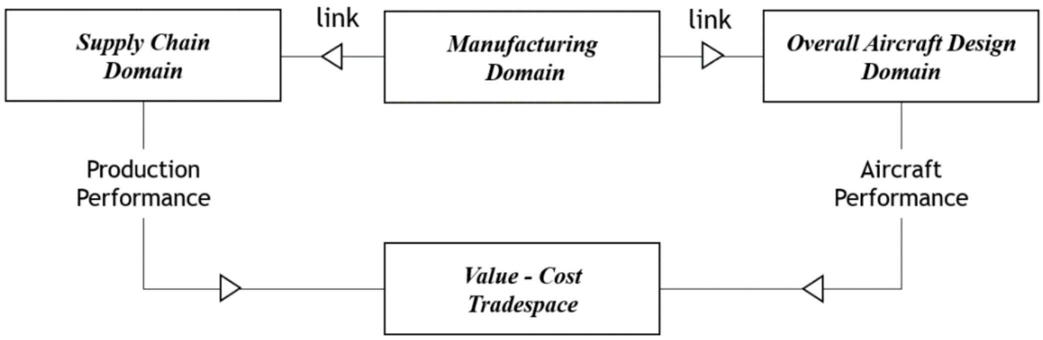

Figure 2 Schematic representation of three-dimensional methodology concurrent coupling product design [5].

A Technology Factor (TF), a dimensionless number ranging from 0 to 1, is proposed as the link between the Manufacturing and Overall Aircraft Design domains. It quantifies the impact that materials, manufacturing and assembly processes, characterizing the HTP components, has on the mass and drag of the HTP and, consequently, on the fuel consumption of the vehicle in cruise. The estimation of the fuel consumption is the main output of the OAD domain.

The Production Quantity (PQ) and the Assembly Quantity (AQ) are instead defined as the links between the Manufacturing and Supply Chain domains. The Production Quantity indicates the percentage of HTP components that each enterprise has to perform. The HTP structure breakdown assumed in this research activity is shown in figure 3 and it includes skin, stringers, spars and ribs. Instead, the reference aircraft is the DC2. Thus, the mass and the drag of the other HTP configurations have been scaled (reduced or increased) according to the DC2-HTP design configuration through the TFs [5]. The Assembly Quantity, instead, indicates the percentage of assembly processes that each enterprise has to perform. The analyzed assembly processes are skin & stringers and main assembly.

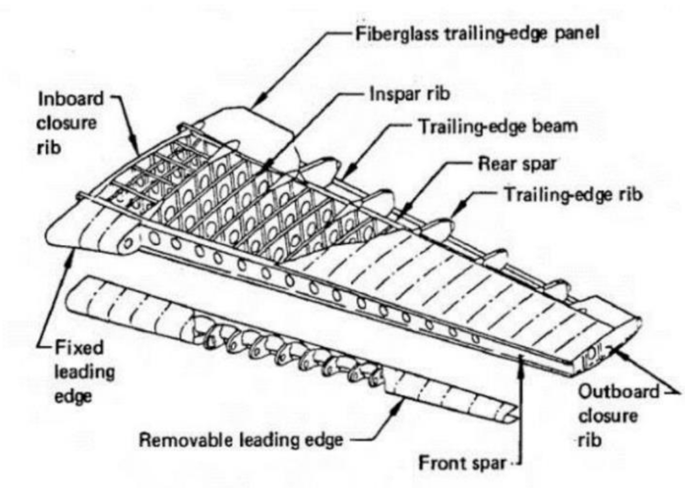

Figure 3 Horizontal tail plane structure breakdown [7]

Based on the production and assembly quantities, the production cost, time, quality and risk (defined as production performance) are estimated in the SC domain for each supply chain, which is a combination of several enterprises. Particularly, depending on the involved enterprises, three possible production scenarios are of interest:

- In House: HTP components are manufactured and assembled in house.
- In House and Outsourced: HTP components are partially manufactured and/or assembled in house.
- Outsourced: HTP components are manufactured and assembled by suppliers or sub-suppliers.

The production cost, time, quality and risk for each supply chain are estimated considering three main contributions:

- *Fixed cost, time, quality, risk:* depending on aspects strictly related to each enterprise, e.g. size of the factory, the energy and labor cost of the country where it is placed etc.;
- *Transportation cost, time, risk:* based on the distance among factories involved in the supply chain. Particularly, four means of transport are used in the model: road, air, water, railway. A linear semi-empirical method, found in literature, have been used to estimate the transportation performance [8]. The curves used to estimate the transportation performance are shown in figure 4. First the distances between

enterprises involved in the supply chain are estimated and then, based on the means of transport used, the cost is estimated. The same approach has been used to estimate the transportation risk and time. Instead, it has been assumed that quality is not impacted by transports.

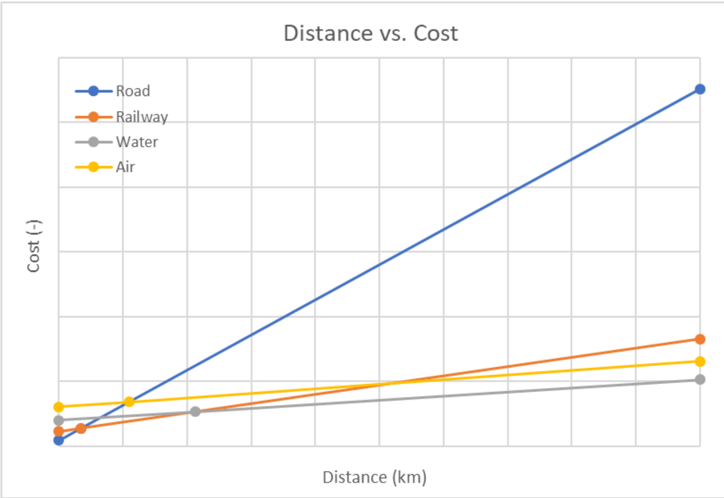

Figure 4 Distance vs Transportation Cost for each mean of Transport [8]

- *Manufacturing cost, time, quality, risk.* mainly depending on the enterprises competences thus on the skills that each enterprise has in performing selected manufacturing and assembly processes.

Once defined the main output of each domain, as shown in Figure 2, the value-cost tradespace finalizes the methodology. Particularly, the value-model theory has been adopted as main enabling the concurrent coupling of multiple domains. For the value estimation, three key features have to be defined [9]:

- Attributes: key parameters for the decision maker.
- Single Attribute Utility (SAU) Functions: curves expressing decision maker´s preferences.
- Weights: relative importance of each attribute.

In this research activity, the value model theory has been leveraged to linearly aggregate parameters with different unit of measures in a single, dimensionless measure which is the value. Particularly, four attributes have been aggregated in the value. Three attributes characterize the SC domain and they are production risk, quality and time; one the overall aircraft design domain and it is the aircraft the fuel consumption. The production cost has instead considered as other independent variable to generate the value-cost tradespace. The best solution, the one with the highest value, can so be identified on this tradespace. In fact, higher is the value, better is the solution. An example of value-driven tradespace is shown in figure 5.

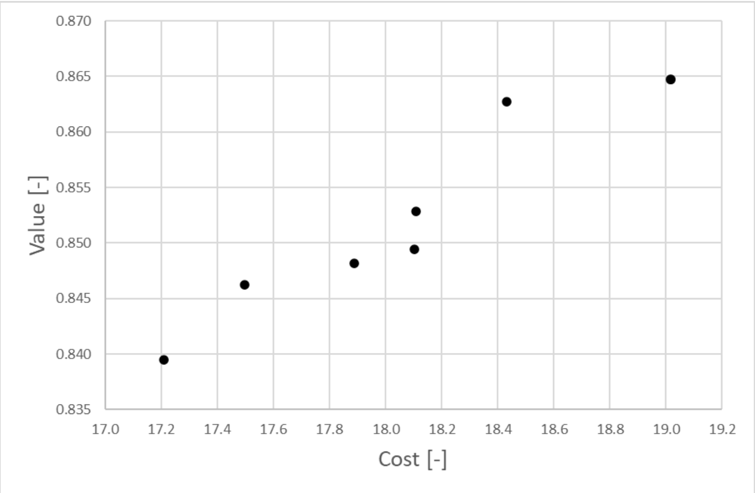

Figure 5 Example of Pareto Front in the Value-Cost Tradespace

The new challenge is to address an optimization design campaign aiming at finding the global optimum simultaneously accounting for design, manufacturing and supply chain variables. However, before introducing the MDO problems examined in this master thesis work and described in chapter III, in the next paragraphs the enhancements made on the value-driven methodology are reported. Several activities have in fact been performed for setting the MDO problems correctly.

II.2. Methodology Enhancement

Before focusing on the MDO campaign, it has been necessary to perform several activities in order to set the MDO case studies in the right way. The analysis performed are the following:

- *Manufacturing & OAD: Validation of TFs.*
- *Manufacturing & SC: Competences methods and models.*

A) Manufacturing & OAD: Validation of TFs

The purpose of this analysis is to get the mass $and\ C_{D_0}$ of the different HTP configurations and the fuel consumption of the vehicle in cruise to validate the link between the MfG and OAD domain. These nine HTPs configurations differentiate for the choice of materials, manufacturing and assembly processes, as shown in Table 1. The HTP8 is representative of the DC-2 aircraft, used as baseline in this research activity. The HTPs examples refer to a baseline provided by the industrial partners, which are indicated with "E" and "F".

ID	Materials	Components	MfG Processes	Owner
1	Thermoset	Skin - Stringers - Spars	Hand Lay Up, Automated Tape Lay up	F
	Aluminum	Ribs	Machining	
2	Aluminum	Skin - Stringers - Spars - Ribs	Machining, Stretch Formed and Press Formed, Z-Extrusion and doublers	E
3	Thermoset	Skin - Stringers - Spars	Hand Lay Up, Automated Tape Lay up, Fiber Placement	E
	Aluminum	Ribs	Machining	
	Thermoplastic	Ribs	Thermoforming	
4	Thermoset	Skin - Stringers - Spars	Hand Lay Up, Automated Tape Lay up, Fiber Placement	E
	Aluminum	Ribs	Machining	
	Thermoplastic	Ribs	Thermoforming	
5	Thermoset	Skin - Stringers - Spars	Hand Lay Up, Automated Tape Lay up, Fiber Placement	E
	Aluminum	Ribs	Machining, Z-Extrusion and doublers	
	Thermoplastic	Ribs	Thermoforming	
6	Aluminum	Skin - Stringers - Spars - Ribs	Machining, Z-Extrusion and doublers	E
7	Aluminum	Skin - Stringers - Spars - Ribs	Machining, Z-Extrusion and doublers	E
8	Aluminum	Skin - Stringers - Spars - Ribs	Machining, Stretch Formed and Press Formed, Z-Extrusion and doublers	E
9	Aluminum	Skin - Stringers - Spars - Ribs	Machining, Stretch Formed and Press Formed, Z-Extrusion and doublers	E

Table 1 9 HTP examples example cases definition to validate the Weight, Aerodynamic Performance and Fuel Consumption model

The results, shown in Table 2, are coherent with expected ones.

Owner	ID	Mass HTP [kg]	Cd0 in Cruise [-]	Fuel Consuption in Cruise [kg]
F	HTP 1	422	0.0019	4784
	HTP 2	456	0.0020	4822
E	HTP 3	412	0.0019	4784
	HTP 4	410	0.0019	4783
	HTP 5	411	0.0019	4785
	HTP 6	474	0.0019	4811
	HTP 7	468	0.0020	4815
	HTP 8	458	0.0021	4837
	HTP 9	457	0.0021	4839

Table 2 9 HTP examples cases definition results to validate the Weight, Aerodynamic performance and Fuel consumption model

B) Manufacturing & SC: Competences methods and models

The manufacturing performance indicates the enterprises skills in performing selected manufacturing and assembly process. Our purpose is to estimate the manufacturing performance: cost, time, risk and quality basing on the manufacturing competences of the enterprises involved.

Curves Models

The relation between the manufacturing competences and performance may be returned by two types of curves: linear and not linear. Examples of both relations are provided in figure 6.

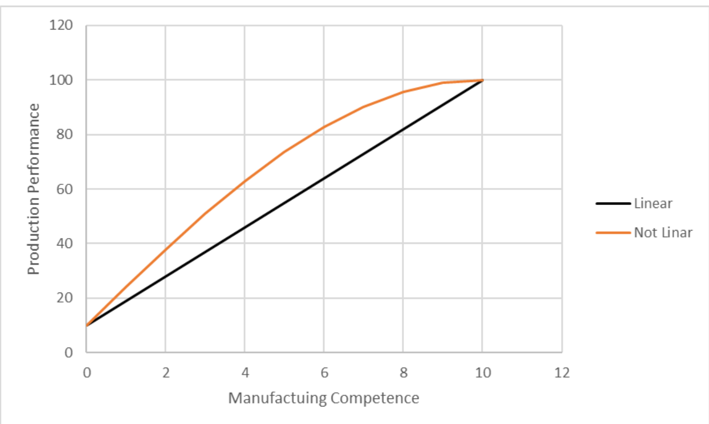

Figure 6 Example of linear and not linear curves used in the estimation of production performance

In this study, analyses have been performed to understand the differences in using linear or not linear curves for the competence model. The comparison is done considering a specific HTP configuration, which is the HTP8, made by aluminum (Table 1) and three supply chain options, indicated as 1SC, 2SC and 3SC:

- *HTP8-1SC: produced and assembled in house.*
- *HTP8-2SC: produced by suppliers, assembled in house.*
- *HTP8-3SC: produced and assembled by suppliers.*

These supply chain options are proposed in Table 3.

SC Options		Enterpirses									
		1	2	3	4	5	6	7	8	9	10
HTP 8 -1SC	Skin	■									
	Stringers	■									
	Spars	■									
	Ribs	■									
	Skin&Stringer Ass.	■									
	Main Assembly	■									
HTP 8 -2SC	Skin				■				■		
	Stringers								■		
	Spars				■			■			
	Ribs				■						■
	Skin&Stringer Ass.			■							
	Main Assembly		■								
HTP 8 -3SC	Skin						■				
	Stringers						■				
	Spars						■				
	Ribs						■			■	
	Skin&Stringer Ass.					■					
	Main Assembly				■						

Table 3 Manufacturing & SC: Competences methods and models: 3 supply chain options specifications

By applying linear and not-linear curves, different results are obtained. For industrial intellectual properties, curves are not reported in this research activity. Instead, results related to the linear competence curves are reported in Table 4, for not-linear competence curves in Table 5.

Results		HTP 8 -1SC	HTP 8 -2SC	HTP 8 -3SC
Cost [-]	Fixed	22.0	32.8	32.5
	Transport	1.3	4.4	3.3
	Manufacturing	39.1	34.0	41.6
	TOTAL	20.8	23.7	25.8
Value [-]		0.788	0.741	0.760

Table 4 Manufacturing & SC: Detailed cost and value results for linear curves of 3 HTP supply chain options

The solution only involving suppliers (HTP 8 – 3SC) has the highest cost, as expected. Instead, solution HTP 8 – 1SC has the highest value, which indicates the best solution.

Results		HTP 8 -1SC	HTP 8 -2SC	HTP 8 -3SC
Cost [-]	Fixed	22.0	32.8	32.5
	Transport	1.3	4.4	3.3
	Manufacturing	58.1	53.2	65.4
	TOTAL	27.2	30.1	33.7
Value [-]		0.835	0.786	0.807

Table 5 Manufacturing & SC: Detailed cost and value results for not linear curves of 3 HTP supply chain options

Using distinct types of curves, the results change, but the best-worst order remains the same. The mutual position of configuration in Value-Cost Tradespace does not depend on the curves used. Results for the linear and not-linear competence curves are reported respectively in Figure 7 and 8. Both linear and not-linear curves will be used in the MDO case studies, depending on the analyzed application case, as described in the next chapter.

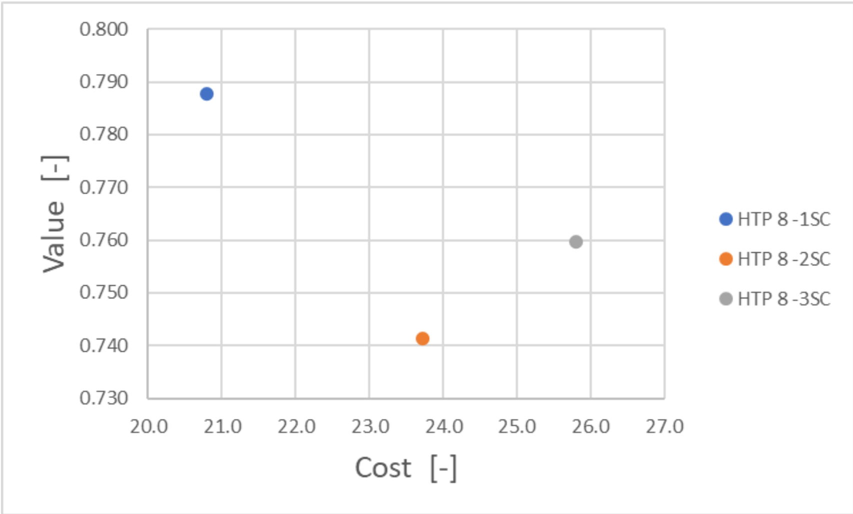

Figure 7 Manufacturing & SC: Competences methods and models: Value-Cost Tradespace for linear curves of 3 HTP supply chain options

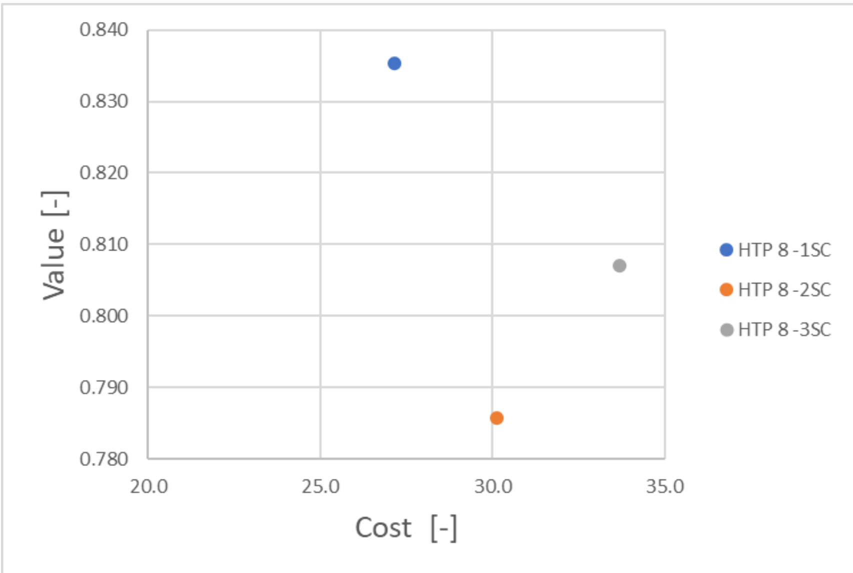

Figure 8 Manufacturing & SC: Competences methods and models: Value-Cost tradespace for not linear curves of 3 HTP supply chain options

Manufacturing Competence Methods

Two methods are compared for the evaluation of Cost, Time, Risk and Quality depending on enterprises competences. The comparison between these methods is done using the HTP 8, which has just been presented in the last paragraph (Table 1). The Manufacturing Competence expresses the enterprises capacity in performing each manufacturing processes. It is expressed on a scale among 1 to 10, the value of 0 is used to indicate an enterprise which is not able to perform the required component.

In method 1 the supply chain competences average is estimated considering OEM and Supplier competences. The Table 6 shows an example of manufacturing competences for the HTP8 production and it does not consider real enterprise competence values.

HTP 8	Skin	Stringers	Spars	Ribs	Skin&Stringers Assembly			Main Assembly		
	2	4	9	4	8	7	9	8	9	9

Table 6 Example values of Manufacturing Competences for HTP 8

The equation 4 calculates the Supply Chain Competence Average (SCCA) of the whole HTP. The SCCA is estimated making the product among the production quantity and the competence of the part and the sum of them is divided by the number of components (Equation 1).

$$SCCA = \frac{1 \cdot 2 + 1 \cdot 4 + 1 \cdot 9 + 1 \cdot 4 + 1 \cdot 8 + 1 \cdot 7 + 1 \cdot 9 + 1 \cdot 8 + 1 \cdot 9}{number\ of\ components} = 6.667 \qquad 1$$

The SCCA is used as input in the curves of Cost, Time, Risk and Quality to estimate the supply chain performance related to competence.

In the method 2 the competences of factories for each component, material, manufacturing and assembly process is used as input of the competence-attributes curves, so we get the Production Performance referred to each enterprise. There are two different formulas for the estimation: time and cost a percentage factor is used which reveals the relevance of each component and assembly process [10]; while for quality and risk the same relevance is given to each part. In figure 9 the relevance factors are shown.

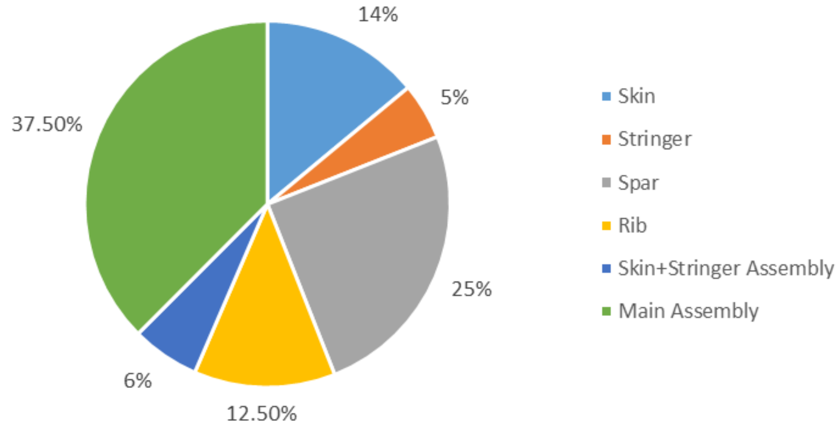

Figure 9 Relevance Factor for Cost and Time in Method 2 for the estimation of Production Performance depending on Manufacturing Competence [10]

The enterprises competences are turned into Cost, Time, Risk and Quality, using linear transformation or not linear curves. After having got the production performance for each enterprise, component and process, the following formulas are used to estimate the Manufacturing Performance of the HTP. The equation 2 is used for time and cost, while the equation 3 is used for quality and risk.

$$Time\ or\ Cost = \sum_{i=1}^{6} RF_i \cdot \left(\sum\nolimits_{Factory} PQ \cdot PP\right)_i \qquad 2$$

The index "i" ranges between components and assembly processes, "PP" stands for production performance, it might be cost or time and RF is the relevance factor.

$$Quality\ or\ Risk = \frac{\sum_{i=1}^{6}(\sum_{site} PQ \cdot PP)}{number\ of\ components} \qquad 3$$

Both two methods are used to estimate the Supply Chain Cost, Time, Quality, Risk:

- In *Method 1* the Curves are used at Supply Chain level after calculating the average of OEM/Supplier Competence.

- In *Method 2* the Curves are used at enterprises level and later the average is done at Supply Chain level.

In the linear case, as expected, the two models result identical (Table 7), because of linear model indeed. Applying curves at supply chain level for the first method, or at enterprises level for the second method, does not change the results of the estimation.

HTP 8	Method 1	Method 2
MfG Cost [-]	31.0	31.0
MfG Time [-]	31.0	31.0
MfG Quality [-]	66.7	66.7
MfG Risk [-]	33.3	33.3

Table 7 Manufacturing Competence Methods: Comparing Production Performance with linear curves for Manufacturing Competences

In the not linear case the methods give different results. In fact, the method 1 has higher cost, quality and risk than method 2. However, they are very close to each other, as it is shown in Table 8.

HTP 8	Method 1	Method 2
MfG Cost [-]	55.1	50.2
MfG Time [-]	27.5	35.0
MfG Quality [-]	98.2	97.9
MfG Risk [-]	49.3	49.2

Table 8 Manufacturing Competence Methods: Comparing Production Performance with not linear curves for Manufacturing Competences

After having consulted the industrial partners, it has been decided to implement the competence method 2 for the estimation of the production performance.

CHAPTER III

VALUE-DRIVEN MDO CASE STUDIES

In the previous section, the value-driven methodology, which simultaneously links the three domains of manufacturing, supply chain and overall aircraft design, have been discussed. Details on the contents of each domain as well as on the links identified between them have been provided. In this chapter, instead, the focus is on the multi-disciplinary design and optimization (MDO) problems that are carried out in this research activity by leveraging the previously described value-driven methodology.

III.1. MDO Case Studies Definition

The MDO problems addressed in this research activity aims at identifying the optimum solution simultaneously accounting for manufacturing, supply chain and overall aircraft design variables. This ambitious objective is extremely challenging due to the number and complexity of the domains, and thus variables involved. For this reason, a value-driven optimization campaign is addressed in this research activity. First optimization algorithms are tested for MDO problems, performing the optimization of two domains. Later, simple but representative optimization cases, dealing with the coupling of three domains, are performed. A complete overview of the MDO multi-domains and multi-disciplinary optimization case studies, which are examined in this research activity, is provided in Table 9.

Case Study	Application Case	Owner	Domain	Method	Design Variable	Objective Functions	Pareto Front
1	1	F	MfG - SC	DOE	Production Quantiy Assembly Quantity	Minimize cost, time, risk Maximize quality	Value-Cost
	2	E	MfG - SC	Remote Optimization	Production Quantiy Assembly Quantity	Minimize cost, time, risk Maximize quality	Value-Cost
	3	E	MfG - SC	Remote Optimization	Production Quantiy Assembly Quantity	Minimize cost, time, risk Maximize quality	Value-Cost
2	1	F	MfG - SC - OAD	DOE	Production Quantiy Assembly Quantity	Minimize cost, time, risk, FC Maximize quality	Value-Cost
	2	E	MfG - SC - OAD	DOE	Production Quantiy Assembly Quantity	Minimize cost, time, risk, FC Maximize quality	Value-Cost

Table 9 Value-driven MDO problems formulation: definition of design variables, method, enterprise data, objective functions and Pareto-front

The case studies are divided into two main groups:

- MDO case study 1: coupling Manufacturing and Supply Chain Domains.
- MDO case study 2: coupling Manufacturing, Supply Chain and OAD Domain.

The application cases are based on input data provided by industrial partners, which are indicated with "E" or "F". The main difference between the two case studies relies on the number of coupled domains (two or three) and thus in the objective functions. In fact, for the MDO applications of the case study 1, the objective functions are based on the minimization of cost, time, risk and on the maximization of quality. In this case, only the production performance characterizing the supply chain domain are considered. Instead, for the MDO applications of the case study 2, the objective functions even include the minimization of the fuel consumption, thus the parameter characterizing the overall aircraft design domain. In both study cases, the value-cost Pareto-front is investigated. It is worth to underline that no constraints are applied in every MDO problems by the optimizer. The design variables characterizing the MDO problems are the production quantity and the assembly quantity, as reported in Table 10 and precisely in Table 10.

Design Variables	Type	Content	Meaning
Production Quantity	Categorical Variables	0	No production site
		0.5	Half of total components
		1	Total components
Assembly Quantity	Categorical Variables	0	No assembly site
		1	Assembly site

Table 10 Design variables characterizing the value-driven MDO problems

The production and assembly quantities are the design variables. In fact, as already explained in paragraph II.1, each enterprise involved in the supply chain performs a specific production quantity. The supply chain cost, risk, quality and time depends on the production quantity allocated to each company. At the same way, the choice of the assembly site, which is represented by the assembly quantity, impacts the supply chain performance, particularly the transportation cost, time and risk. The HTP components are moved from the production sites, in which the manufacturing processes are performed, to the assembly sites, in which the assembly processes are executed. Changing the assembly sites impacts the distances among companies and thus the transportation cost, time and risk (paragraph II.1).

As synthesized in Table 9, two methods are proposed to execute the MDO problems:

- Design of Experiment (DOE).
- Remote Optimization.

Both methods have been addressed in collaboration with the French Aerospace Center ONERA.

A) DOE

DOE stands for "design of experiment" and it is used to explore all the solutions space. The DOE creation process begins with the detection of the variables which can be changed and the mutual relation/constriction between them. In the MDO Application Cases 1.1, 2.1 and 2,2, in which the DOE is used as method, the variables are the production quantity for skin, stringers, ribs, spars and the assembly quantity, thus the design variables reported in Table 10. The constraint regards the capacity of each enterprise, thus the maximum amount of production quantity that can be performed, and the competences of each enterprise, thus the skills in performing the selected material, manufacturing and assembly process. Once set-up the DOE, the execution flow used to launch the DOE is reported in figure 10:

1. Hence, ONERA creates a .csv file with all the possible combinations.
2. All the combinations are performed by DLR.
3. ONERA estimates the Pareto Front.
4. DLR post-processes the results.

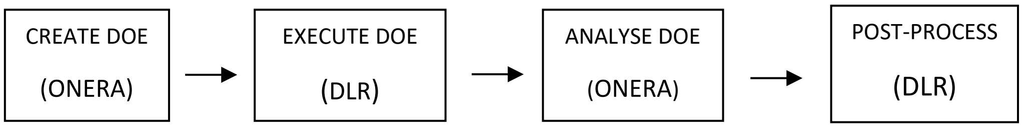

Figure 10 Execution flow used to launch the DOE

This approach explores all the design variables space, returning the output file for each configuration. The output file contains the production performance, fuel consumption and value, this information allows us to compare the solutions and to get the Pareto front.

B) Remote Optimization

The remote optimization has the purpose to find the Pareto Front without running all the possibilities, as DOE does, but using fewer analyses and predicting the Pareto Front points. The optimization algorithm is performed by ONERA, while the values for the objective function by DLR. The execution workflow is reported in figure 11:

1. The optimization algorithm creates and sends to the objective function (DLR) the input HTP information.
2. DLR executes the input file, estimating cost, time, risk, quality and fuel consumption, returning the output data where this information is placed.
3. At this point the algorithm processes the HTP performance, prepares a new input and the cycle restarts.

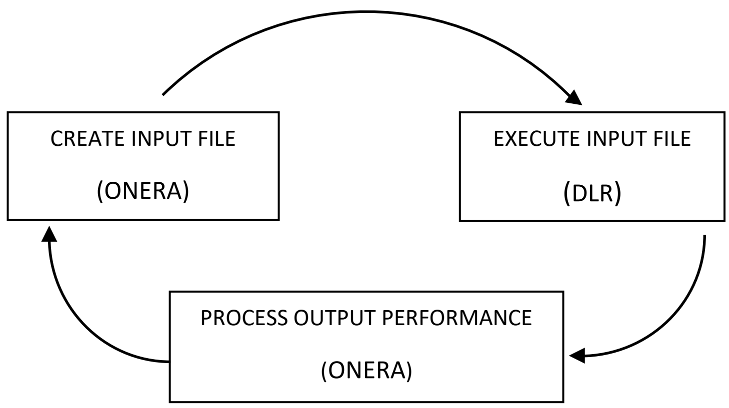

Figure 11 Execution flow of Remote Optimization

At the end of the optimization process the Pareto Front is obtained as follow:

1. The optimization algorithm uses the results of iterations to predict the Pareto Front: it is obtained at the end of the optimization once all iterations have run, then using the RSMs of all objective functions, which is built with all points of the optimization

process, NASG2 is launched and proposes a Predicted Pareto Front with output based on RSMs [11].

2. The Predicted Pareto Front solutions are submitted to the workflow by DLR and the output results (production performance and fuel consumption) are sent to ONERA.
3. The Predicted Pareto Front is filtered by ONERA with the new production performance provided by DLR, reaching the "True Pareto Front".

A schematic representation of the Predicted Pareto Front filtering process is reported in figure 12.

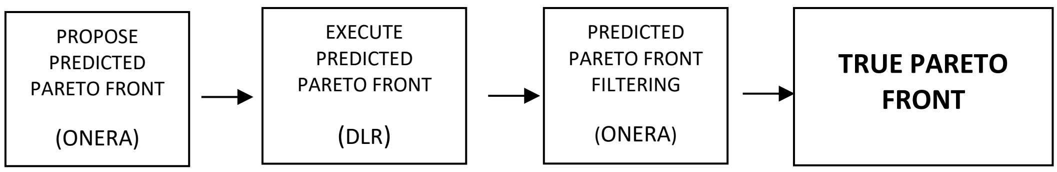

Figure 12 Predicted Pareto Front filtering process

In addition, the optimization runs for MDO Case Study 1 – Application Case 2 are divided into two groups:

- *Clustered optimization.*
- *Unclustered optimization.*

In the first optimization the algorithm is set to find clusters of points to use multiple surrogates per output [12]. This run is done at each iteration and it should be more efficient. In the second optimization clustering is not set, in order to reduce the time consumption of the process, which is roughly 1.5 minutes without clustering and 4.5 with clustering (Table 11).

Optimization	Time Required		
	ONERA	DLR	TOTAL
Clustered	4.5 minutes	30 seconds	5 minutes
Unclustered	1.5 minutes	30 seconds	5 minutes

Table 11 MDO Case Study 1 – Application Case 2: Comparison among clustered and unclustered optimization time

III.2. MDO Case Studies Set-up

In the previous paragraph, a complete overview of the MDO problems addressed in this research activity has been provided. In this paragraph, instead, the focus is on the set-up of each MDO application case. These are performed following the order provided in Table 9.

III.2.1 MDO Case Study 1 – Application Case 1 (DOE)

The first MDO application case, here addressed is a DOE, focuses on the two domains of manufacturing and supply chain. Particularly, the manufacturing properties are fixed, while the supply chain combinations vary (Table 9). In this case, the aim of this MDO problem is to identify the optimum supply chain combination producing a specific HTP configuration, made by selected materials, manufacturing and assembly processes. Particularly, the HTP configuration of interest is the HTP 2 (Table 1). Instead, the enterprises involved in the supply chain are summarized in Table 12. In these cases, only enterprises with the highest competences in performing the selected materials, manufacturing and assembly processes are considered.

Component	Number of Enterprises
Skin	3
Stringers	3
Spars	3
Ribs	4
Skin&Stringers Assembly	2
Main Assembly	2

Table 12 MDO Case Studies 1 – Application Case 1: DOE created by changing the production quantity and the assembly quantity to the enterprises involved in the production and assembly of the HTP 2 components

By changing the production quantity and the assembly quantity to the enterprises involved in this MDO application case, the DOE size reaches 5832 points. These are all the supply chain options analyzed for the HTP 2.

III.2.2 MDO Case Study 1 – Application Case 2 (Optimization)

This optimization focuses on the skin and stringers production and assembly. The manufacturing properties of spars and ribs, as well as the main assembly processes need to be fixed. Particularly, the HTP8 configuration is used as reference to address this MDO application case (Table 1). Thus, only the enterprises having the competences in performing the materials, manufacturing and assembly processes of the HTP8 configuration are selected for this MDO application case. Particularly, 13 enterprises are involved for the skin production, 13 for the stringers production, 4 for their assembly. These details are summarized in Table 13.

Component	Number of Enterprises
Skin	13
Stringers	13
Skin & Stringers Assembly	4

Table 13 MDO Case Studies 1 – Application Case 2: Enterprises involved in the production and assembly of the HTP 8 components

The aim of this MDO problem is to identify a set of non-dominated solutions (Pareto Front points) of supply chain producing a specific HTP configuration, made by selected materials, manufacturing and assembly processes. At the end, the supply chain option in terms of skin and stringers production and assembly is identified for the HTP 8 configuration. For skin it is considered the possibility to divide the production quantity of 50 % among 2 factories, hence the enumeration of possible solutions is 8788.

III.2.3 MDO Case Study 1 – Application case 3 (Optimization)

This MDO application case is a follow-up of the previous one. In fact, in the previous case, the production and the assembly of ribs and spars and their assembly in the HTP have been considered as fixed. In this MDO application case, also the production quantity of spars, ribs and the main HTP production assembly are included. However, another assumption has been introduced to reduce the size of this MDO problem. Particularly, it is assumed that each single component is produced at one specific production site, without the possibility to split the production quantity in more factories. As in the previous MDO application case, the HTP8 configuration is analyzed. Thus, only the enterprises having the competences in performing the materials, manufacturing and assembly processes of the HTP8 configuration are selected for this MDO application case. Particularly, 13 enterprises participate in the skin production, 13 in the stringers production, 14 in the spars production, 10 in the ribs production, 4 for skin and stringers assembly and 9 for the main HTP assembly. These details are summarized in Table 14.

Component	Number of Enterprises
Skin	13
Stringers	13
Spars	14
Ribs	10
Skin & Stringers Assembly	4
Main Assembly	9

Table 14 MDO Case Studies 1 – Application Case 3: Enterprises involved in the production and assembly of the HTP 8 components

The aim of this MDO problem is to identify a set of non-dominated solutions (Pareto Front points) of supply chain producing a specific HTP configuration, made by selected materials, manufacturing and assembly processes. At the end, the best supply chain option producing the HTP configuration can be identified for the HTP 8. The enumeration is roughly $9 \cdot 10^6$ possible combinations.

III.2.4 MDO Case Studies 2 – Application Case 1 and 2 (DOE)

The last two MDO application cases are simple but representative MDO problems addressing the simultaneous optimization of the manufacturing, supply chain and overall aircraft design domains. Thus, in this case, the HTP configuration is not fixed as in the previous MDO application cases, but all the possible HTP configurations that can be made by aluminum components are considered. At the same time, different supply chains including enterprises able to perform the selected materials, manufacturing and assembly processes are included. The aim of this MDO problem is to identify a set of nondominated solutions (Pareto Front points) of supply chain producing a HTP configuration, made by aluminum, allowing manufacturing processes and enterprises involved to change. Each component has a defined number of manufacturing processes available: 2 manufacturing processes available for skin, stringers and ribs, while only 1 is available for spars. Considering all the constraints among materials and processes, 8 HTP configurations for manufacturing are possible. This information is summarized in Table 15.

Component	Manufacturing processes
Skin	2
Stringers	2
Spars	1
Ribs	2

Table 15 MDO Case Studies 2 – Application Case 1/2: Manufacturing options made by aluminum

The main difference between the MDO Application Case 2.1 and 2.2 relays in the supply chain options analyzed. In the MDO Application Case 2.1, proposed by the industrial partner "F", two different supply chain options are considered:

- Supply Chain option 1: production is performed at OEM4, assembly at OEM1
- Supply Chain option 2: production is performed at OEM4, assembly at OEM5.

So, in both cases, the production site is fixed, while the assembly sites change.

In the MDO Application Case 2.2 instead, proposed by the industrial partner "E", production and assembly are performed at same enterprise:

- Supply Chain option 1: production and assembly at OEM 1.
- Supply Chain option 2: production and assembly at OEM 5.

For MDO Case Study 2.1 linear curves are used for the competence model, for MDO Case Study 2.2 not linear curves are used, instead.

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CHAPTER IV

MDO CASE STUDIES IMPLEMENTATION

In the previous chapter the MDO studies have been addressed and theoretically presented. In this chapter the tools and technologies enabling the automatization of the MDO problems are introduced and explained.

IV.1. Tools and Technologies

The manufacturing, the supply chain and the overall aircraft design domains, theoretically described in the previous chapter are implemented in specific Python tools, showed in figure 13. Similarly, for the value model theory. In particular, the supply chain, the overall aircraft design (OpenAD) and the value model tools have been implemented before this master thesis work [5] [13], while the manufacturing tool is created de novo and integrated with the others.

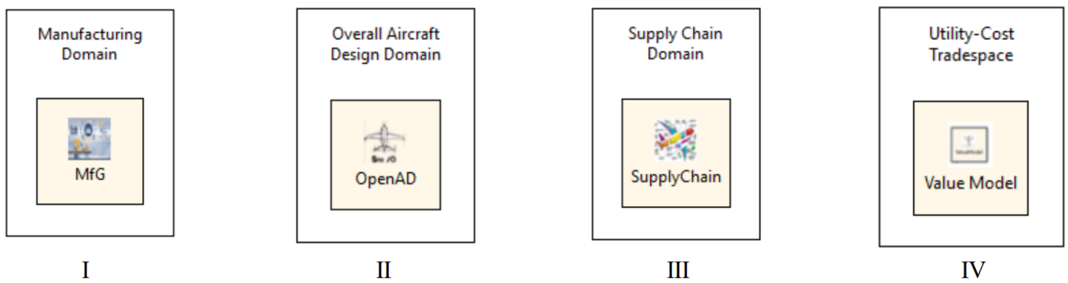

Figure 13 Disciplinary codes as implementation, respectively, of the manufacturing domain (I), overall aircraft design domain (II), supply chain domain (III), and value model (IV) [5]

The exchange of information between the tools is obtained via the Common Parametric Aircraft Configuration Schema (CPACS).

CPACS

CPACS is a data definition for the air transportation system. It is therefore a driver for multi-disciplinary and multi-fidelity design in distributed environments [14]. CPACS describes the characteristics of aircraft, rotorcraft, engines, climate impact, fleets and mission in a structured, hierarchical manner. Not only product but also process information is stored in CPACS, which is fundamental for our purpose. Every tool needs of a CPACS input and returns a CPACS output, which preserves all the previous information and adds the analysis results of its domain. The tools integration is necessary to execute the MDO studies presented in the previous chapter. In fact, the tools need to exchange information to run. For instance, the TF which is an output of the manufacturing tools is needed to OpenAD to perform the aircraft performance estimation. The standard CPACS structure is shown in figure 14.

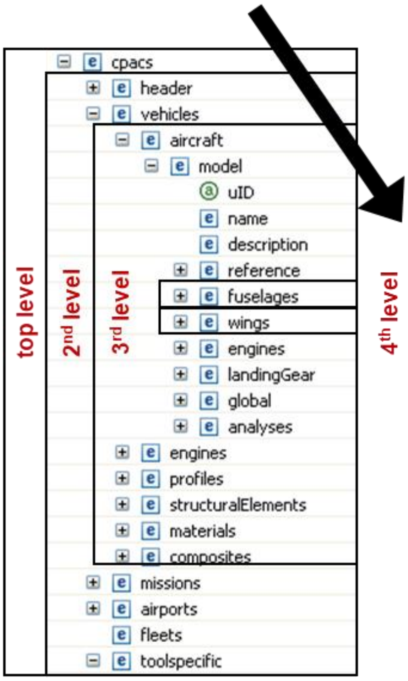

Figure 14 Hierarchical Structure example of the CPACS format

The address <toolspecific> allows users to add new specification about the vehicle and create new custom ones. In fact, now a general hierarchical structure for this type of information does not exist yet, hence in our case new branches have been added to include manufacturing, supply chain and value model results. Figure 15 shows how the new information is implemented in the CPACS

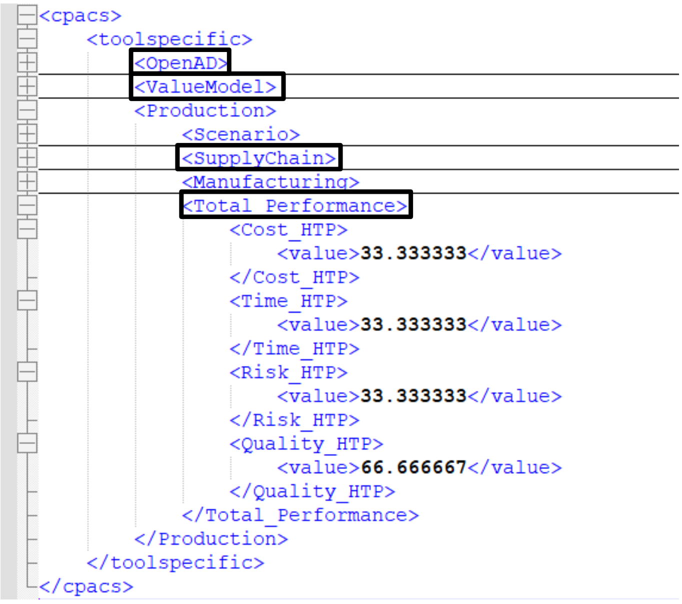

Figure 15 implementation of domains in the CPACS structure.

Through the CPACSization process, in which each tool is able to read a CPACS file, run and store information on a CPACS output, tools automatically exchange information among them. A toolchain, including all the tools, is so built and executed within Remote Component Environment (RCE).

RCE

RCE is a workflow-driven integration environment which allow us to analyze and optimize the complex system which consists in the union of several domain [15]. An example of workflow is reported in figure 16, which represents the MDO Application Case 1.1

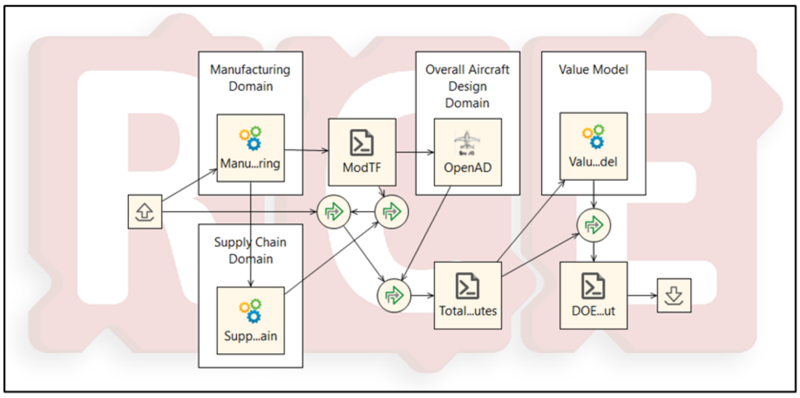

Figure 16 Workflow of MDO Case Study 1 – Application Case 1; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value

The workflow in RCE begins with a CPACS input, which contains all the information about the technical requirement of the vehicle and with specific vectors it indicates the material, manufacturing processes and the company where it is produced. The manufacturing tool considering this information is able to provide:

- *Technology factor*.
- *Cost, Time, Quality, Risk.*

The supply chain tool follows the manufacturing one and gives the fixed and transportation performance. At this point cost, time, risk and quality are combined among manufacturing, fixed and transportation ones. The overall aircraft design (OpenAD) returns the fuel consumption, the aerodynamic performance and the mass of the HTP. It is based on the technical requirement and the technology factor estimated by the manufacturing tool. The value model transforms the attributes in the SAU numbers. The SAU of time, quality, risk and fuel consumption are combined in the value. In this way several configurations may be placed in the Value-Cost tradespace plane and compared (Paragraph II.1, Figure 5). RCE can be also used to perform analysis involving partners spread all over the world. In this case, the remotely exchange of the CPACS is possible via a special component, called BRICS and provided by NLR partners [16].

BRICS

BRICS allows to share file in common online space accessible from all the company involved and it is integrable in RCE in order to automatize the exchange of information.

Figure 17 is a schematic representation of the BRICS method of operating.

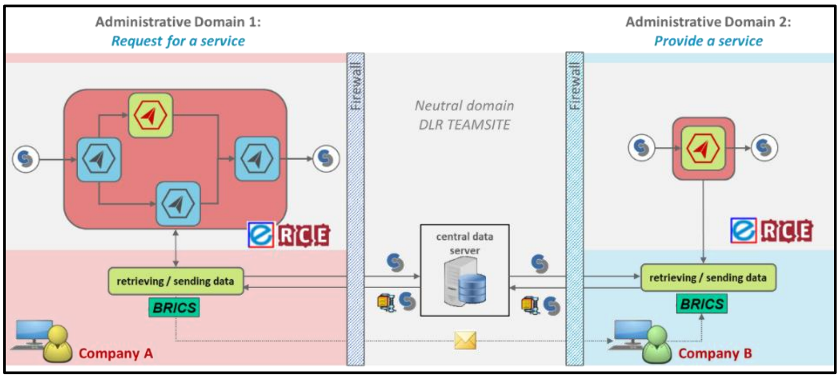

Figure 17 Schematic representation of the BRICS method of operating

Once addressed all the tools and technologies, in the next chapter, instead, the results obtained after the execution of these workflows are presented.

CHAPTER V

MDO CASE STUDIES POST-PROCESS

By leveraging the tools and technologies described in the previous chapter, the MDO case studies presented in paragraph III.2, and summarized in Table 9, are executed and the results are discussed in this chapter. Therefore, in the next paragraphs, the results of the following MDO case studies are respectively presented:

- *MDO Case Study 1 – Application Case 1 (DOE)*
- *MDO Case Study 1 – Application Case 2 (Optimization)*
- *MDO Case Study 1 – Application Case 3 (Optimization)*
- *MDO Case Study 2 – Application Case 1 (DOE)*
- *MDO Case Study 2 – Application Case 2 (DOE)*

V.1. MDO Case Study 1 – Application Case 1 (DOE)

Within the MDO case study 1, the first application case aims at identifying the best supply chain for a specific HTP configuration. Details are described in paragraph II.2.1 and the workflow is reported in figure 18.

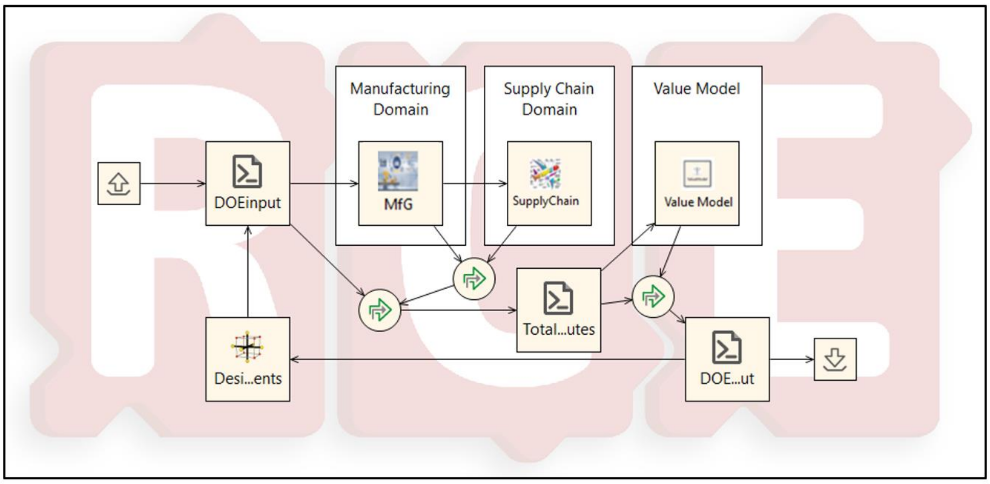

Figure 18 MDO Case Study 1 – Application Case 1: DOE RCE Workflow including manufacturing and supply chain; Design Variables: Production Quantity and Assembly Quantity Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 2, Enterprises involved 6

The value-cost tradespace generated by running the workflow in figure 18 is reported in figure 19. In this figure, with "Database" are marked all the HTP configurations estimated, while with "True Pareto" is identified the Pareto Front (DOE flow execution has been explained in paragraph III.1.B).

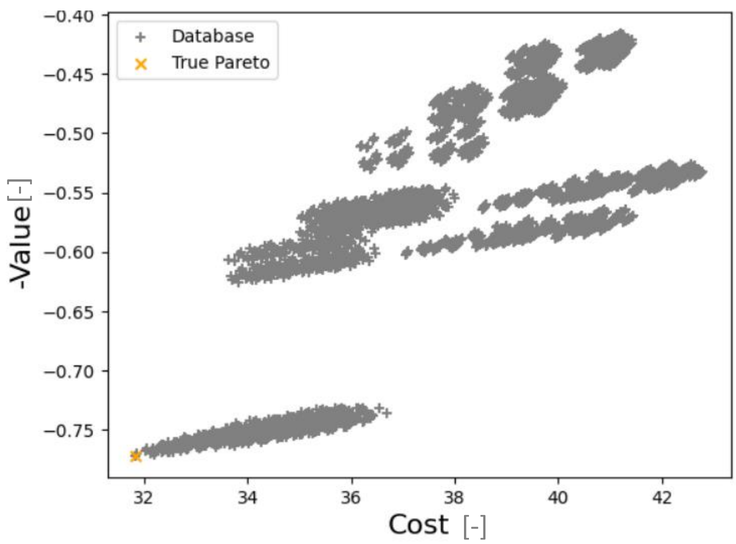

Figure 19 MDO Case Study 1 – Application Case 1: Value-driven Pareto Front; DOE Design Variables: Production Quantity and Assembly Quantity Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 2, Enterprises involved 6

The value-driven pareto front highlights one single point. The enterprises involved in the supply chain characterizing this solution are summarized in Table 16.

Pareto Front Point	Skin		Stringers		Ribs		Spars		Skin&Stringers Assembly		Main Assembly	
	PQ	Enterprise	PQ	Enterprise	PQ	Enterprise	PQ	Enterprise	AQ	Enterprise	AQ	Enterprise
	1	OEM 1	1	OEM 1	0.1	OEM 1	1	Supplier 1	1	OEM 1	1	OEM 1
					0.9	Supplier 1						

Table 16 Enterprises involved in the Supply Chain of MDO Case Study 1 – Application Case 1: 4-objectives optimization characterizing the solution of the Pareto Front; DOE Design Variables: Production Quantity and Assembly Quantity Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 2, Enterprises involved 6

As shown in Table 17, the solution highlighted on the Pareto Front is mainly produced at OEM 1. Only spars and 90 % of ribs are performed at Supplier 1. The contents of the attributes aggregating in the value are reported in Table 17. For quality, the transportation contribution is not considered since it is assumed that quality is not impacted by the means of transportations used (see Chapter II).

Pareto Front Point		Fixed	Manufacturing	Transportation	Total
	Cost [-]	66.3	17.8	11.4	31.8
	Quality [-]	60.0	87.8	-	73.9
	Risk [-]	27.5	22.2	13.1	20.9
	Time [-]	25.7	17.8	20.7	21.4
	Value [-]	0.772			

Table 17 MDO Case Study 1 – Application Case 1: Production Performance and Value results of Pareto Front; DOE Design Variables: Production Quantity and Assembly Quantity Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 2, Enterprises involved 6

The Pareto Front solution is recognized as the optimum one for two reasons. The first one is related to the transportation performance, since in this case only stringers and spars are moved from the supplier site to the OEM. The second one relays in competences of the enterprise involved in the supply chain, which are high.

V.2. MDO Case Study 1 – Application Case 2 (Optimization)

As in the previous case, the secondo MDO application case also addresses the two domains or MfG and SC. However, it´s remotely executed through BRICS and it considers only skin and stringers and their assembly, while spars, ribs and main HTP assembly is fixed. Also in this case, the aim is to identify the best supply chain option producing a specific HTP configuration, which the HTP8 in this case. The optimization algorithm is performed by ONERA, while the values for the objective faction by DLR. Two runs of optimization have been performed: the first run uses the clustering of solutions, while the second one does not use the clustering process (further information about the clustering processes in paragraph III.1.B). To run optimization remotely the flow in figure 19 is executed in RCE.

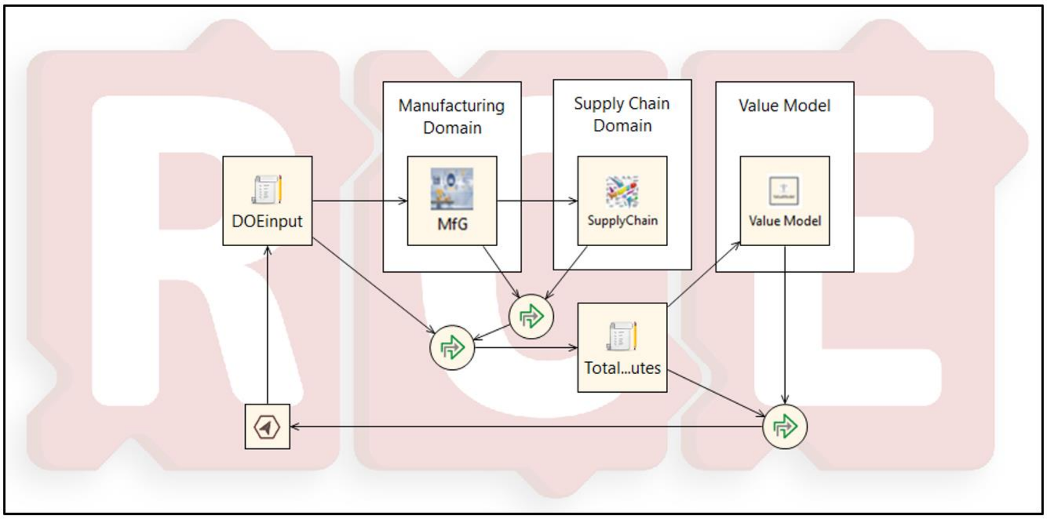

Figure 20 MDO Case Study 1 – Application Case 2: Workflow; Design Variables are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

V.2.1 *Optimization with Clustering*

Before starting the optimization with clustering process, a DOE is run to initialize the process. This DOE, including 81 point is shown in figure 21 provided by ONERA.

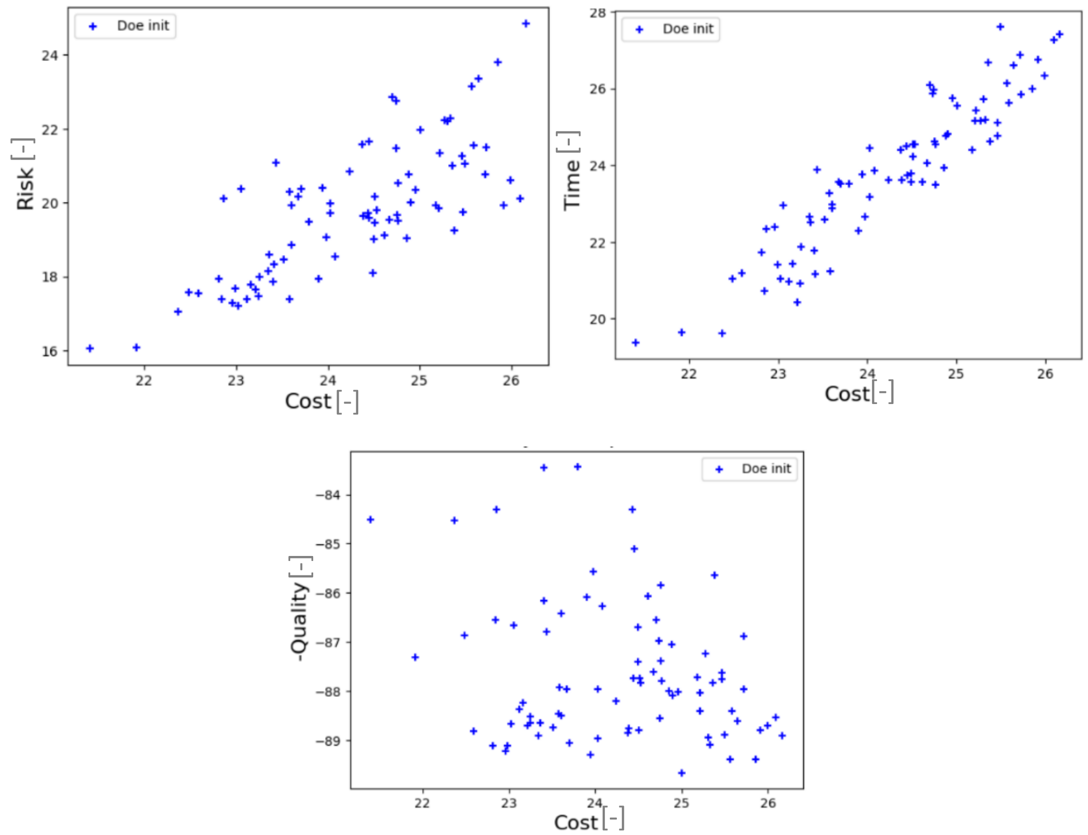

Figure 21 MDO Case Study 1 – Application Case 2: Attributes vs Cost tradespace of 81 initial DOE; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14; Figure provided by ONERA

Once assessed the initial DOE, the first run of clustered optimization, based on 202 points, the predicted Pareto Front is found. Also, in this case, the details of the 15 points of the Pareto Front in terms of enterprises involved in the supply chain are summarized in Table 18.

ID	Skin&Stringers Assembly	Skin		Stringer
	AQ 1	PQ 0.5	PQ 0.5	PQ 1
1	OEM 1	OEM 5	Supplier 6	Supplier 6
2	OEM 1	OEM 3	Supplier 6	OEM 3
3	OEM 1	OEM 3	OEM 3	Supplier 6
4	OEM 1	Supplier 6	Supplier 6	Supplier 6
5	OEM 1	OEM 3	OEM 3	Supplier 7
6	OEM 1	OEM 3	OEM 3	OEM 3
7	OEM 1	OEM 3	OEM 3	Sub-Supplier 9
8	OEM 1	Sub-Supplier 3	Supplier 6	Supplier 6
9	OEM 1	OEM 1	OEM 3	Sub-Supplier 9
10	OEM 1	Supplier 6	OEM 3	Sub-Supplier 9
11	OEM 1	OEM 3	Supplier 6	Supplier 6
12	OEM 1	OEM 3	OEM 3	Supplier 5
13	OEM 1	OEM 3	OEM 3	Sub-Supplier 8
14	OEM 1	Supplier 6	Sub-Supplier 3	Supplier 6
15	OEM 1	Supplier 6	OEM 3	OEM 3

Table 18 MDO Case Study 1 – Application Case 2: Supply chain options for predicted Pareto Front points (First run of clustered optimization); Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

Results are shown in figure 22 provided by ONERA and they categorized by colors in the first optimization (grey, 202 points), Pareto Front on current iterations (yellow), Predicted Pareto Front (red, 15 points) and the initial DOE (blue, 81 points).

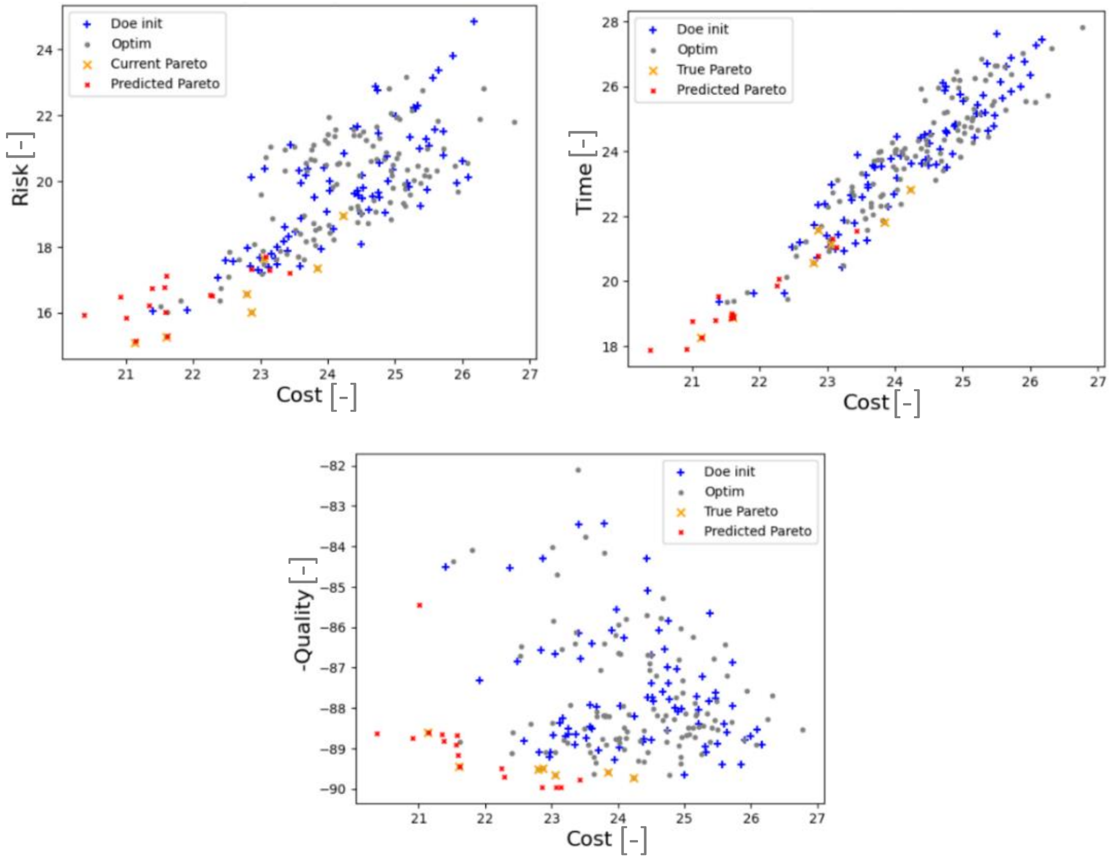

Figure 22 MDO Case Study 1 – Application Case 2: Attributes vs Cost tradespace with initial DOE, optimization points, Pareto Front on current iterations, Predicted Pareto Front; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14; Figure provided by ONERA

After this run, a second one has been launched by increasing the number of points analyzed in the DOE and first optimization run to understand whether predicted points were coherent with the model. Even if the production performance of predicted Pareto Front is strictly closed to the estimated one, more points are required to the optimization algorithms to produce even more accurate results. Hence, a new optimization has been run, increasing the number of evaluation points to 303, thus adding101 points. In figure 23, provided by ONERA, the estimated points are reported. They are categorized by colors in the first optimization (yellow, 202 points), second optimization (red, 303 points) and the initial DOE (black, 81 points).

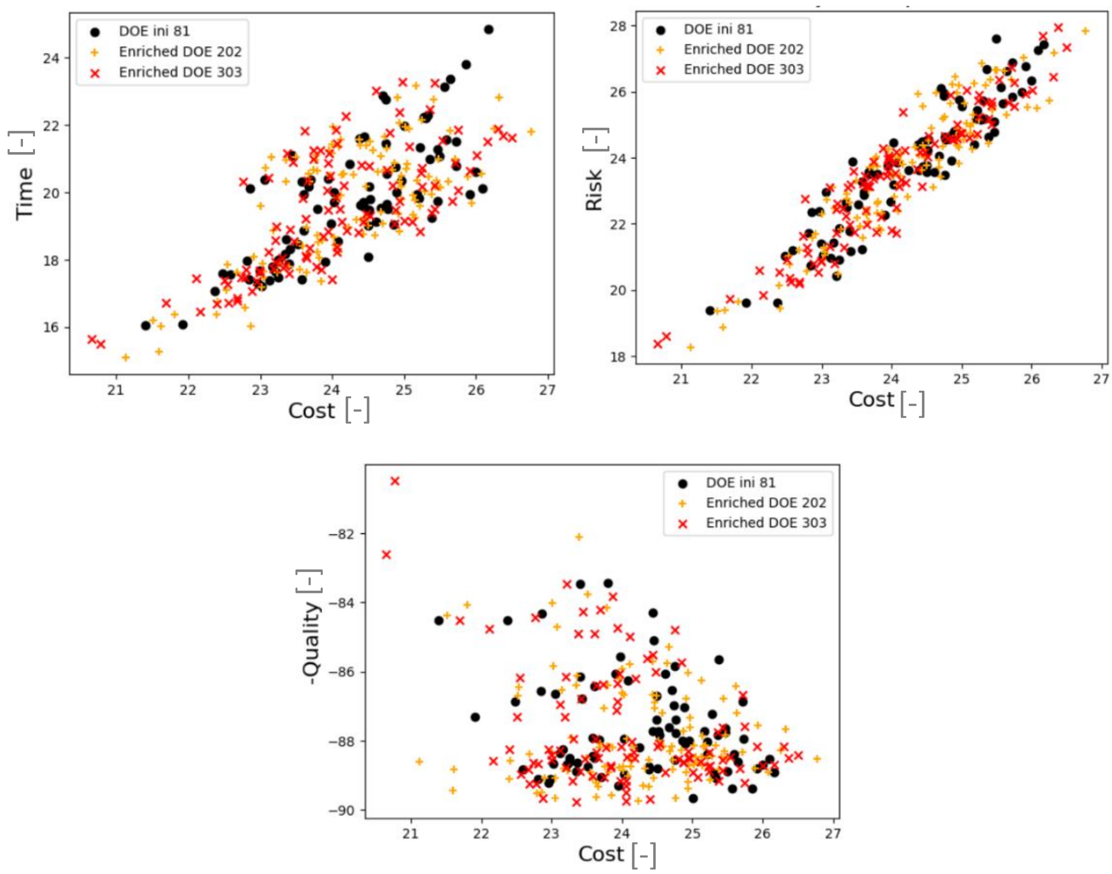

Figure 23 MDO Case Study 1 – Application Case 2: Attributes vs Cost for initial DOE, first and second run of clustered optimization; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14; Figure provided by ONERA

The second run of the optimization with clustering returns 13 points, 10 of them, among the first and the second run, have the same supply chain specification. It means that the first run of optimization, even with fewer iterations, returns optimum results. In table 19 the 13 Pareto Front points of the second run are reported.

ID	Skin&Stringers Assembly	Skin		Stringer
	AQ 1	PQ 0.5	PQ 0.5	PQ 1
1	OEM 1	Sub-Supplier 3	Supplier 6	Supplier 6
2	OEM 1	Supplier 6	OEM 3	Supplier 6
3	OEM 1	OEM 3	OEM 3	Supplier 6
4	OEM 1	Supplier 6	Supplier 6	Supplier 6
5	OEM 1	OEM 3	OEM 3	Supplier 7
6	OEM 1	OEM 3	OEM 3	Sub-Supplier 9
7	OEM 1	OEM 3	Supplier 6	Supplier 6
8	OEM 1	OEM 3	Supplier 6	OEM 3
9	OEM 1	Supplier 6	OEM 3	OEM 3
10	OEM 1	OEM 3	OEM 3	OEM 3
11	OEM 1	OEM 3	OEM 3	OEM 1
12	OEM 1	Supplier 6	Supplier 6	OEM 1
13	OEM 1	OEM 3	OEM 3	Sub-Supplier 8

Table 19 MDO Case Study 1 – Application Case 2: Supply chain options for Predicted Pareto Front points (Second run of clustered optimization); Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

In Table 20 the output performance results are reported and in figure 24 the solutions are placed in the value-cost tradespace.

ID	Time [-]	Quality [-]	Risk [-]	Cost [-]	Value [-]
1	17.3	90.0	21.2	23.1	0.838
2	16.0	89.7	19.9	22.2	0.846
3	15.3	89.4	18.9	21.6	0.851
4	16.0	90.0	20.4	22.7	0.845
5	15.1	88.6	18.3	21.1	0.851
6	14.8	84.7	17.6	20.3	0.841
7	16.0	89.7	19.9	22.2	0.846
8	15.5	89.2	18.5	21.5	0.851
9	15.5	89.2	18.5	21.5	0.851
10	14.6	88.9	17.5	20.7	0.856
11	15.1	89.0	20.1	21.5	0.846
12	16.0	89.5	21.6	22.9	0.840
13	16.1	89.2	19.4	21.3	0.845

Table 20 MDO Case Study 1 – Application Case 2: Predicted Pareto Front output results (second run of clustered optimization) ; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

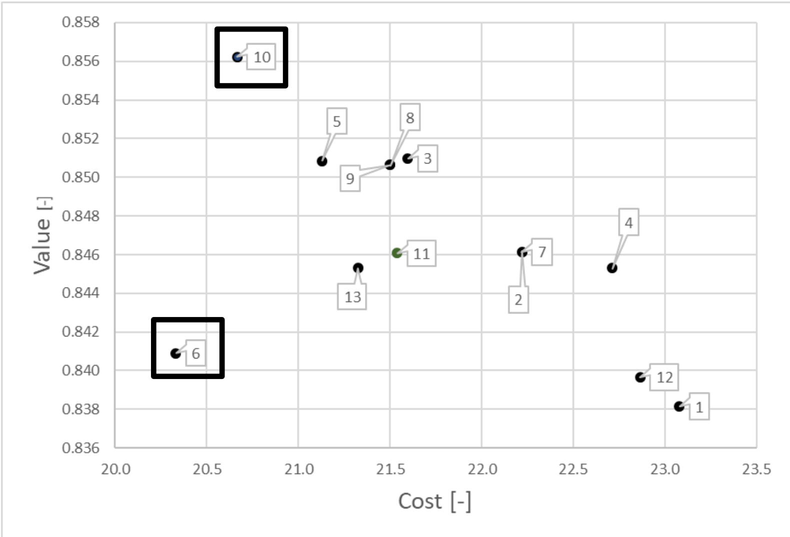

Figure 24 MDO Case Study 1 – Application Case 2: Predicted Pareto Front value-cost tradespace, value-cost Pareto Front points are evidenced; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

The value-cost Pareto Front contains two elements: solution 6 and solution 10, which are reported in Table 21 with detailed performance.

	Time [-]		Quality [-]		Risk [-]		Cost [-]		Value [-]	
Solutions	**10**	**6**	**10**	**6**	**10**	**6**	**10**	**6**	**10**	**6**
Total	14.6	14.8	88.9	84.7	17.5	17.6	20.7	20.3	0.856	0.841
Manufacturing	22.2	22.4	99.0	98.9	33.5	34.7	39.0	39.7	-	-
Fixed	21.5	18.5	78.9	70.6	18.9	16.4	22.9	20.0	-	-
Transport	0.1	3.5	-	-	0.0	1.7	0.2	1.3	-	-

Table 21 MDO Case Study 1 – Application Case 2: Detailed performance comparison for points of the value-cost Pareto Front; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

The manufacturing and transportation performance are better in solution 10 because of manufacturing competences and the distance of the enterprises which perform components. While the skin is for both HTPs produced at OEM 3, the stringers are produced at OEM 3 for configuration 10 and at Sub-Supplier 9 for configuration 6 (Table 19). The fixed cost has the opposite behavior, it is lower for the HTP solution 6 than solution 10, because labor cost of Sub-Supplier 9 is lower than OEM 3, but fixed quality, time and risk are better in solution 10 at OEM 3. A summary related to the comparison of the two solutions is reported in figure 25.

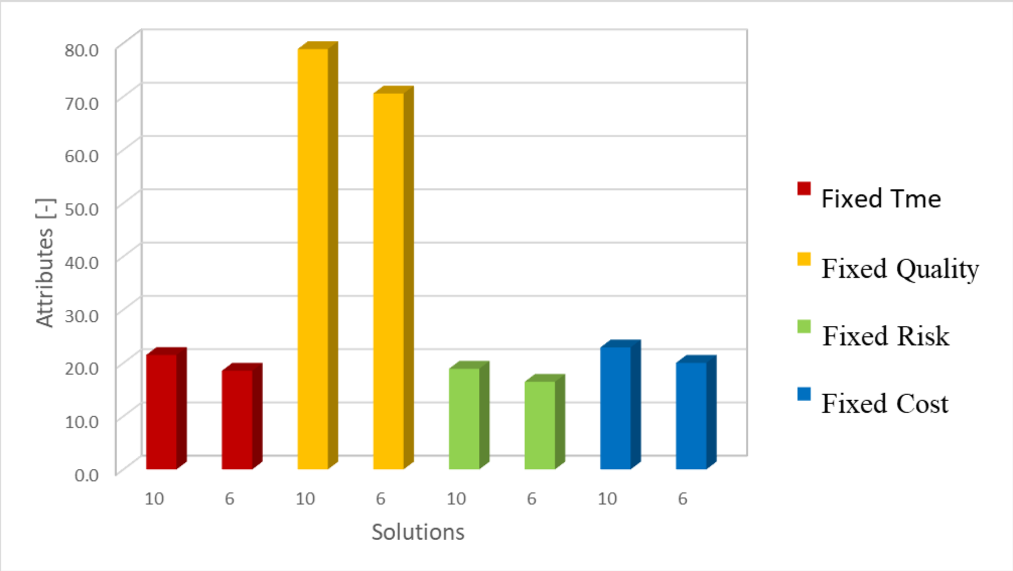

Figure 25 MDO Case Study 1 – Application Case 2: Histogram comparing points of value-cost Pareto Front; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

Comparing the results of the first and second run of the unclustered optimization, increasing the number of points the production performance of the predicted Pareto Front are closer to the value directly evaluated by the workflow, but the value-cost Pareto Front has been already detected at the first run of clustered optimization. It means that doing more iteration, which means increasing time, let us to predict better the value of production performance, but the best solutions are returned even with 202 points (First run). This assumption is verified increasing the number of iterations over 303 (Second run) and the Pareto Front remains stable.

V.2.2 *Optimization without Clustering*

The unclustered optimization has been done to verify if the approach without clustering might have been effective in order to find the Pareto Front of multi-dimensional problem, reducing calculus time. The first run has the same points (202 iterations) of the clustered optimization, but the time is saved over 60%. The Pareto Front of optimization without clustering is a subset of the clustered one. It has 10 points, and 9 of them have the same supply chains found in the clustered optimization. The figure 26 provided by ONERA compares the Pareto Front resulting from the first run of clustered optimization (yellow), second run of clustered optimization (red) and the first run of unclustered optimization (blue).

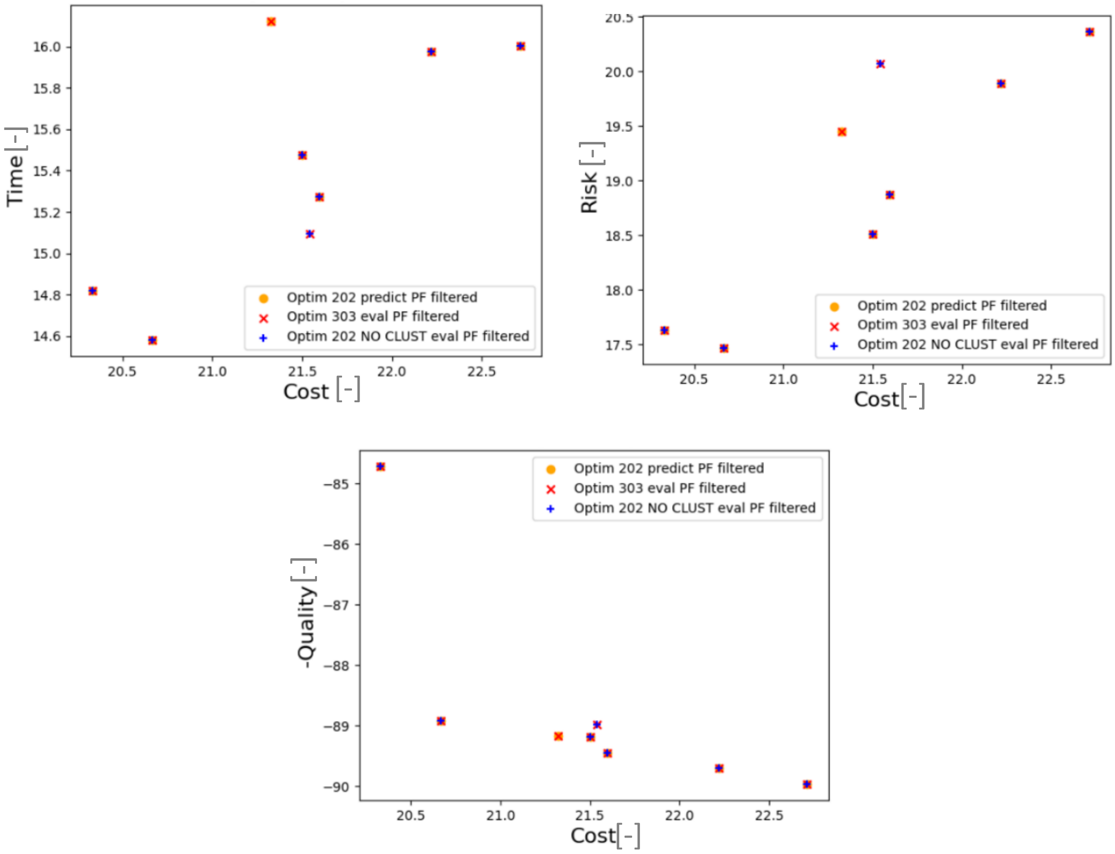

Figure 26 MDO Case Study 1 – Application Case 2: Comparison between the Predicted Pareto Front of clustered and uncluttered optimization; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14; Figure provided by ONERA

Supply chain option specifications are shown in Table 22.

ID	Skin&Stringers Assembly	Skin		Stringer
	AQ 1	PQ 0.5	PQ 0.5	PQ 1
1	OEM 1	OEM 3	OEM 3	Supplier 6
2	OEM 1	OEM 5	Supplier 6	Supplier 6
3	OEM 1	Supplier 6	Supplier 6	Supplier 6
4	OEM 1	OEM 3	OEM 3	Sub-Supplier 9
5	OEM 1	Sub-Supplier 9	OEM 3	Sub-Supplier 9
6	OEM 1	OEM 3	Supplier 6	Supplier 6
7	OEM 1	Supplier 6	OEM 3	Supplier 6
8	OEM 1	OEM 3	Supplier 6	OEM 3
9	OEM 1	OEM 3	OEM 3	OEM 1
10	OEM 1	OEM 3	OEM 3	OEM 3

Table 22 MDO Case Study 1 – Application Case 3: Supply chain options for predicted Pareto Front points (first run of unclustered optimization) ; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

The value-cost Pareto Front in figure 27 has the same configurations of the case with clustering, so we are able to get the same optimum solutions even with a faster method. The production performance of Predicted Pareto Front is reported in Table 23.

ID	Time [-]	Quality [-]	Risk [-]	Cost [-]	Value [-]
1	15.3	89.4	18.9	21.6	0.851
2	17.3	89.8	21.6	23.4	0.836
3	16.0	90.0	20.4	22.7	0.845
4	14.8	84.7	17.6	20.3	0.841
5	15.6	82.6	18.4	20.7	0.829
6	16.0	89.7	19.9	22.2	0.846
7	16.0	89.7	19.9	22.2	0.846
8	15.5	89.2	18.5	21.5	0.851
9	15.1	89.0	20.1	21.5	0.846
10	14.6	88.9	17.5	20.7	0.856

Table 23 MDO Case Study 1 – Application Case 2: Predicted Pareto Front output results (first run of clustered optimization) ; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

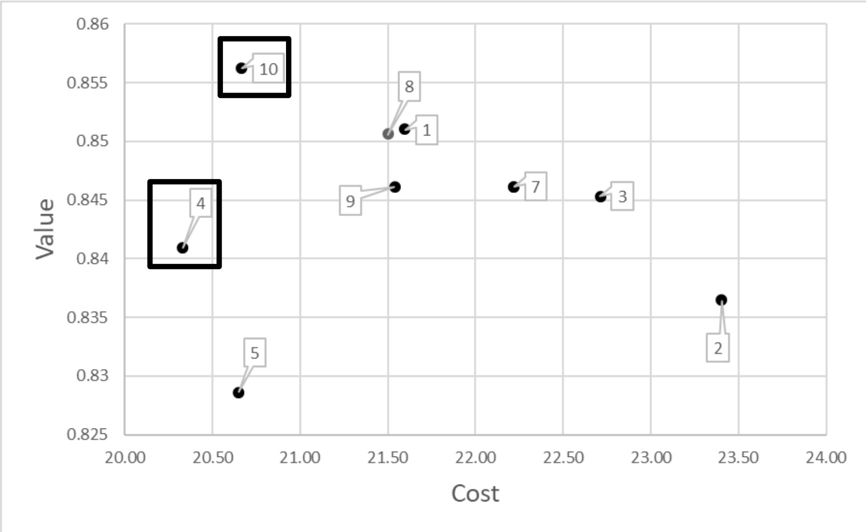

Figure 27 MDO Case Study 1 – Application Case 2: Predicted Pareto Front value-cost tradespace (first run of unclustered optimization), value-cost Pareto Front points are evidenced; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

The next step is to verify if increasing the number of iterations, the Pareto Front solutions are stable and how the reliability of the predicted performance changes.

The Predicted Pareto Front of the second run for the unclustered optimization has 11 points, of which 7 have the same supply chain option of clustered optimization. Supply chain option specifications are shown in Table 24.

ID	Skin&Stringers Assembly	Skin		Stringer
	AQ 1	PQ 0.5	PQ 0.5	PQ 1
1	OEM 1	OEM 3	Supplier 6	Supplier 6
2	OEM 1	OEM 3	OEM 3	Sub-Supplier 8
3	OEM 1	OEM 3	OEM 3	Sub-Supplier 9
4	OEM 1	OEM 3	OEM 3	Supplier 6
5	OEM 1	Supplier 6	Sub-Supplier 3	Supplier 6
6	OEM 1	Sub-Supplier 3	Sub-Supplier 3	Supplier 6
7	OEM 1	Supplier 6	Supplier 6	Supplier 6
8	OEM 1	OEM 3	OEM 3	OEM 3
9	OEM 1	OEM 3	Supplier 6	OEM 3
10	OEM 1	Supplier 6	OEM 3	Supplier 6
11	OEM 1	Sub-Supplier 3	Supplier 6	Supplier 6

Table 24 MDO Case Study 1 – Application Case 2: Supply chain options for Predicted Pareto Front points (Second run) ; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

As in the optimization without clustering, even in this case the predicted performance is closer to the workflow results increasing the number of iterations, but the optimal solutions of Pareto Front are as expected (Table 25 and Figure 28).

ID	Time [-]	Quality [-]	Risk [-]	Cost [-]	Value [-]
1	16.0	89.7	19.9	22.2	0.846
2	16.1	89.2	19.4	21.3	0.845
3	14.8	84.7	17.6	20.3	0.841
4	15.3	89.4	18.9	21.6	0.851
5	17.3	90.0	21.2	23.1	0.838
6	17.0	90.0	20.8	23.1	0.841
7	16.0	90.0	20.4	22.7	0.845
8	14.6	88.9	17.5	20.7	0.856
9	15.5	89.2	18.5	21.5	0.851
10	16.0	89.7	19.9	22.2	0.846
11	17.3	90.0	21.2	23.1	0.838

Table 25 MDO Case Study 1 – Application Case 2: Predicted Pareto Front value-cost tradespace (second run of unclustered optimization); Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

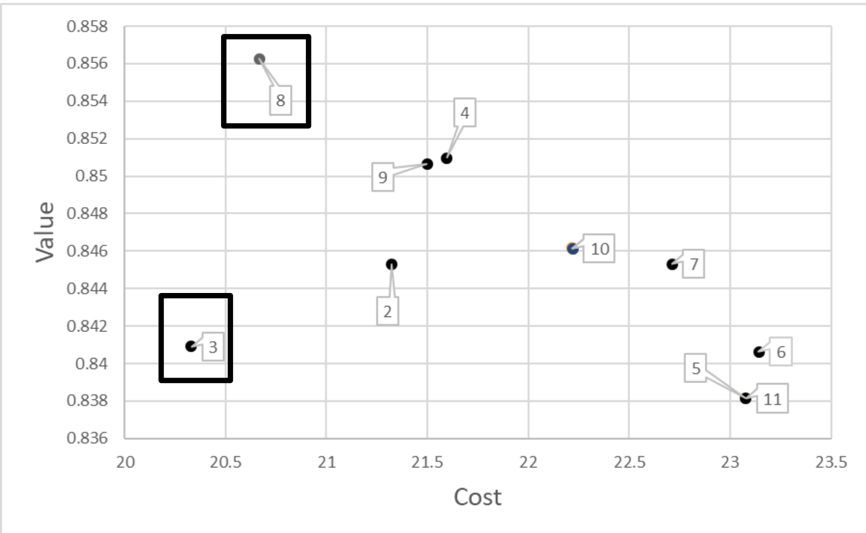

Figure 28 MDO Case Study 1 – Application Case 2: Predicted Pareto Front value-cost tradespace (second run of unclustered optimization), value-cost Pareto Front points are evidenced; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 14

V.2.3 *Conclusions of MDO Case Study 1 – Application Case 2*

Four optimizations have been run. Two optimizations include clustering, while the others are without. Comparing all the optimization runs what it has been noticed is that doing more iterations helps us to predict better the value of the performance, but the optimum solutions (Supply Chain choices) are returned even with 202 points. In the specific case, the use of clustering results useless compared to the dimension of the problem, increasing the computation time, without a return in term of accuracy of predicted performance or for finding new Pareto Front points.

V.3. MDO Case Study 1 – Application Case 3 (Optimization)

As in the previous case, the secondo MDO application case also addresses the two domains of MfG and SC. However, it extends the number of components, including spars, ribs and main assembly. The aim is to identify the best supply chain for a specific HTP configuration, the HTP 8 (Table 1). To run optimization remotely the workflow in figure 29 is executed.

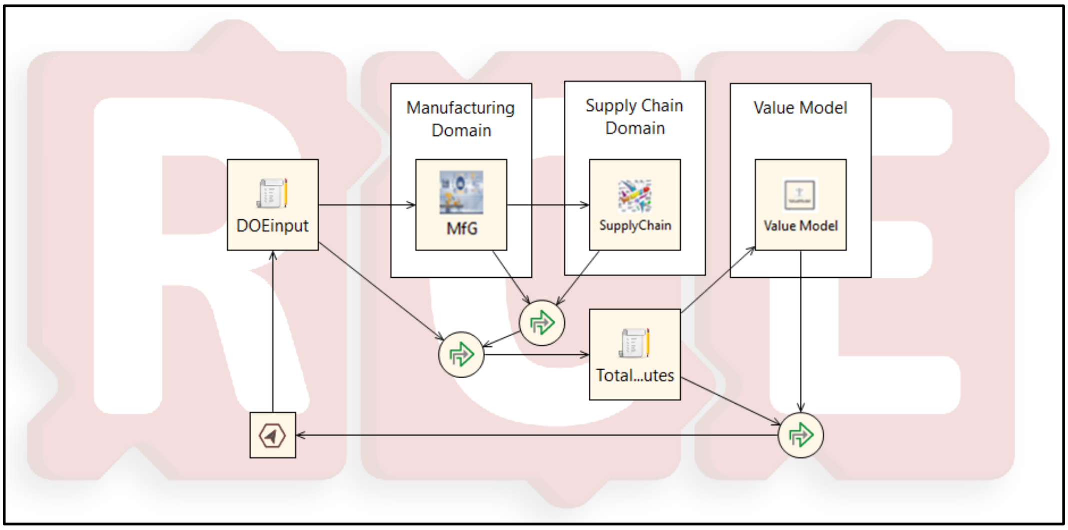

Figure 29 MDO Case Study 1 – Application Case 3: Workflow; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 21

As the MDO Case Study 1 – Application Case 2, the aim of this MDO application case is to identify a set of nondominated solutions (Pareto Front points) of supply chain producing a specific HTP configuration, made by selected materials, manufacturing and assembly processes. This MDO application case is run without clustering because of the results of MDO Case Study 1 – Application Case 2 showing that the same results can be achieved in less time. The optimization needs of an initial DOE of 250 points and the following optimization performs 160 further iterations. In figure 30, provided by ONERA, the results points are categorized by colors in the initial DOE (orange, 250 points) and optimization (blue, 160 points)

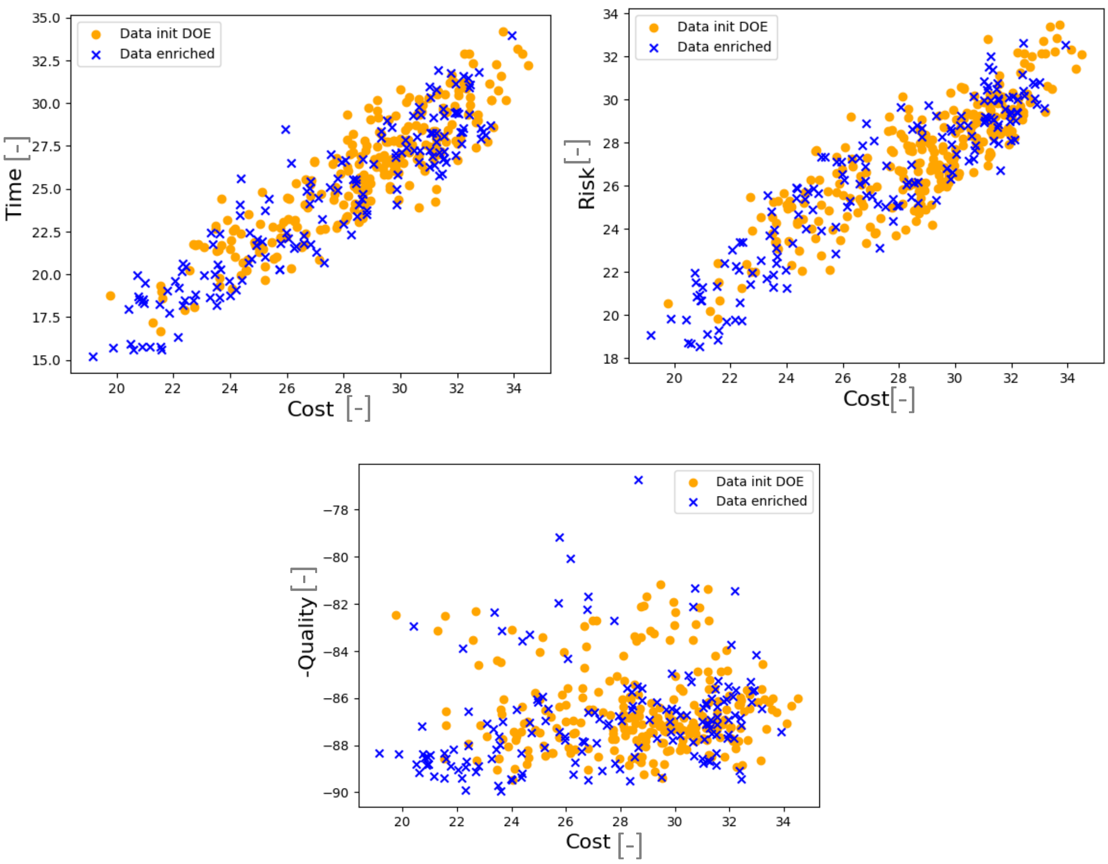

Figure 30 MDO Case Study 1 – Application Case 3: Attributes vs Cost of Initial 250 CPACS DOE + 160 iterations; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 21; Figure provided by ONERA

Figure 31 shows the Predicted Pareto Front compared to the iterations submitted to the workflow. They are categorized by colors in the initial DOE + optimization (orange, 410 points), Pareto Front of current iterations (blue), Predicted Pareto Front (black, 30 points).

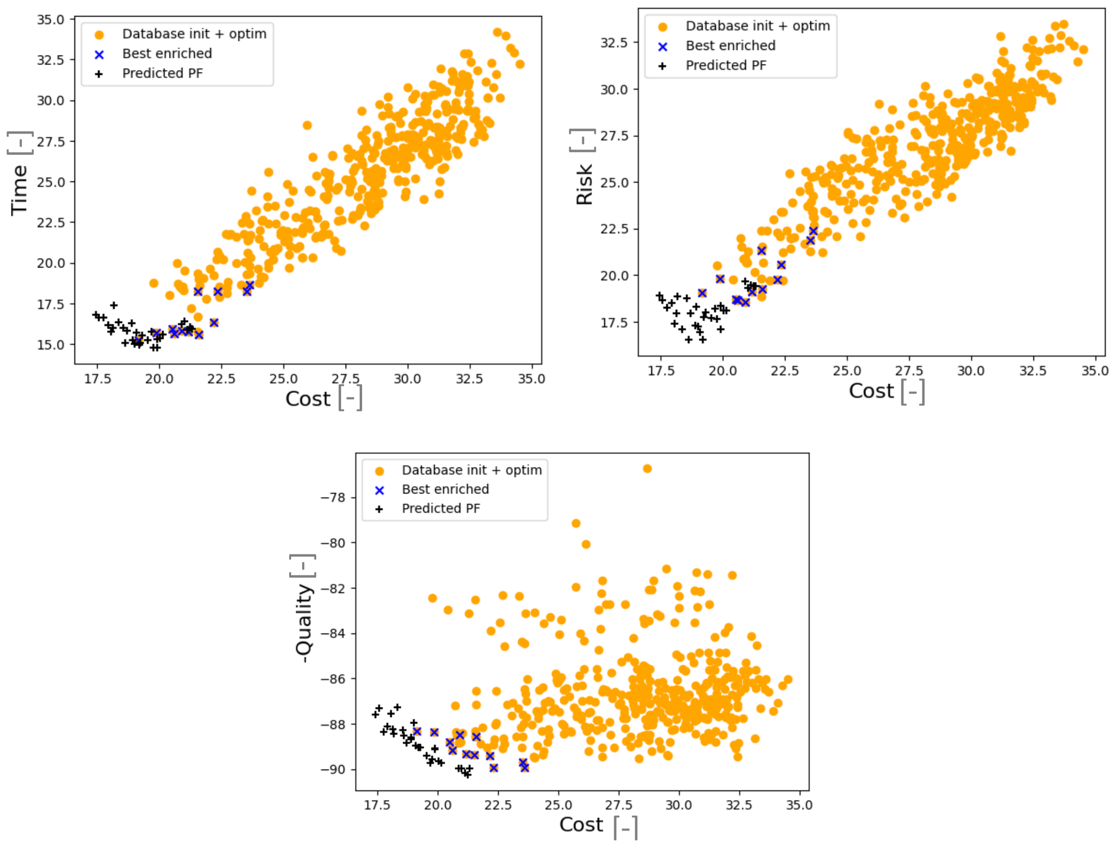

Figure 31 MDO Case Study 1 – Application Case 3: Attributes vs Cost of Initial DOE, optimization and Predicted Pareto Front; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 21; Figure provided by ONERA

The remote optimization returns 30 Predicted Pareto Front points. They are submitted to the workflow which updates the production performance of the Predicted Pareto Front. After the Predicted Pareto Front filtering process (Figure 12, paragraph II.1) only 7 are confirmed as Pareto Front points. Table 26 and 27 shows the supply chain configurations and the output results, respectively.

ID	Skin&Stringers Assembly	Main Assembly	Skin	Stringer	Spar	Rib	
	AQ 1	AQ 1	PQ 1	PQ 1	PQ 1	PQ 0.3	PQ 0.7
1	OEM 1	OEM 1	OEM 3	OEM 3	OEM 1	OEM 3	Sub-Supplier 5
2	OEM 1	OEM 3	OEM 3	OEM 3	OEM 1	OEM 3	Sub-Supplier 5
3	OEM 1	OEM 2	OEM 3	OEM 3	OEM 1	Sub-Supplier 9	Supplier 3
4	OEM 1	OEM 3	OEM 3	OEM 3	OEM 1	Supplier 5	Supplier 2
5	OEM 1	OEM 3	OEM 3	Sub-Supplier 9	OEM 1	OEM 3	Sub-Supplier 5
6	OEM 1	OEM 2	OEM 3	Sub-Supplier 9	OEM 1	OEM 3	Supplier 3
7	OEM 1	OEM 2	OEM 3	Sub-Supplier 9	OEM 1	OEM 3	Supplier 2

Table 26 MDO Case Study 1 – Application Case 3: Supply chain options for Pareto Front points; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 21

ID	Time [-]	Quality [-]	Risk [-]	Cost [-]	Value [-]
1	14.0	89.1	15.6	19.0	0.865
2	14.2	88.5	15.5	18.4	0.863
3	15.4	87.3	16.0	18.1	0.853
4	15.7	87.6	17.1	18.1	0.849
5	14.2	84.3	15.7	17.9	0.848
6	14.7	84.3	15.8	17.5	0.846
7	15.2	83.6	16.5	17.2	0.840

Table 27 MDO Case Study 1 – Application Case 3: Pareto Front performance results; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 21

In figure 32 the results are placed in the value-cost tradespace.

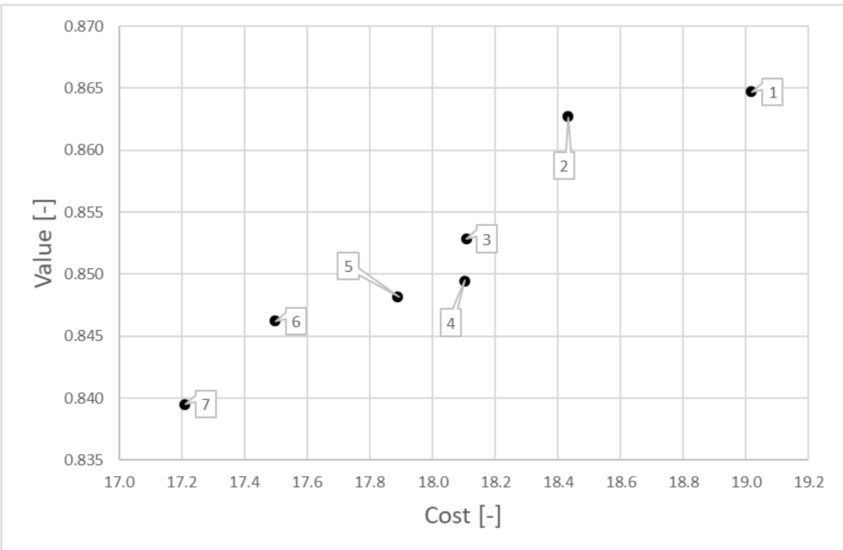

Figure 32 MDO Case Study 1 – Application Case 3: Pareto Front value-cost tradespace; Design Variables of the optimization are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk and maximize quality, value; HTP configuration 8, Enterprises involved 21

The solution 1, which has the highest value, has the highest manufacturing competences of enterprises involved in the production, while the solution 2, even whether it has the same production site of solution 1, it is assembled in two different enterprises and the transportation cost influenced the results.

The worst solution in value is the configuration 7, which even has the lowest cost, because of the selection of the enterprises involved, which has high manufacturing competence anyway, but the enterprises involved in the supply chain of the configuration 7 are closer (lower transportation cost) and they have cheaper maintenance cost (lower fixed cost) than solution 1.

V.4. MDO Case Study 2 – Application Case 1 (DOE)

In contrast with previous case, the MDO Study Case - Application Case 1 addresses the three domains of MfG, SC and OAD. The MDO has been run by the workflow showed in figure 33 and the DOE is executed.

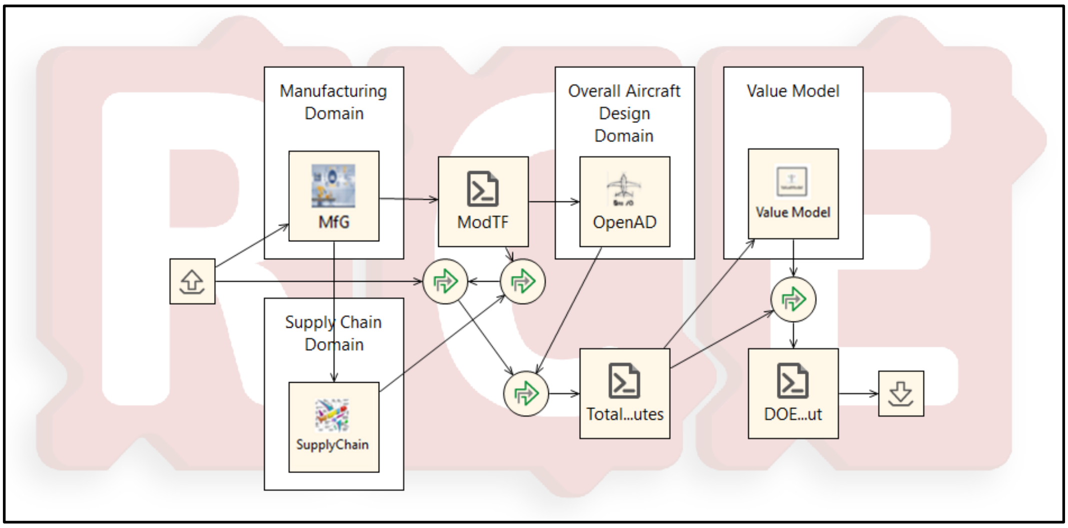

Figure 33 MDO Case Study 2 – Application Case 1: workflow; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value

The aim of this MDO problem is to identify a set of nondominated solutions (Pareto Front points) of supply chain producing a specific HTP configuration, made by aluminum, allowing manufacturing processes and enterprises involved to change. The MDO Application Case 2.1 considers 8 cases of manufacturing processes combination of aluminum among components and 2 supply chain options (SC Options). The results are reported in Table 28 and the value-cost tradespace in figure 34.

		Time [-]		Quality [-]		Risk [-]		Cost [-]		Fuel Consumption [kg]	Value [-]	
	SC Options	**SC 1**	**SC 2**	**SC 1**	**SC 2**	**SC 1**	**SC 2**	**SC 1**	**SC 2**		**SC 1**	**SC 2**
Manufacturing cases	**HTP case 1**	14.4	21.5	89.4	89.2	17.7	24.6	21.0	25.9	4802	0.668	0.633
	HTP case 2	14.4	19.5	89.4	89.4	17.7	23.4	21.0	24.7	4807	0.668	0.640
	HTP case 3	15.1	22.6	89.2	89.0	20.4	27.4	22.0	27.0	4811	0.658	0.621
	HTP case 4	15.1	20.6	89.2	89.1	20.4	26.3	22.0	25.9	4816	0.657	0.629
	HTP case 5	17.6	22.7	89.2	89.1	19.7	26.7	23.0	27.6	4825	0.652	0.621
	HTP case 6	17.6	20.7	89.2	89.3	19.7	25.5	23.0	26.5	4830	0.651	0.629
	HTP case 7	18.3	23.8	88.9	88.8	22.4	29.6	24.1	28.8	4834	0.641	0.609
	HTP case 8	18.3	21.9	88.9	89.0	22.4	28.4	24.1	27.6	4839	0.641	0.617

Table 28 MDO Case Study 2 – Application Case 1: performance results; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value; 2 supply chain options

The production performance is not influenced by production site, but by OAD factors, which change among different manufacturing production. Hence, for any HTP cases C_{D_0}, mass and fuel consumption in cruise are the same for both supply chain options.

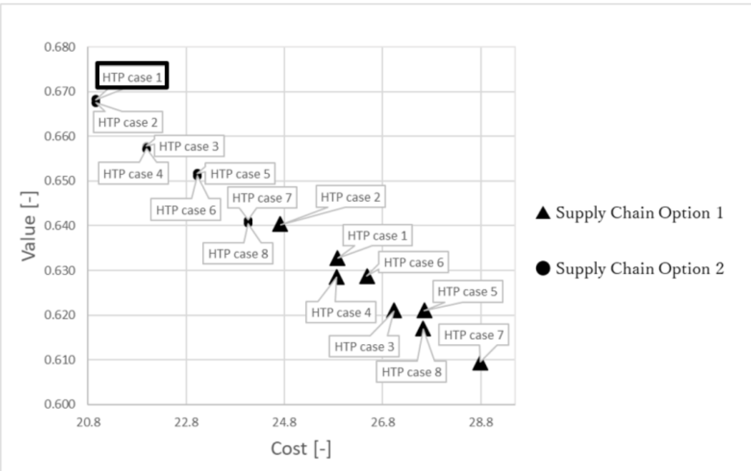

Figure 34 MDO Case Study 2 – Application Case 1: Value-Cost tradespace, value-cost Pareto Front evidenced; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value; 2 supply chain options

The Pareto front, reported in figure 34, has one element: The HTP case 1 with SC option 1 (Produced and assembled in OEM 1).

Two post-processes have been done:

- *Comparison among manufacturing HTP case 1 and 2 for SC option 1.*
- *Comparison among SC option 1 and 2 for manufacturing HTP case 1.*

V.4.1 *Comparison among manufacturing HTP case 1 and 2 for SC Option 1*

In this paragraph HTP case 1 and 2 for SC option 1 are compered. They are evidenced in figure 35.

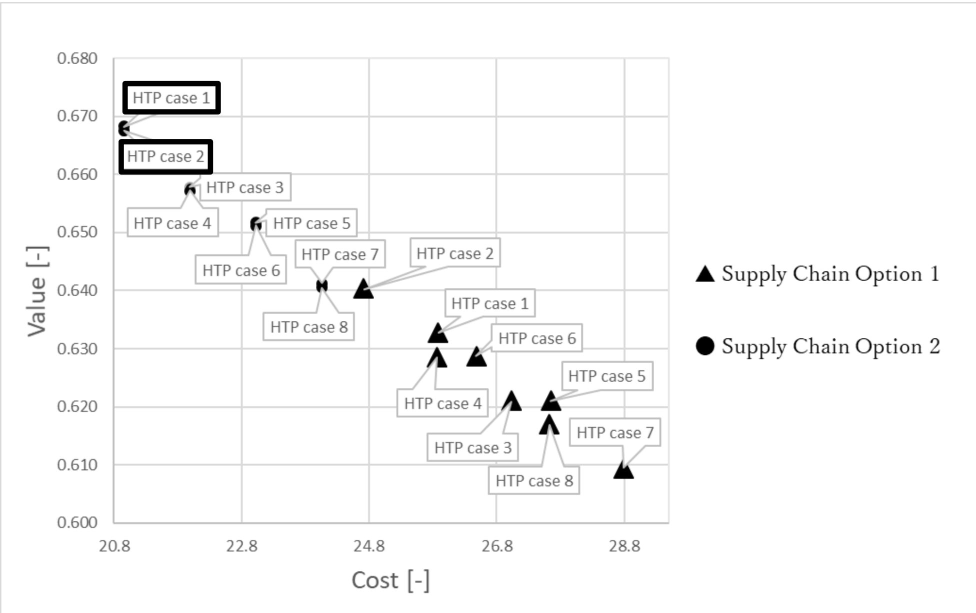

Figure 35 MDO Case Study 2 – Application Case 1: Value-Cost tradespace, evidencing the solutions considered in the current results analysis; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value; 2 supply chain options

First, the reason HTP 1 and 2 are the best configurations for SC option 1 has not to be sought in transportation because in any HTPs the production and assembly is in OEM 1, but the reason is in the manufacturing competence of the enterprises involved in each manufacturing process. HTP case 1 and 2 have the highest manufacturing competence and they have the same one. In fact, looking at Table 28, this 2 HTPs have the same Cost, Time, Risk and Quality, but the fuel consumption is different. The OAD factors for the manufacturing processes of HTP case 1 and HTP case 2 have different values, so they differently impact the vehicle performance. For HTP case 2 the mass has higher OAD, while for the aerodynamic shape the OAD is higher in the HTP case 1. It means that the HTP case 2 will be lighter, but the HTP case 1 will have less drag. The fuel consumption combines both and the result is better for HTP case 1 than HTP case 2. Hence, the value is higher for HTP case 1 because it considers time, risk, quality and fuel consumption, while time, risk and quality are equal, the fuel consumption is lower in HTP case 1.

V.4.2 *Comparison among SC Option 1 and 2 for manufacturing HTP case 1*

The comparison is among SC option 1 and 2, fixing the manufacturing processes at HTP case 1. The compared solutions in the current results analysis are evidenced in figure 36.

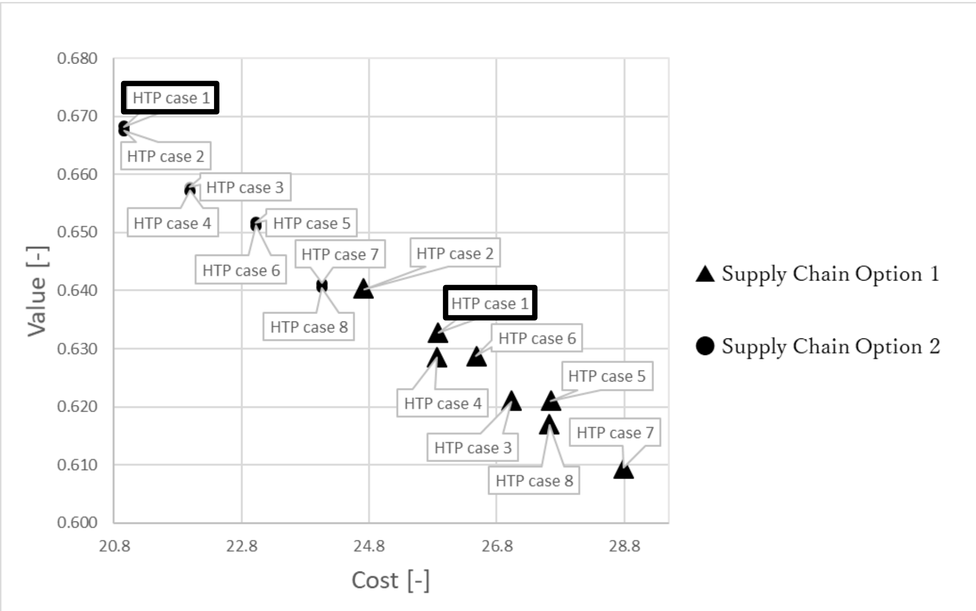

Figure 36 MDO Case Study 2 – Application Case 1: Value-Cost tradespace, evidencing the solutions considered in the current results analysis; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value; 2 supply chain options

They have the same manufacturing and assembly processes, for this reason they have even the same performance. The differences are for the supply chain, in the first case everything is made at OEM 1, while in the second production and assembly are at OEM 5 and delivered at the vehicle assembly site. In Table 29 the detailed results for HTP case 1 in these for both SC options.

		Time [-]		Quality [-]		Risk [-]		Cost [-]	
SC options		SC 1	SC 2	SC 1	SC 2	SC 1	SC 2	SC 1	SC 2
HTP case 1	Total	14.6	21.5	89.4	89.2	17.7	24.6	21.4	26.2
	Manufacturing	23.1	25.7	98.9	98.5	35.0	40.4	40.9	40.8
	Fixed	20.0	36.7	80.0	80.0	18.0	32.0	22.0	36.0
	Transport	0.0	2.0	-	-	0.0	1.4	0.0	0.9

Table 29 MDO Case Study 2 – Application Case 1: Detailed results comparing HTP case 1 with SC options 1 and 2; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value; 2 supply chain options

The manufacturing performance are close to each other because Manufacturing Competence of OEM 1 and OEM 5 for manufacturing and assembly processes used are similar. The transportation performance is 0 in the SC option 1 because the distance covered is 0 km, being everything produced and assembled at the same site, without the needed to send the components to other enterprises. In the SC option 2 production and assembly are at the same enterprise (OEM 5), but the HTP has to be delivered to the vehicle assembly site and it gives an additional cost and higher risk and time than SC option 1.

V.5. MDO Case Study 2 – Application Case 2 (DOE)

As the previous application case, the MDO Study Case 2 - Application Case 1 addresses three domains (MfG, SC and OAD). The MDO has been run by the workflow showed in figure 37 and the DOE is executed.

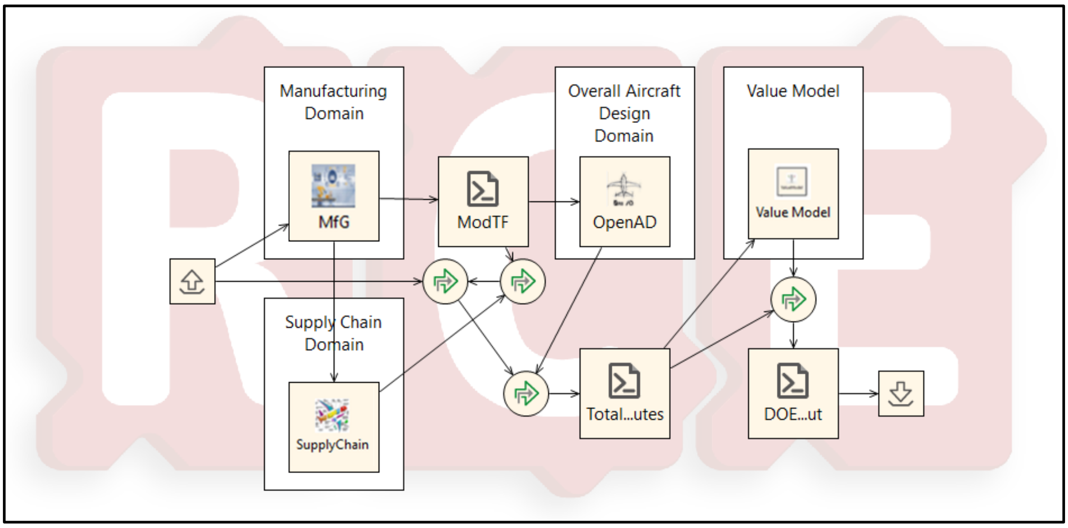

Figure 37 MDO Case Study 2 – Application Case 2: workflow; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value; 2 supply chain options

The aim of this MDO problem is to identify a set of nondominated solutions (Pareto Front points) of supply chain producing a specific HTP configuration, made by aluminum, allowing manufacturing processes and enterprises involved to change. The MDO Application Case 2.2 considers 8 cases of manufacturing processes combination of aluminum among components and 2 supply chain options (SC Options). The results are reported in Table 30.

		Time [-]		Quality [-]		Risk [-]		Cost [-]		Fuel Consumption [kg]	Value [-]	
	SC Options	**SC 1**	**SC 2**	**SC 1**	**SC 2**	**SC 1**	**SC 2**	**SC 1**	**SC 2**		**SC 1**	**SC 2**
Manufacturing cases	**HTP case 1**	40.4	35.8	67.3	60.4	37.9	31.5	38.9	39.8	4802	0.497	0.508
	HTP case 2	41.2	36.5	66.3	59.4	38.6	32.2	39.7	40.6	4807	0.490	0.501
	HTP case 3	40.7	36.1	66.3	59.4	38.6	32.2	39.2	40.1	4811	0.491	0.502
	HTP case 4	41.5	36.8	65.3	58.4	39.2	32.8	40.0	40.9	4816	0.484	0.495
	HTP case 5	41.3	36.6	66.3	59.4	38.6	32.2	39.8	40.6	4825	0.488	0.498
	HTP case 6	42.0	37.4	65.3	58.4	39.2	32.8	40.5	41.4	4830	0.481	0.492
	HTP case 7	18.3	23.8	88.9	88.8	22.4	29.6	24.1	28.8	4834	0.641	0.609
	HTP case 8	18.3	21.9	88.9	89.0	22.4	28.4	24.1	27.6	4839	0.641	0.617

Table 30 MDO Case Study 2 – Application Case 2: performance results; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value; 2 supply chain options

The Pareto Front, whose value-cost tradespace is reported in figure 38, has 2 elements:

- *HTP case 1 with SC option 1.*
- *HTP case 1 with SC option 2.*

The results analysis has been done comparing these two configurations included in Pareto Front.

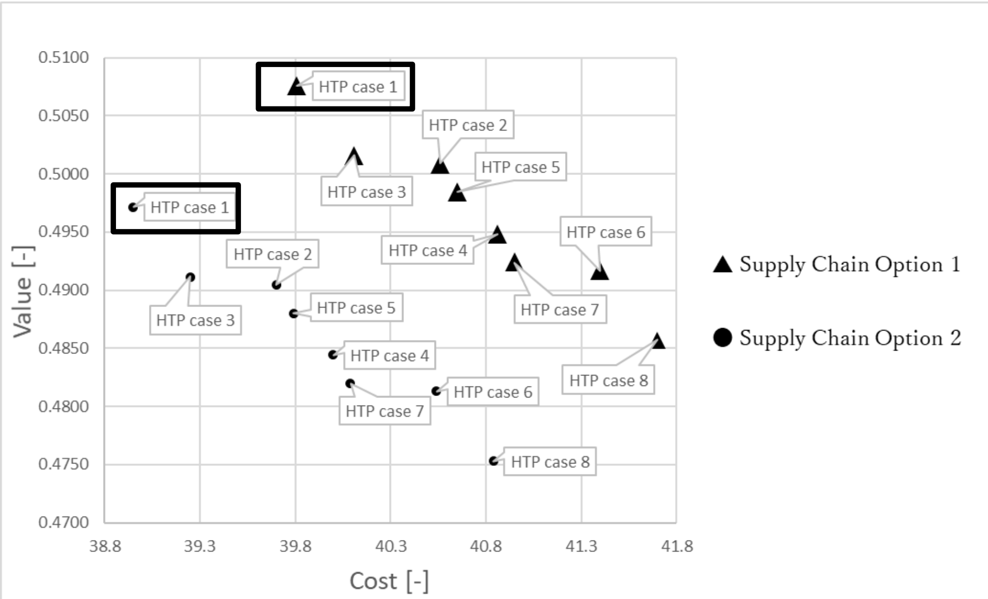

Figure 38 MDO Case Study 2 – Application Case 2: Value-Cost tradespace for HTPs in aluminum, value-cost Pareto Front points are evidenced; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality, value; 2 supply chain options

The value-cost Pareto Front points have the same manufacturing processes, the difference is in SC option, both are produced at OEM 4, but SC option 1 assembles at OEM 1, while SC option 2 assembles at OEM 5. Both HTPs have the same mass and aerodynamic performance and even the same fuel consumption, so the difference in value is related to the attributes. The HTP case 1, for both the SC options, represents the Pareto Front because the OEM 4 (production site) has the highest competences for material, manufacturing and assembly processes among the solutions. Even the assembly competences of SC option 1 are higher than SC option 2.

In Table 31 the detailed results for HTP case 1 are shown for these two supply chain options.

		Time [-]		Quality [-]		Risk [-]		Cost [-]	
SC options		SC 1	SC 2	SC 1	SC 2	SC 1	SC 2	SC 1	SC 2
HTP case 1	Total	40.4	35.8	67.3	60.4	37.9	31.5	38.9	39.8
	Manufacturing	29.9	35.6	79.0	72.6	31.0	37.4	29.9	35.6
	Fixed	29.2	41.7	55.6	48.1	33.9	47.8	61.5	50.4
	Transport	62.2	30.1	-	-	48.8	9.3	25.5	33.5

Table 31 MDO Case Study 2 – Application Case 2: Detailed results comparison of HTP case 1 with SC options 1 and 2; Design Variables of DOE are Production Quantity and Assembly Quantity, with Objective Function: minimize cost, time, risk, fuel consumption and maximize quality; 2 supply chain options

The manufacturing performance are better in SC option 1 because of assembly competences which are higher in this case. For the transportation performance, SC option 2 has lower cost, time and risk. In fact, in the SC option 2 production and assembly sites are closer and it reduces time and risk during the delivery. The cost has the opposite behavior, analyzing results in detailed, the distance covered for SC option 2 is lower, but it is mainly covered on road, while SC Option 1, despite following a longer route, it is mainly shipped on water, reducing costs. For this reason, the HTP case 1 with SC option 2 has higher value than SC option 1, and the cost of SC option 1 is lower than SC option 2.

CHAPTER VI

CONCLUSIONS AND FUTURE DEVELOPMENTS

In this chapter, conclusions on the work accomplished in this thesis are drawn and some recommendations regarding future research activities for improvements are given.

VI.1. Conclusions

In this work, a value-driven optimization campaign has been performed. It addresses manufacturing, supply chain and overall aircraft design domains in the early development stage. Before focusing on the MDO campaign, it has been necessary to perform several activities in order to set the MDO case studies in the right way. Results in Table 2, paragraph II.2.A, validates the aerodynamic and mass performance estimation, based on the approach of the Technology Factor. In paragraph II.2.B, two methods for the estimation of manufacturing competence are compared and method 2 is selected for the MDO activities.

After these analyses, five MDO application cases have been performed. As reported in table 9, paragraph III.1, in MDO Application Cases 1.1, 1.2, 1.3 manufacturing and supply chain domains are involved. Instead MDO Application Cases 1.4, 1.5 involve all the three domains: manufacturing, supply chain and overall aircraft design. The MDO Application Case 1.1 is performed with a Design of Experiments (DOE); the design variables are Production Quantity and Assembly Quantity, the Objective Function are the minimization of cost, time, risk and the maximization of quality, value. The MDO Application Case 1.1 has one optimum solution, whose production performance is better than others in terms of both supply chain and manufacturing ones. The MDO Application Case 1.2 and 1.3 are performed with a remote optimization. The optimization algorithm runs at ONERA, while the objective faction is at DLR. In both cases the design variable are Production Quantity and Assembly Quantity; the Objective Function are minimization of cost, time, risk and maximization of quality, value. In the Application Cases 1.2, the optimization involves skin and stringers as components, and skin & stringers assembly. It has been launched two kinds of optimization: with and without clustering. Even if the clustering process often may return better results in effective computational time, comparing the two approaches, the unclustered one needed less time to achieve the same Pareto Front solutions (Figure 27, paragraph V.2). The MDO Application Case 1.3, in contrast to the MDO Application Case 1.2, involves skin, stringers, spars and ribs, as component, and skin & stringers and main HTP assembly. A single optimization run has launched. It has only few iterations (250 initial points + 160 optimization points) compared to the size of the MDO challenge full enumeration (9 million combinations), but the optimization effectively returns the solutions of Pareto Front we expected (Table 26-27 and Figure 32: paragraph V.3). The MDO Application Case 2.1 and 2.2 are performed with Design of Experiments, with all the manufacturing processes combinations of HTP components in aluminum. In both cases the design variable are Production Quantity and Assembly Quantity; with Objective Function: minimize cost, time, risk and maximize quality, value, fuel consumption. In addition to the previous application cases, the fuel consumption is considered because of the overall aircraft design domains. These application cases confirmed how important is the OAD in the early aircraft development stage. In fact, looking at Table 28 and Figure 35 in paragraph

V.4, two solutions appear identical to each other for the production performance, but they are different in the fuel consumption of the vehicle in cruise, depending on mass and aerodynamic shape, and this difference allows a solution to return a higher value than the other.

VI.2. Future Developments

Several future developments can be applied to this research activity. In terms of MDO activities, the MDO Application Cases 2.1 and 2.2considering all the three domains of manufacturing, supply chain and overall aircraft design might be expanded by considering other materials, manufacturing and assembly processes. In addition, other optimization algorithms might be tested for these MDO application cases. At the same time, further developments can be executed to enhance the methodology. Most of the equations implemented in each single domain are based on semi-empirical formulas, found in literature. Similarly, even more complex tools might be used to implement each single domain. Concluding, other value theory methods might be applied to allow the concurrent coupling of multiple domains.

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