DELIVERABLE D 6.5

UPGRADE DRIVEN STREAM MDO FRAMEWORK DESCRIPTIONS AND TRADE OF RESULTS

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WorkPackage N°: WP6
Due date of deliverable: 31.12.2022
Actual submission date: 16.02.2023
Document ID: AGILE4.0_D6.5_v7.0.docx

Grant Agreement number: 815122
Project acronym: AGILE 4.0
Project title: Towards cyber-physical collaborative aircraft development
Start date of the project: 01/09/2019
Duration: 42 months

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THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME UNDER GRANT AGREEMENT NO 815122

DOCUMENT INFORMATION

Document ID	AGILE4.0_D6.5_v7.0.docx		
Version	7.0		
Version Date	02/08/2023		
Author	A.H. van der Laan		
Dissemination level	Public		

APPROVALS

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Review	H Timmermans	NLR	22-02-2023	

DOCUMENTS HISTORY

Version	Date	Modification	Authors
0.1	12/01/2022	Template	A.H. van der Laan
0.2	01/27/2023	Added workflow implementation and trade-off	J.S. Sonneveld
0.3	01/29/2023	Added surrogate based optimization approach by NLR	J. Vankan
0.4	01/30/2023	Added all content from previous deliverables	J.S. Sonneveld
0.5	07/02/2023	Added AC2. Editing	A.H. van der Laan
4.0	08/02/2023	Final additions and editing. This is the final draft	J.S. Sonneveld, A.H. van der Laan
5.0	08/02/2023	Minor editing	L. Boggero
7.0	13/02/2023	Minor editing	H. Timmermans, Ton van der Laan

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GLOSSARY

Acronym	Signification
A4F	AGILE 4.0 framework
AC	Application Case
AEA	All-Electric Aircraft
MEA	More-Electric Aircraft
MDO	Multi-Disciplinary Optimization
OBS	On-Board System
OCE	Operational Collaborative Environment
QoI	Quantity of Interest
RSM	Response Surface Method
RVF	Requirements Verification Framework
SOI	System Of Interest

1 EXECUTIVE SUMMARY

1.1 Introduction

The deliverable 6.5 will present and describe the results of the two use cases within WP6 obtained by executing the AGILE 4.0 framework (A4F).

The main objectives for WP 6 are:

1. Provide requirements and feedback for the MDO tools and methods developed in other WP's
2. Apply the MDO tools and methods in use case scenarios based on experience from industry
3. Develop and use a production driven instance of the MDO framework
4. Develop and execute trade off scenarios with the production driven optimization framework

This document will focus on objective 2-4 and will address all the steps in the A4F framework. The A4F involved steps are depicted in Figure 1.

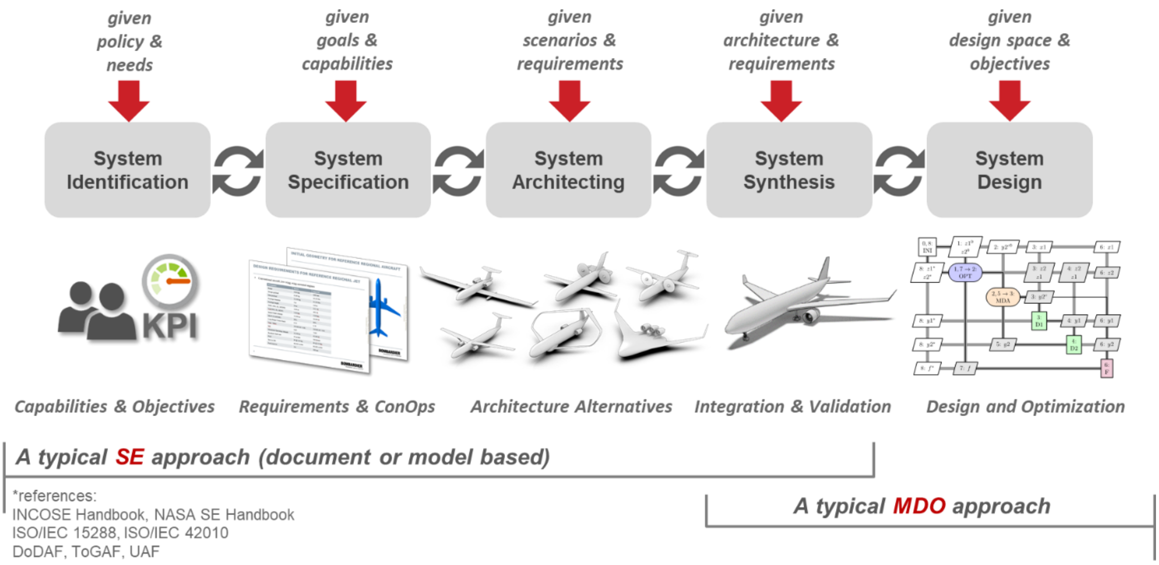


Figure 1 AGILE 4.0 Overall Steps

In work package 6 two application cases are used to test the technologies of the A4F. These are:

- **AC1: Manufacturing driven design,** assess the influence of the design on manufacturing and find the optimum design with respect to manufacturing, represented by cost, and other performance indicators such as weight

- **AC2: Supply chain driven design,** assess interaction between the aircraft design and the manufacturing supply chain. Find the optimum supply chain using different supply chain performance indicators, cost, risk, etc. while ensuring aircraft performance

Many results and models have been produced in work package 6, which are presented and explained in the deliverable and made publicly available on the AGILE 4.0 project website, respectively in https://www.agile4.eu/ac1-manufacturing/ (AC1) and https://www.agile4.eu/ac2-supply-chain/ (AC2).

1.2 Brief description of the work performed and results achieved

Application cases 1 and 2 have been used to test the OCE developed technologies (e.g. ADORE, MultiLinQ KADMOS/CMDOWS, MDAx, RVF, Valorize, see WP4 deliverables for further details) highlighting the flexibility in the definition of multiple architectures, different layers/systems (SoI's and enabling systems), formalization of workflow strategies, verification of requirements compliancy and trade-off of the results.

AC1 and AC2 have gone through the whole Agile 4.0 process. More details of the results from this process can be found in Chapter 2 for AC1 and Chapter 3 for AC3. These results include document-based definition which is formalized according to the MBSE paradigm and translated into models using the OCE.
Using MBSE formalization collaborative workflow executions are defined and executed. Finally the results from these workflow executions are traded.
The steps taken in each application case are:

- Needs and requirements of the System of Interest (SoI) are defined in the OCE
- Based on the functional requirements the architecture of the SoI and a second system (in this work package production related systems like manufacturing or supply chain system) are implemented into ADORE, highlighting architectures modelling and decisions.
- SoI and enabling system architectures are evaluated using test cases (e.g. design competences), used into workflow implementation.
- Once architectures and tests cases are in place, the connection between them is checked using MultiLinQ technology.
- The Requirements Verification Framework (RVF) allows automatic verification of the requested quantities of interest and their compliancy with the requirements requested by ACs owners. This results in workflows that can verify the specified requirements.
- The workflows are used to run Design of Experiments and optimizations.
- Finally the DOE and optimization results are traded to discover the system designs with the best value.

1.3 Deviation from the original objectives

1.3.1 Description of the deviation

The main deviation with respect to the scheduling is the due date, initially planned at M40 (means December 2022). This is mainly due to trouble with the robustness of the workflows in AC1 and planning issues.

1.3.2 Corrective actions

The correction action was to shift the Deliverable D6.5 due date to 42 (February 2023).

2 APPLICATION CASE 1

AC1 focuses on the design and manufacturing of a flap, as visualized in Figure 2. The application case assesses the influence of the design of the flap on the manufacturing processes, and vice versa. Therefore, the first System of Interest (SOI) of AC1 is the flap, while the second SoI or enabling system is the production system. In the production system, both the part manufacturing as well as the assembly are considered.

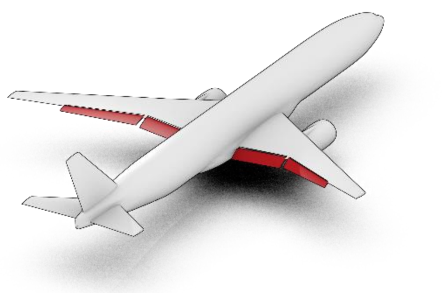


Figure 2: Main System of Interest of AC1 - the flap

The trade-off in AC1 focuses on the flap weight versus the production cost (including both manufacturing and assembly costs). Two different flap designs are considered, namely a dropped hinged flap and an advanced kinematics flap. A schematic drawing of the dropped hinged flap and advanced kinematics flap are shown in Figure 3 and Figure 4, respectively.

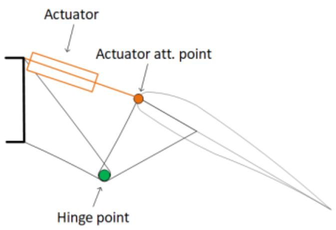


Figure 3: Schematic drawing of the dropped hinged flap

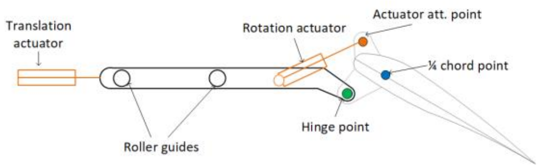


Figure 4: Schematic drawing of the advanced kinematics flap

Both flaps will be designed for the same performance target (similar CL_{max} during landing conditions) and the flap weight and production costs of both flaps will be compared. The expectation is that the advanced kinematics flap will be more efficient than the dropped hinged flap, as the advanced kinematics flap has a decoupled translation and rotation. Therefore, this flap can be smaller and thus lighter than the dropped hinged flap. However, the advanced kinematics flap is more complex and therefore the manufacturing is more difficult. For this reason, it is expected that the production costs will be higher for this flap when compared to the dropped hinged flap. For a more detailed description of the application case, the reader is referred to D6.1 [1].

As mentioned above, the second system of interest is the production system, consisting of both the part manufacturing and the assembly of the flap. The part manufacturing focusses on the material choice of the part and the corresponding manufacturing methods. The assembly focusses on the definition of the different (sub-)assemblies and the corresponding assembly stations.

2.1 System Identification

The first step of the AGILE4.0 MBSE-MDO framework is the system identification. In this step, the scenario is modelled.

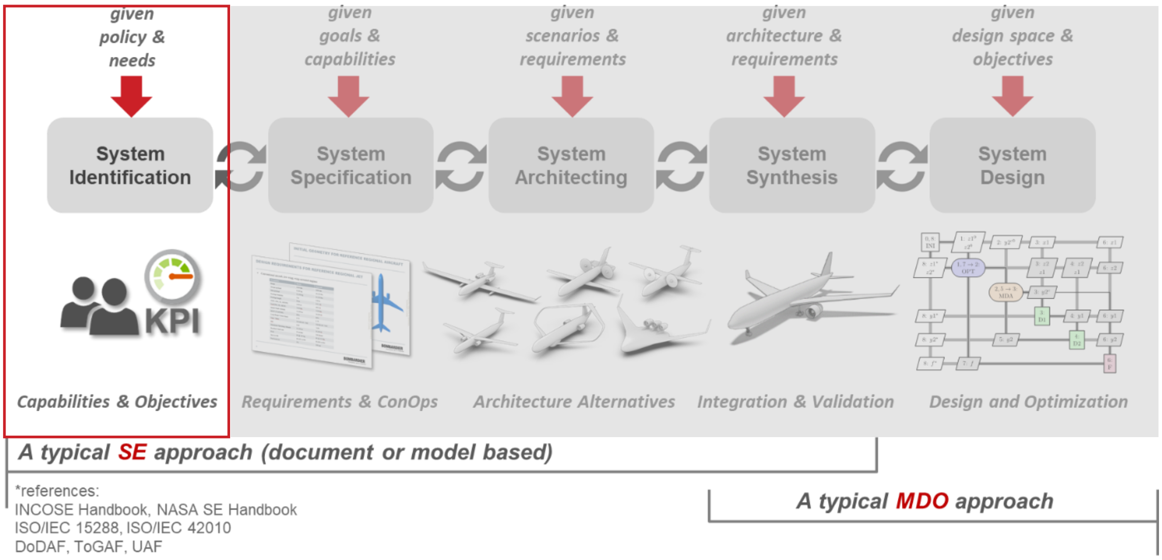


Figure 5: AGILE 4.0 Step I: System Identification.

For AC1, one scenario has been chosen to be fully modelled in the OCE and Capella. This scenario focuses on the activities related to the design of the simple hinged flap before the contract between the OEM and Flap Manufacturer (FM) is finalized. In this scenario a first design of the flap is made by the FM, based on the requirements set by the OEM. Based on the initial designs, the FM decides whether it wants to make a proposal to the OEM. If the answer is yes, a proposal is sent to the OEM. The OEM evaluates proposed designs from multiple FMs and then decides which FM the contract is awarded to. Figure 6 shows this scenario in the OCE.

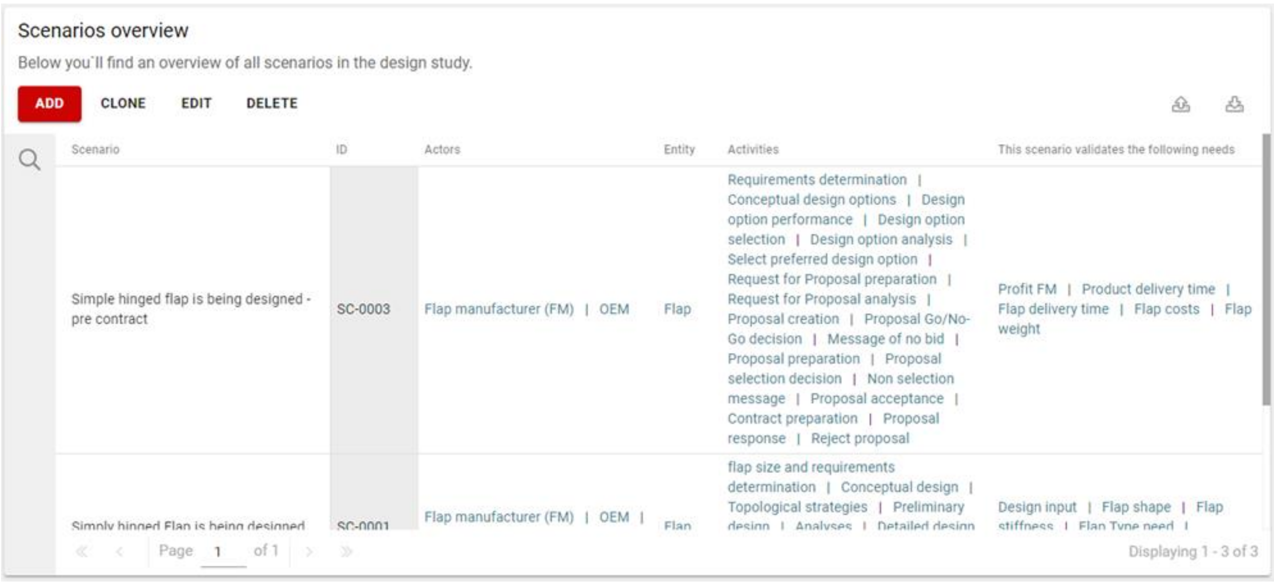


Figure 6: Scenario overview as defined in KE-chain

The different activities that are part of this scenario are added to the OCE as well, as shown in Figure 7. An activity corresponds to a step that must be performed within the scenario. Several activities combined, form together the full scenario. This can be seen in fifth column of Figure 6, where several activities are linked to the scenario. Besides the activities, the scenario is also linked to several needs as can be seen in the sixth column of Figure 6. The pre-contract scenario will validate five needs from both the OEM as well as the FM, concerning the profitability, weight and delivery times of the flap.

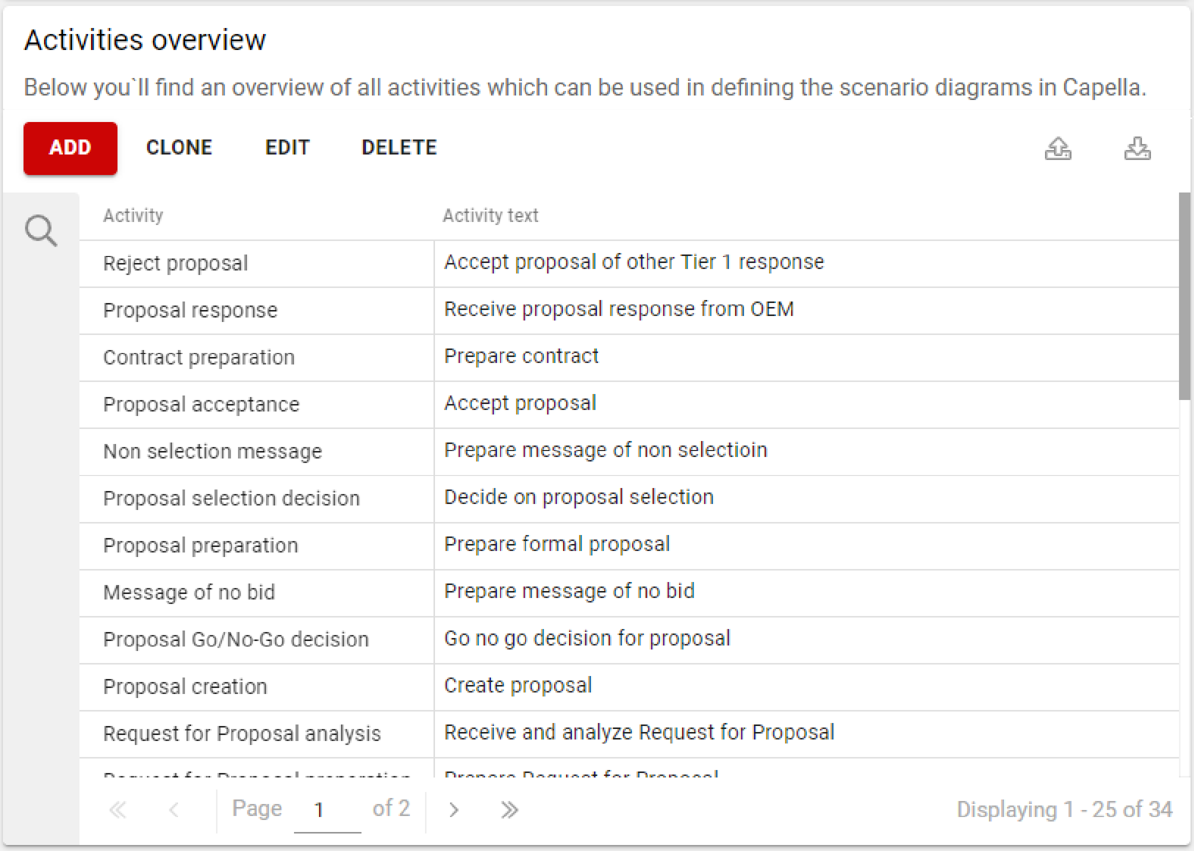


Figure 7: Activities overview as defined in KE-chain

Once the activities and scenario is filled in the OCE, the scenario can be modelled in Capella. The result can be seen in Figure 8. Three entities are relevant to this scenario (OEM, FM and flap), however only two have activities assigned to them. The scenario has two ALT boxes, indicating the decisions that have to be made by the FM and OEM on whether to proceed with the proposals and initial designs or not.

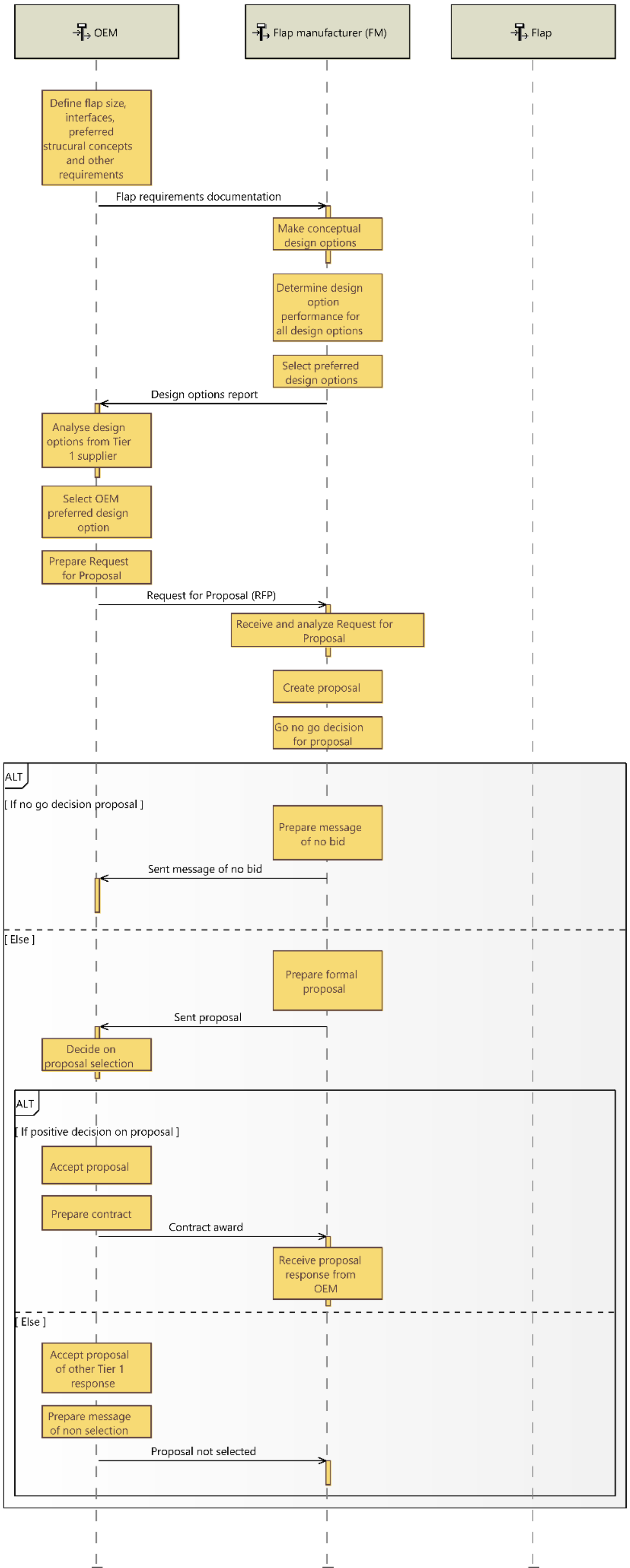


Figure 8: Scenario overview as generated in Capella

2.2 System Specifications

The second step of the AGILE4.0 MBSE-MDO framework is the system specification dealing with the modelling of stakeholders, needs and requirements.

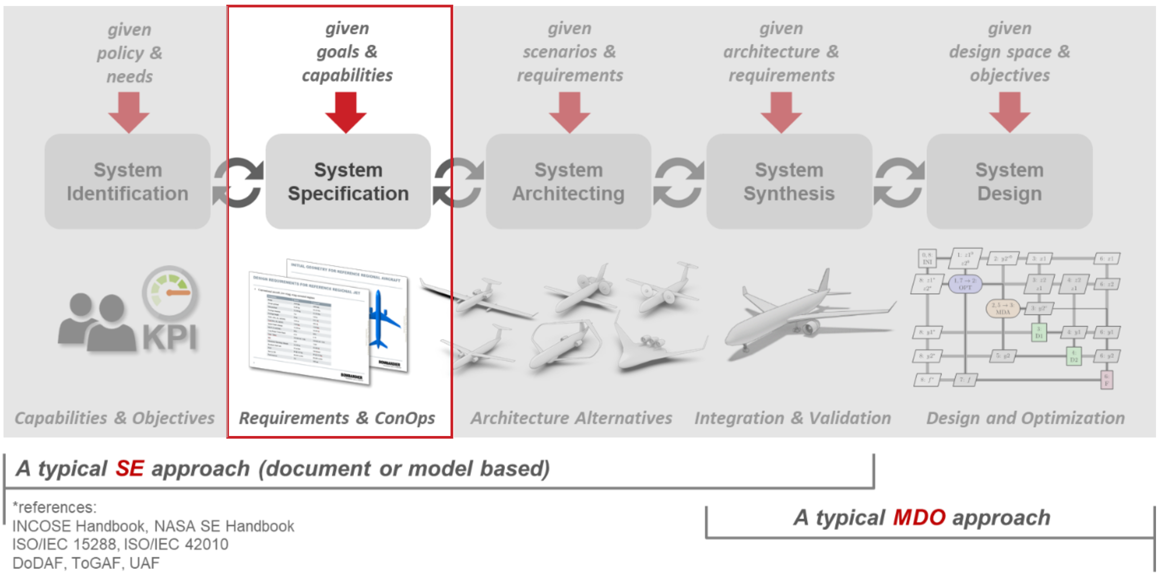
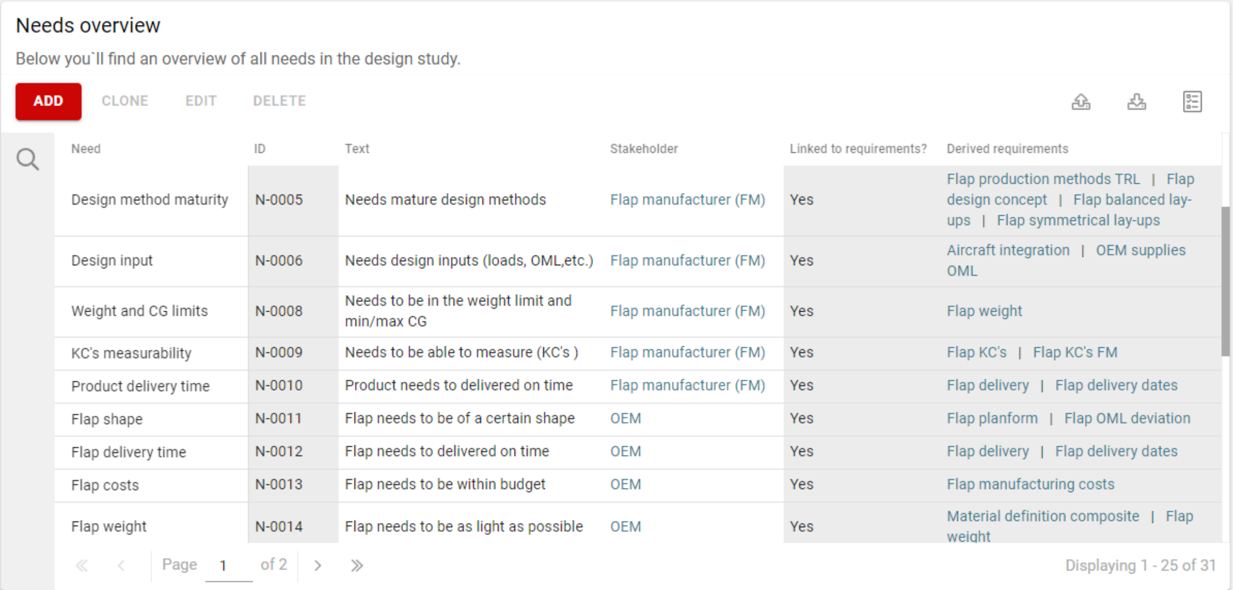


Figure 9: AGILE 4.0 Step II: System Specification.

Within AC1, six different stakeholders have been identified that have an influence on the design and manufacturing of the flap:

- **Flap Manufacturer** (FM): The FM designs and produces the flap. They deliver the flap to the OEM.
- **Original Equipment Manufacturer** (OEM): The flap must be fitted on the aircraft that is designed by the OEM. The OEM specifies many of the requirements that the flap must fulfill, because it is type certificate holder and therefore type design owner.
- **Tier 2 supplier** (T2SUP): The design and manufacturing of some parts of the flap may be outsourced to Tier 2 suppliers.
- **Certification authority** (CERT): The flap must comply with all the requirements set by the certification authority.
- **Government** (GOV): The flap must comply with regulations set by the government, for example regarding noise and emission regulations.
- **Aircraft operators** (OPS): The aircraft operators is the group that are going to use the aircraft. They have several needs with respect to the performance and maintenance of the flap.

All six stakeholders have been added to the OCE as can be seen in Figure 11.



Needs overview

Below you'll find an overview of all needs in the design study.

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Need	ID	Text	Stakeholder	Linked to requirements?	Derived requirements
Design method maturity	N-0005	Needs mature design methods	Flap manufacturer (FM)	Yes	Flap production methods TRL | Flap design concept | Flap balanced lay-ups | Flap symmetrical lay-ups
Design input	N-0006	Needs design inputs (loads, OML,etc.)	Flap manufacturer (FM)	Yes	Aircraft integration | OEM supplies OML
Weight and CG limits	N-0008	Needs to be in the weight limit and min/max CG	Flap manufacturer (FM)	Yes	Flap weight
KC's measurability	N-0009	Needs to be able to measure (KC's)	Flap manufacturer (FM)	Yes	Flap KC's | Flap KC's FM
Product delivery time	N-0010	Product needs to delivered on time	Flap manufacturer (FM)	Yes	Flap delivery | Flap delivery dates
Flap shape	N-0011	Flap needs to be of a certain shape	OEM	Yes	Flap planform | Flap OML deviation
Flap delivery time	N-0012	Flap needs to delivered on time	OEM	Yes	Flap delivery | Flap delivery dates
Flap costs	N-0013	Flap needs to be within budget	OEM	Yes	Flap manufacturing costs
Flap weight	N-0014	Flap needs to be as light as possible	OEM	Yes	Material definition composite | Flap weight

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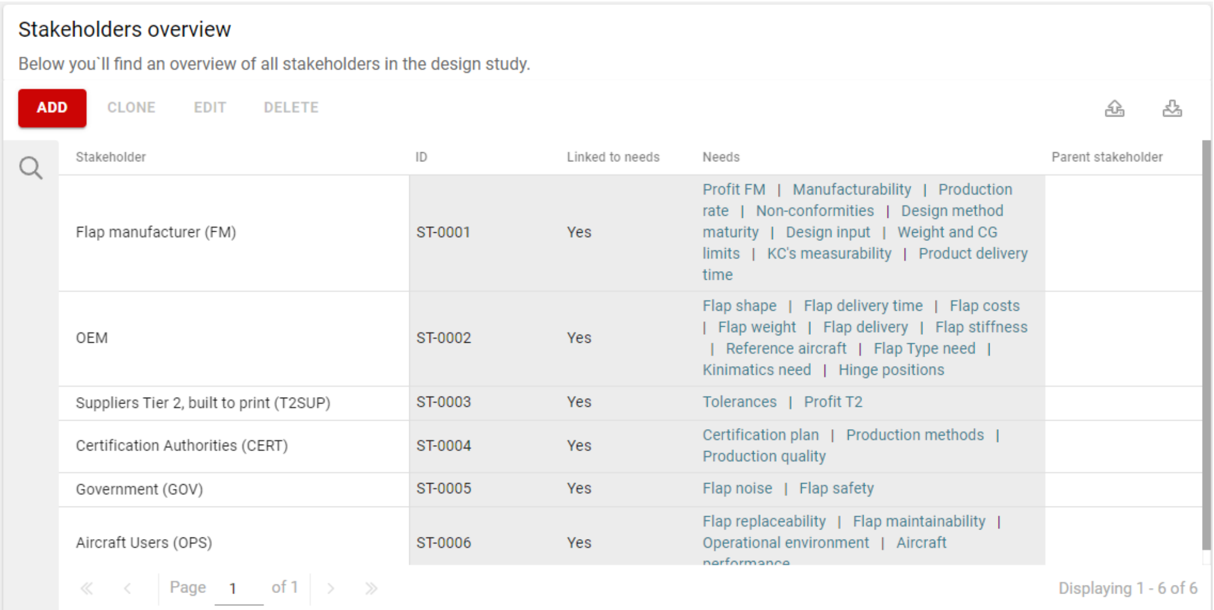
Figure 10: Needs overview as defined in KE-chain



Stakeholders overview

Below you'll find an overview of all stakeholders in the design study.

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Stakeholder	ID	Linked to needs	Needs	Parent stakeholder
Flap manufacturer (FM)	ST-0001	Yes	Profit FM | Manufacturability | Production rate | Non-conformities | Design method maturity | Design input | Weight and CG limits | KC's measurability | Product delivery time	
OEM	ST-0002	Yes	Flap shape | Flap delivery time | Flap costs | Flap weight | Flap delivery | Flap stiffness | Reference aircraft | Flap Type need | Kinimatics need | Hinge positions	
Suppliers Tier 2, built to print (T2SUP)	ST-0003	Yes	Tolerances | Profit T2	
Certification Authorities (CERT)	ST-0004	Yes	Certification plan | Production methods | Production quality	
Government (GOV)	ST-0005	Yes	Flap noise | Flap safety	
Aircraft Users (OPS)	ST-0006	Yes	Flap replaceability | Flap maintainability | Operational environment | Aircraft performance	

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Figure 11: Stakeholders overview as defined in KE-chain

Each stakeholder has several needs. These needs were identified and also added to the OCE as can be seen in Figure 10. This resulted in 31 different needs. Each need is coupled to a stakeholder as can be seen in the fourth column of Figure 10. Due to this coupling, an overview of the needs per stakeholder is automatically generated as can be seen in the fourth column of Figure 11. The OCE also automatically checks whether each stakeholder has a connected need. As can be seen in the third column of Figure 11, all six stakeholders have needs linked to them.

The modelled stakeholders and needs are visualized using Papyrus. Figure 12 shows the stakeholders hierarchy view. As can be seen in this Figure, no subdivisions or hierarchy in stakeholders have been made. For example, the OEM or FM are not further specified into different departments within the company. Therefore, all stakeholders are on the same line (or level).

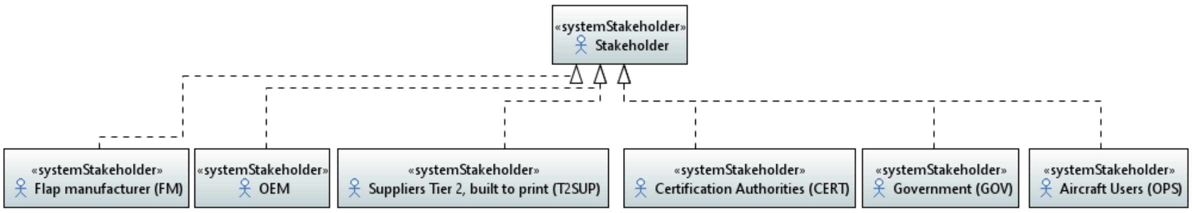


Figure 12: Stakeholders Hierarchy View as generated in Papyrus

Figure 13 shows an example of the needs as visualized in Papyrus. Only a small subset, the needs of the Certification Authorities, are visualized as an example. This figure shows that the Certification Authorities have three different needs, focusing mainly on certification and quality. Furthermore, the connection between the needs package and Certification Authorities Needs package in this Figure indicate that indeed a subset of all needs are visualized.

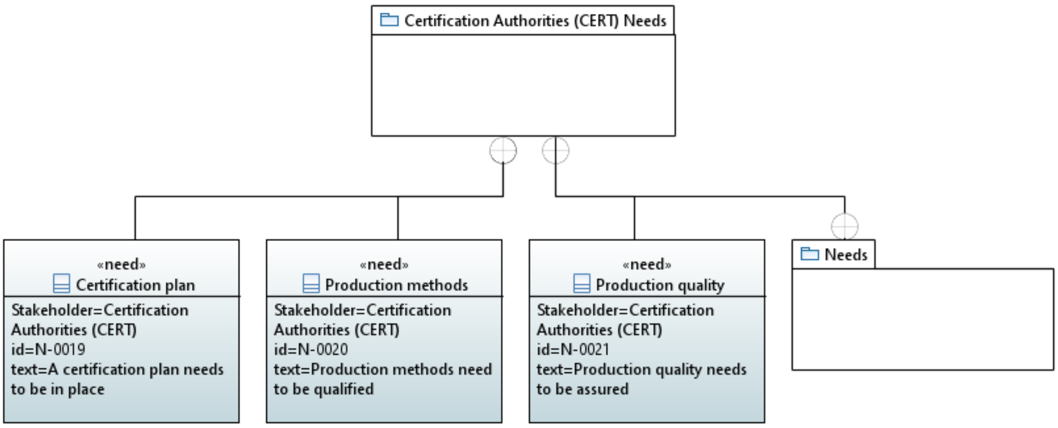
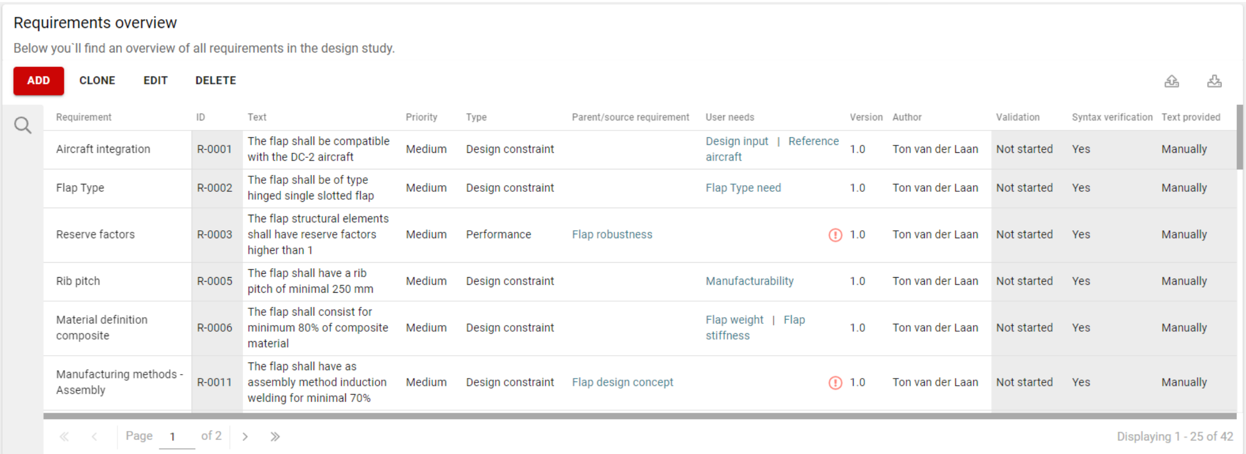


Figure 13: Example of a needs overview as generated in Papyrus. In this case the needs from the Certification Authorities are visualized.

42 requirements have been formulated. All requirements have been filled in the OCE and a selection is shown in Figure 14. Each requirement is linked to either one or more needs or a parent requirement (sixth and seventh column).



Requirements overview

Below you`ll find an overview of all requirements in the design study.

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Requirement	ID	Text	Priority	Type	Parent/source requirement	User needs	Version	Author	Validation	Syntax verification	Text provided
Aircraft integration	R-0001	The flap shall be compatible with the DC-2 aircraft	Medium	Design constraint		Design input | Reference aircraft	1.0	Ton van der Laan	Not started	Yes	Manually
Flap Type	R-0002	The flap shall be of type hinged single slotted flap	Medium	Design constraint		Flap Type need	1.0	Ton van der Laan	Not started	Yes	Manually
Reserve factors	R-0003	The flap structural elements shall have reserve factors higher than 1	Medium	Performance	Flap robustness		1.0	Ton van der Laan	Not started	Yes	Manually
Rib pitch	R-0005	The flap shall have a rib pitch of minimal 250 mm	Medium	Design constraint		Manufacturability	1.0	Ton van der Laan	Not started	Yes	Manually
Material definition composite	R-0006	The flap shall consist for minimum 80% of composite material	Medium	Design constraint		Flap weight | Flap stiffness	1.0	Ton van der Laan	Not started	Yes	Manually
Manufacturing methods - Assembly	R-0011	The flap shall have as assembly method induction welding for minimal 70%	Medium	Design constraint	Flap design concept		1.0	Ton van der Laan	Not started	Yes	Manually

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Figure 14: Requirements overview as defined in KE-chain

The requirements have then been divided into five requirements sets, as shown in Figure 15. Each requirement set focusses on one (sub)system or stakeholder:

- **Flap requirements**: The flap requirements set contains all requirements that are related to the flap design, flap performance, flap producibility and flap maintainability.
- **Aircraft requirements**: The aircraft requirements set contain all requirements related to the overall aircraft design.
- **Machined hinge brackets requirements**: The hinge brackets are a subsystem of the flap and are essential for the flap deflection. This requirement set contains requirements on the position, costs and tolerances of the hinge brackets.
- **Flap structural elements requirements**: The flap structural elements consist amongst others of the ribs, spars and skins of the flap. This set contains only one requirement that focuses on the reserve factor of these elements.
- **OEM requirements**: The OEM requirements set contains the requirements related to the OEM. These requirements focus on the outer mould line that the OEM has to deliver to the FM and the flap delivery dates.

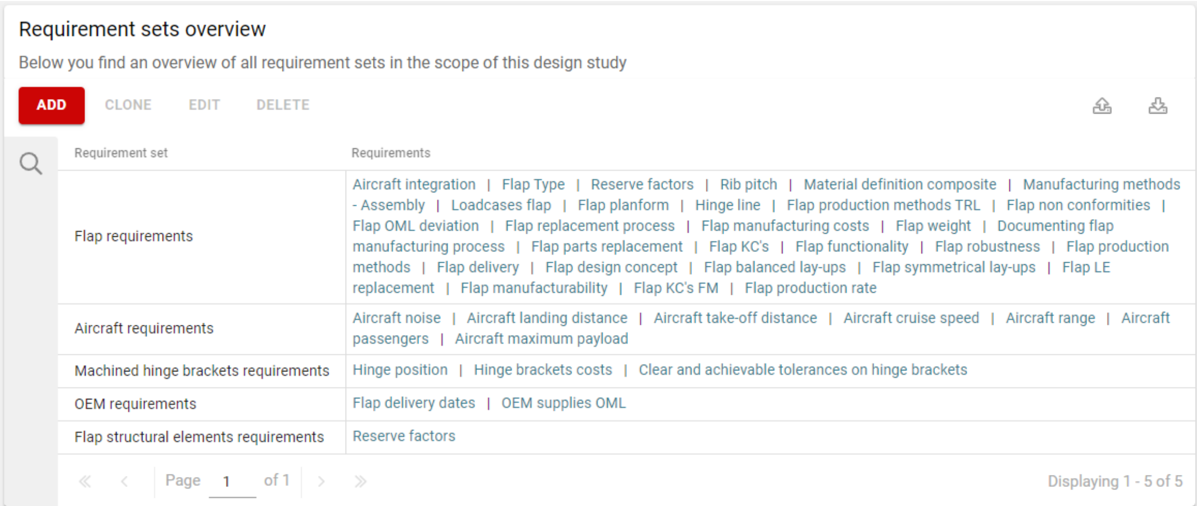


Figure 15: Requirements sets overview as defined in KE-chain

After the requirements have been filled in in the OCE, they were exported to Papyrus. An example of is shown in Figure 16. In this case only a <u>subset</u> of the flap requirements set is visualized. This figure shows how several requirements are derived from other requirements. For example R-0012 is derived from R-0003, which is on its turn derived from R-0034. This overview clearly shows the link between the different requirements.

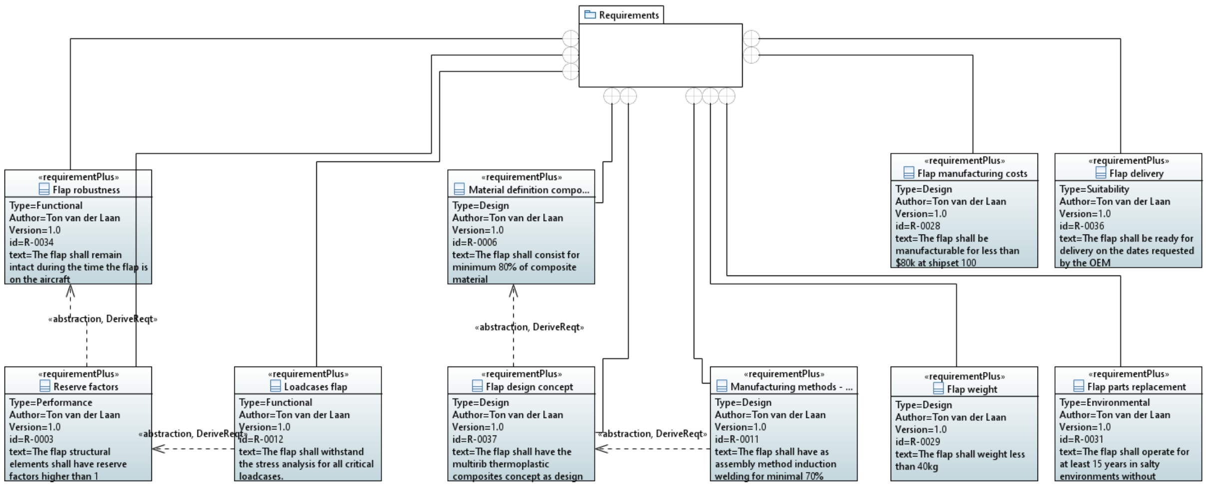
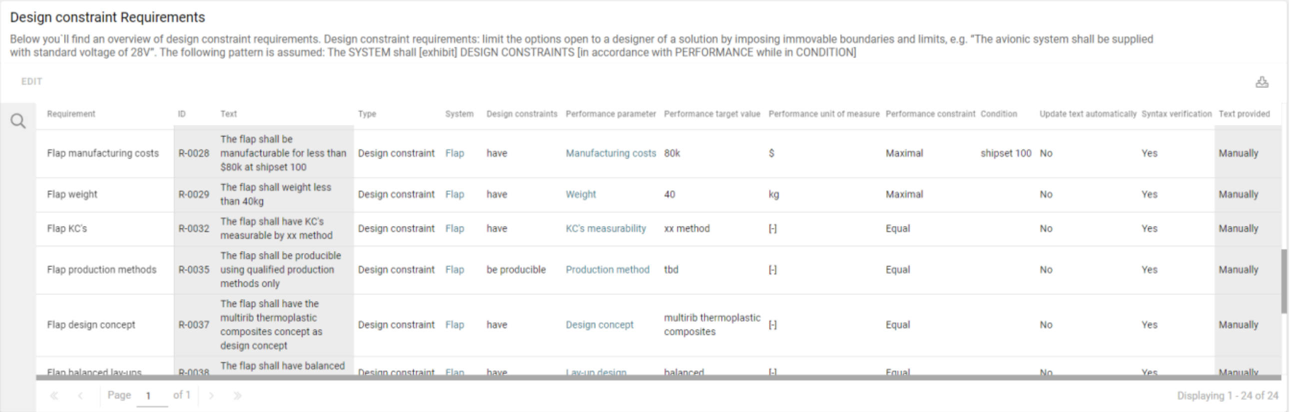


Figure 16: Requirements overview as generated in Papyrus. Only a small subset of the flap requirements are shown

For each requirement, the requirement pattern has been filled. An example of the patterns as filled in the KE-chain for the design constraint requirements can be seen in Figure 17. Each design requirement is linked to a (sub)system object as can be seen in the fifth column of the figure. In this example, all requirements are connected to the flap. Each requirement with type design requirement is also linked to a parameter and a value with a unit as can be seen from the seventh to the tenth column. Some requirements also have a condition, although the condition is optional. Note, that even though the pattern has been filled for each requirement, the text for the requirements were not created automatically (as is indicated in the eleventh column). Similar patterns were created for the other requirements types (performance, functional, environment and suitability requirements).

Once all the patterns are filled in the KE-chain, they can be imported and visualized in Papyrus. Figure 18 shows an example of an environment requirement. In this case, the system is the flap, the characteristic is that the flap has to operate without replacement of class 1 parts and a salty environment. In the exposureDuration block, the constraint indicates that the flap has to be able to withstand the salty environment for at least 15 years. Combined these parts are the building blocks for the complete requirement which is “The flap shall operate for at least 15 years in salty environments without replacement of class 1 parts.”.


Design constraint Requirements

Below you`ll find an overview of design constraint requirements. Design constraint requirements: limit the options open to a designer of a solution by imposing immovable boundaries and limits, e.g. "The avionic system shall be supplied with standard voltage of 28V". The following pattern is assumed: The SYSTEM shall [exhibit] DESIGN CONSTRAINTS [in accordance with PERFORMANCE while in CONDITION]

EDIT

Requirement	ID	Text	Type	System	Design constraints	Performance parameter	Performance target value	Performance unit of measure	Performance constraint	Condition	Update text automatically	Syntax verification	Text provided
Flap manufacturing costs	R-0028	The flap shall be manufacturable for less than $80k at shipset 100	Design constraint	Flap	have	Manufacturing costs	80k	$	Maximal	shipset 100	No	Yes	Manually
Flap weight	R-0029	The flap shall weight less than 40kg	Design constraint	Flap	have	Weight	40	kg	Maximal		No	Yes	Manually
Flap KC's	R-0032	The flap shall have KC's measurable by xx method	Design constraint	Flap	have	KC's measurability	xx method	[-]	Equal		No	Yes	Manually
Flap production methods	R-0035	The flap shall be producible using qualified production methods only	Design constraint	Flap	be producible	Production method	tbd	[-]	Equal		No	Yes	Manually
Flap design concept	R-0037	The flap shall have the multirib thermoplastic composites concept as design concept	Design constraint	Flap	have	Design concept	multirib thermoplastic composites	[-]	Equal		No	Yes	Manually
Flap balanced lay-ups	R-0038	The flap shall have balanced	Design constraint	Flap	have	Lay-up design	balanced	[-]	Equal		No	Yes	Manually

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Figure 17 Requirements patterns for some design constraint requirements as filled in in the KE-chain

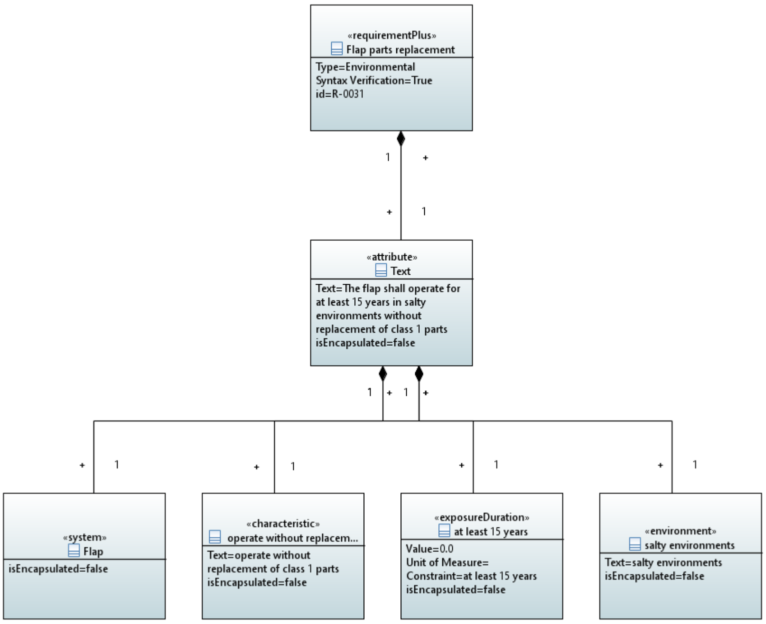


Figure 18 Example of a requirement pattern as visualized in Papyrus

Each requirement has a means of compliance and a test case connected to it. In Figure 19, several examples are visualized (using Papyrus), which show how the test cases are connected to the different requirements. The attribute ‘MeansOfCompliance’ indicate the type of means of compliance. In this example, two

requirements are verified using analysis tools, while one is verified using a physical test. Each of the test cases correspond to the means of compliance (MoC) type. As can be seen in the example, the environmental requirement is verified using a galvanic corrosion analysis (MoC = analysis), the noise requirement is verified using a noise analysis (MoC = analysis), and the weight requirement is verified by actually weighing the component (MoC = test). The test cases described represent the use of actual analysis tools.
Another interesting attribute that is visualized for each requirement is the responsible stakeholder. This stakeholder is not necessarily the stakeholder that has the need from which the requirement is derived from. The responsible stakeholder is the stakeholder that is responsible for complying with the requirement. In this case the FM is responsible for complying with the weight and salt resistance requirement, while the OEM is responsible for complying with the noise requirement.

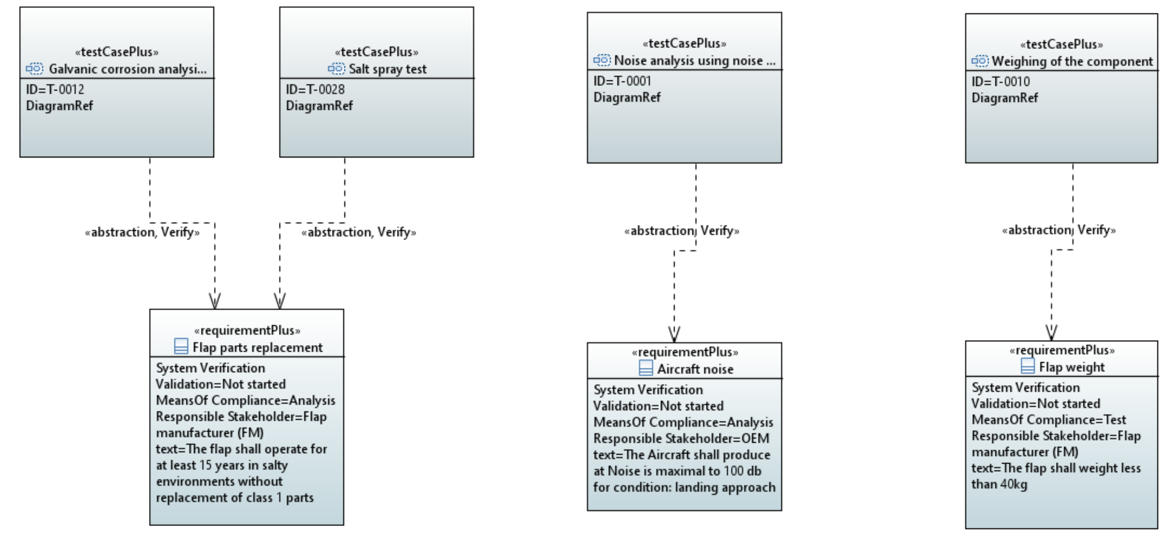


Figure 19 Examples of requirement verification views. The requirement on the left is an environment requirement, in the middle a performance requirement is visualized and the requirement on the right is a design constraint requirement

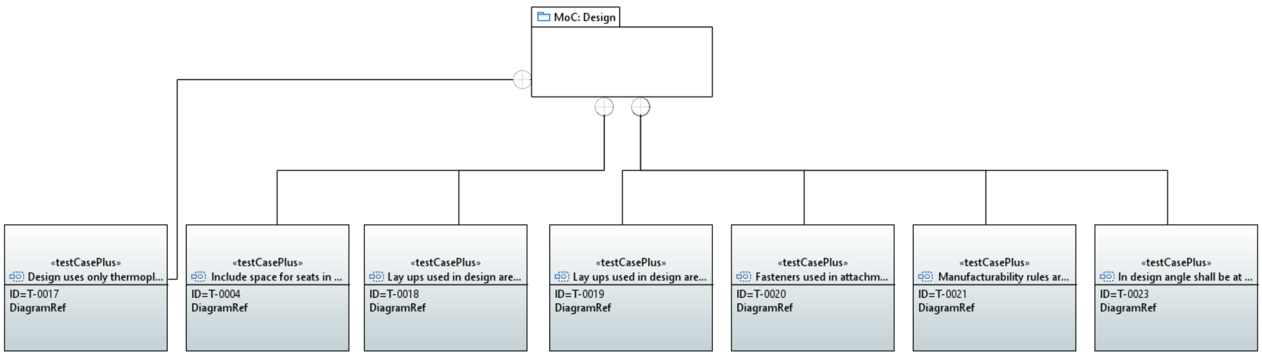


Figure 20 Example of a Means of Compliance view, indicating the test cases related to one Means of Compliance

Besides the requirement verification view, also a MoC view is generated in Papyrus. Figure 20, shows an example for the design MoC. This view indicates all test cases that are connected to this type of MoC. As can be seen from the figure, 7 different test cases have been defined that fall in the category ‘verified by design’.

The last view that has been generated in Papyrus is the requirements traceability view. This view shows the entire trace from the need, stakeholder, requirement to consequence. In this case, consequence means the consequence of not meeting the requirement. Figure 21 shows an example of a requirement traceability view. In this case, the flap robustness requirement is derived from two needs: the certification and safety needs from the certification authorities and government, respectively. If the flap robustness requirement is not met, the consequence is possible fatalities because of an aircraft crash.

The figure clearly shows the difference between the ‘need stakeholder’ and the ‘responsible stakeholder’. The certification authorities and government are the stakeholders that have the need that the flap is safe. However, the FM is responsible for making the flap safe. Therefore, the FM is the responsible stakeholder for this requirement. Figure 21 also indicates that the flap robustness requirement has one derived requirement, which states that the reserve factors of the flap structural elements have to be higher than one. This requirement also has a derived requirement which states that the flap has to withstand all the critical load cases. For both requirements, the consequence of meeting the requirements is missing as this was not filled in KE-chain.

The requirements traceability view is useful in understanding the relationships between the different requirements, needs and stakeholders and identifying gaps in the model (as is the case with the missing consequences).

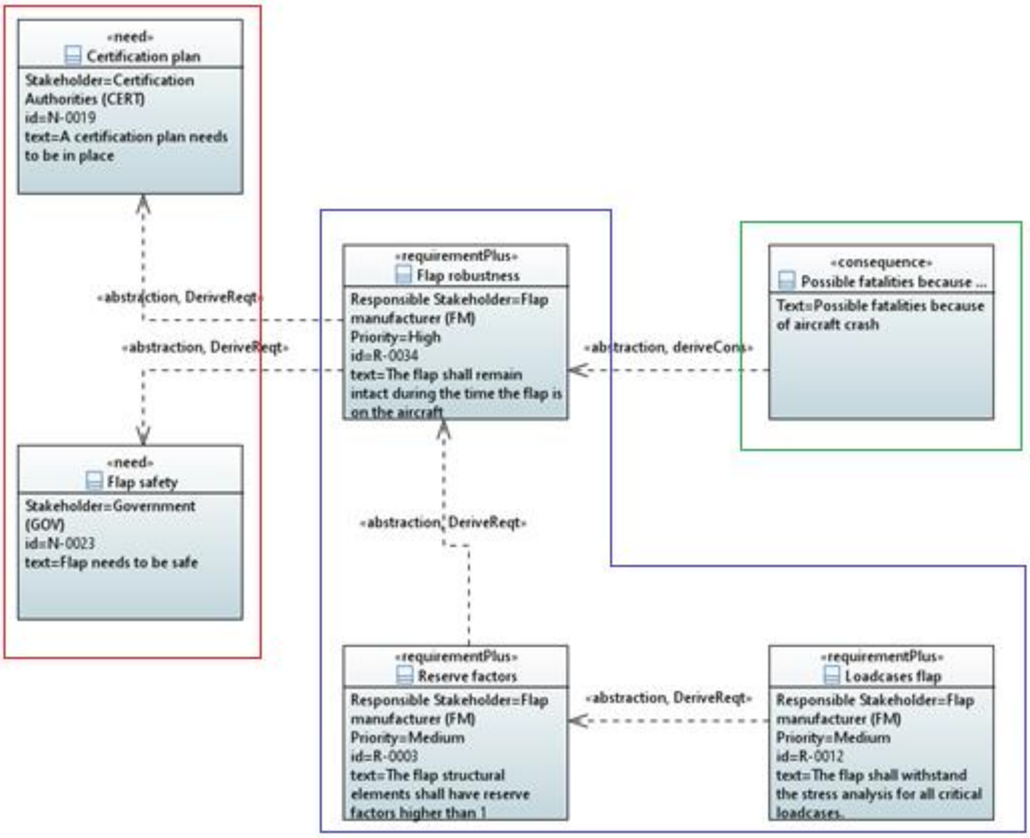


Figure 21 Example of a requirement traceability view

2.3 System Architecting

After the system specification step addressed in the previous section, in the AGILE4.0 MBSE-MDO Framework there is the system architecting step, which is the focus of this section.

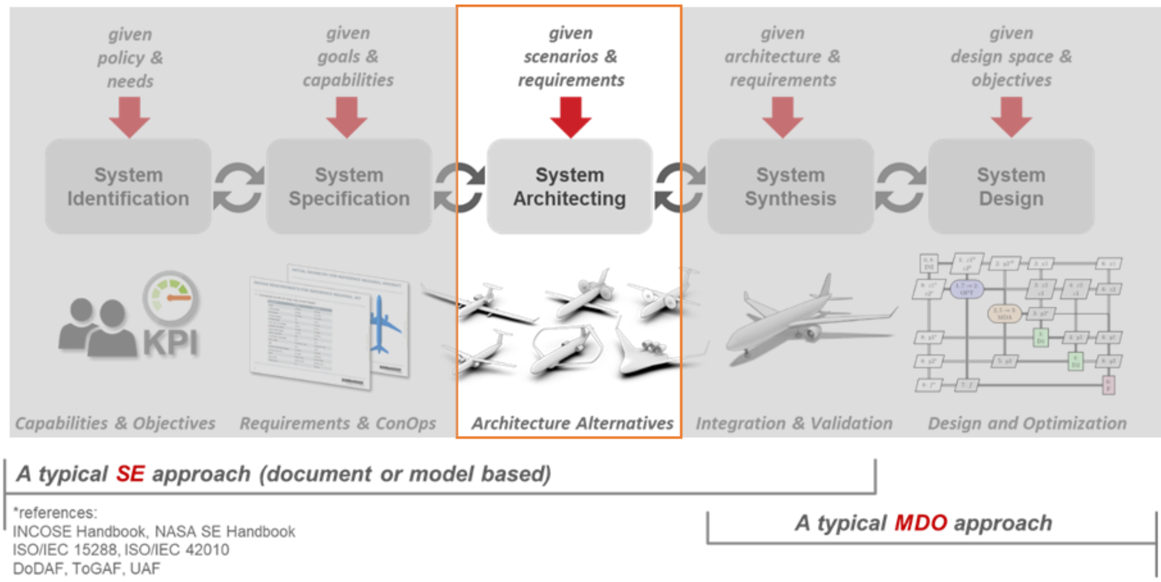


Figure 22: AGILE 4.0 Step III: System Architecting.

The starting point of the architecture modelling process are the boundary functions. The boundary functions are derived from the functional requirements as formulated in D6.3 [1]. The following five boundary functions were used as the starting point for the architecting modelling process:

1. *Withstand stresses and strains*
   The flap has to be able to withstand all load cases that can be applied to the flap.
2. *Deploy flap*
   It must be possible to deploy the flap to obtain the required change in lift.
3. *Change aerodynamics of the wing*
   The flap must be able to change the aerodynamics of the wing such that the required change in lift is achieved.
4. *Restrain skin movement*
   The shape of the flap has to remain within bounds when the loads are applied on the flap. This means that there is a limit on the skin movement during loading.
5. *Transfer load to aircraft*
   The flap has to transfer the loads applied on the flap to the aircraft.

From the boundary functions, the first system of interest and the second system of interest or enabling system are derived. The full architecture model is shown in Figure 23. In this figure, the boundary functions are indicated in purple, the first system of interest in yellow, the part manufacturing in green and the assembly architecture in red. Each of these elements will be explained in more detail below.

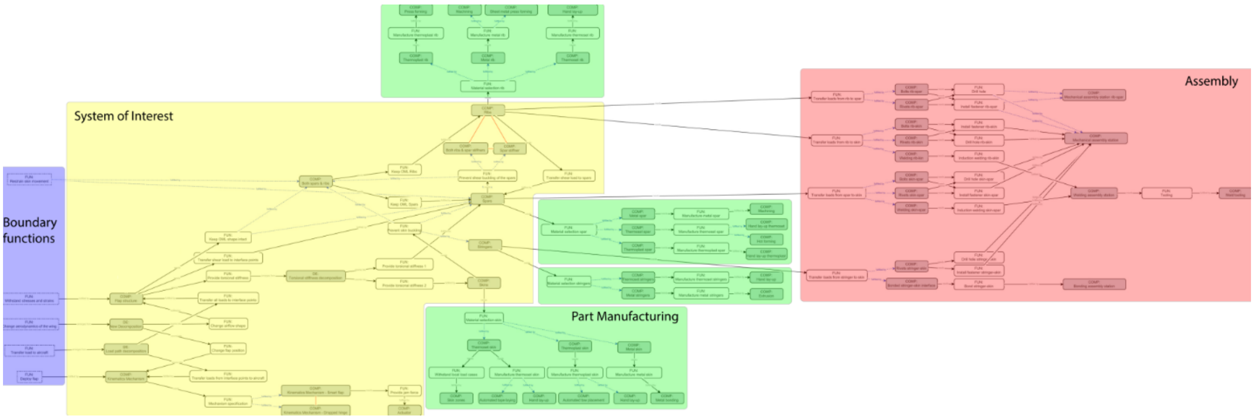


Figure 23: AC1 Architecture model of the System of Interest (flap), Part Manufacturing and Assembly

The first step in the architecting modelling process was to model the first system of interest: the flap. The result of this process is shown in Figure 24.

From the boundary functions two main components are derived: the flap structure and the flap kinematics system. The flap kinematics system is required for boundary functions 2, 3, and 5 (boundary functions can be found in the list below the first paragraph). Two options are available for the kinematics system: the dropped hinge and the smart kinematics flap.

The main function of the flap structure is to keep the shape of the flap and provide proper stiffness to the flap. Therefore, it is required to fulfill boundary functions 1, 3 and 5. Several concepts have been modelled to achieve the required flap stiffness. One is the multi-rib concept, in which both spars and ribs are present within the flap. The other concept is the multi-spar concept, in which no ribs are present. In this case, spar stiffeners could be used to increase the stiffness of the flap.

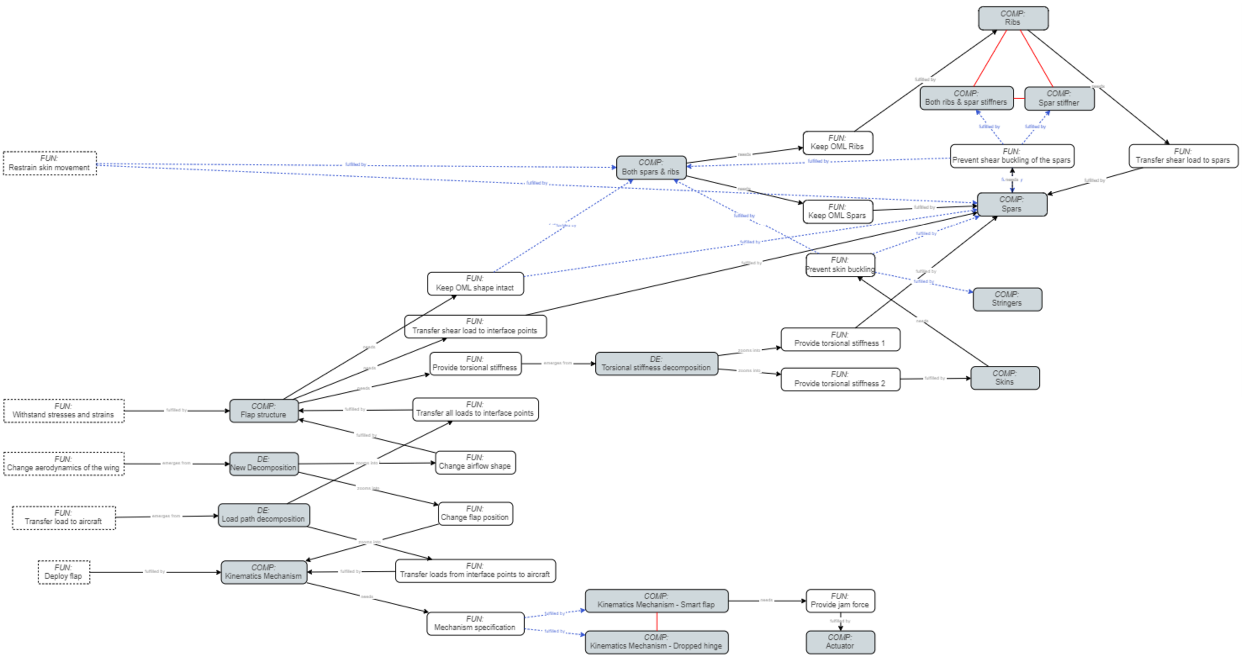


Figure 24: AC1 Architecture model of the System of Interest (flap)

Once the system of interest was modelled, the part manufacturing of the different structural elements were modelled. An example for the skin can be seen in Figure 25.

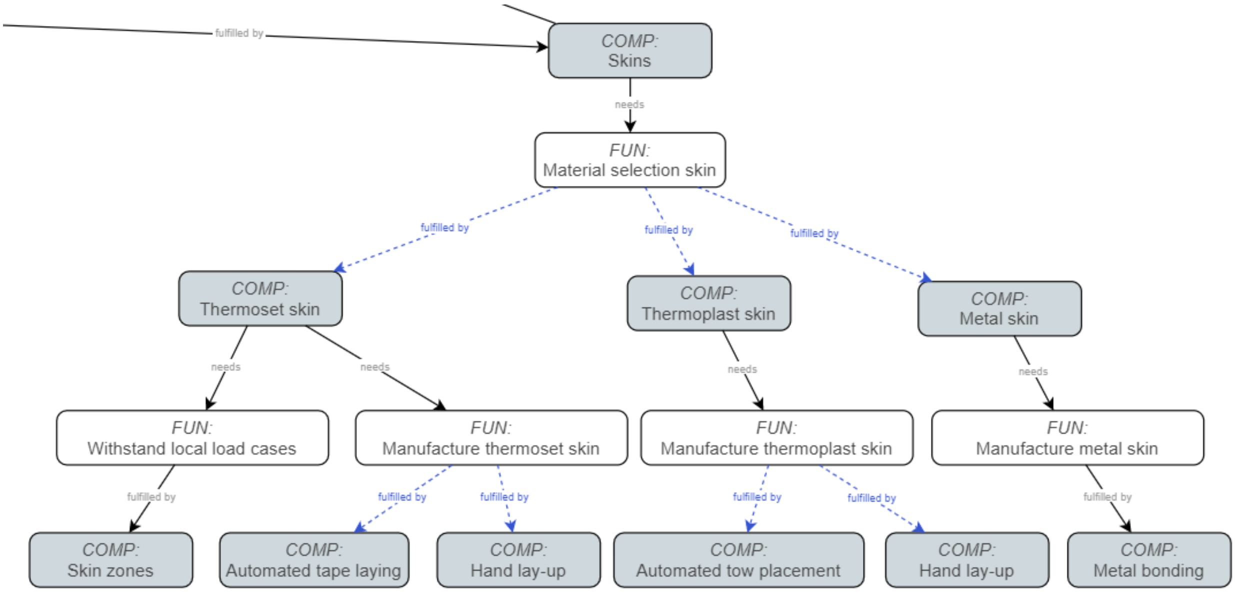


Figure 25: AC1 Architecture model of the skin part manufacturing

As can be seen in Figure 25, the manufacturing method is mainly determined by the material the part is made of. Therefore, the material needs to be selected first. For each type of material, several manufacturing options are available. For example, automated tow placement for a thermoplastic skin or metal bonding for a metal skin.

Once the part manufacturing system was modelled, the assembly of the different parts were modelled. The results are shown in Figure 26. The main function of assembly is to connect the different parts and transfer loads between these elements. Therefore, '*transferring loads*' is the connecting function between the system of interest and the assembly system.

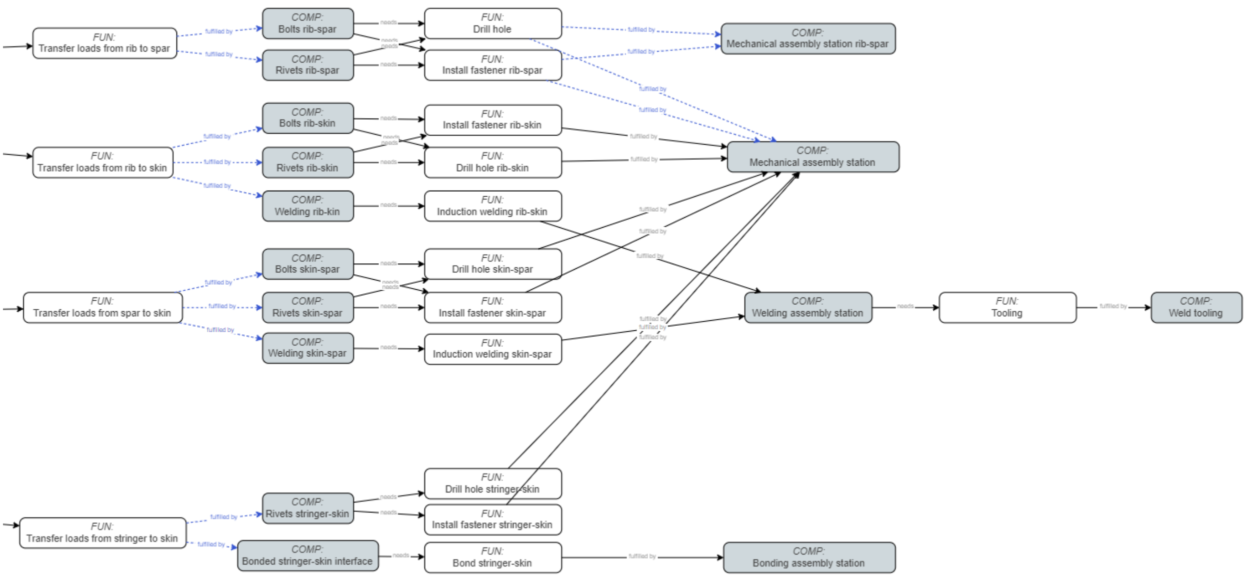


Figure 26: AC1 Architecture model of the assembly system

For each interface between two parts, multiple assembly options were modelled as shown in Figure 26. For example, one can use bolts or rivets to connect the ribs to the spars or one can use welding to connect the spars to the skin. Different functions need to be fulfilled depending on the assembly method that has been chosen. For example, when bolts or rivets are chosen, a hole needs to be drilled and the fastener needs to be installed.

The different functions that need to be fulfilled for a certain assembly option, can be fulfilled at different assembly stations. For example the ribs can be attached to the spars at a dedicated subassembly station or this can be performed at the final assembly station. Within AC1, three different assembly stations were modelled. The '*Mechanical assembly station rib-spar*' station is a subassembly station where ribs are connected to the spars using fasteners. The '*Welding assembly station*' is a subassembly station where the spars are attached to the skin using induction welding. Finally, the '*Mechanical assembly station*' is the final assembly station where all parts and subassemblies are connected to each other using fasteners.

2.4 System Synthesis

The system synthesis step in the AGILE4.0 MBSE-MDO Framework link the MBSE upstream activities with the MDO exploration activities.

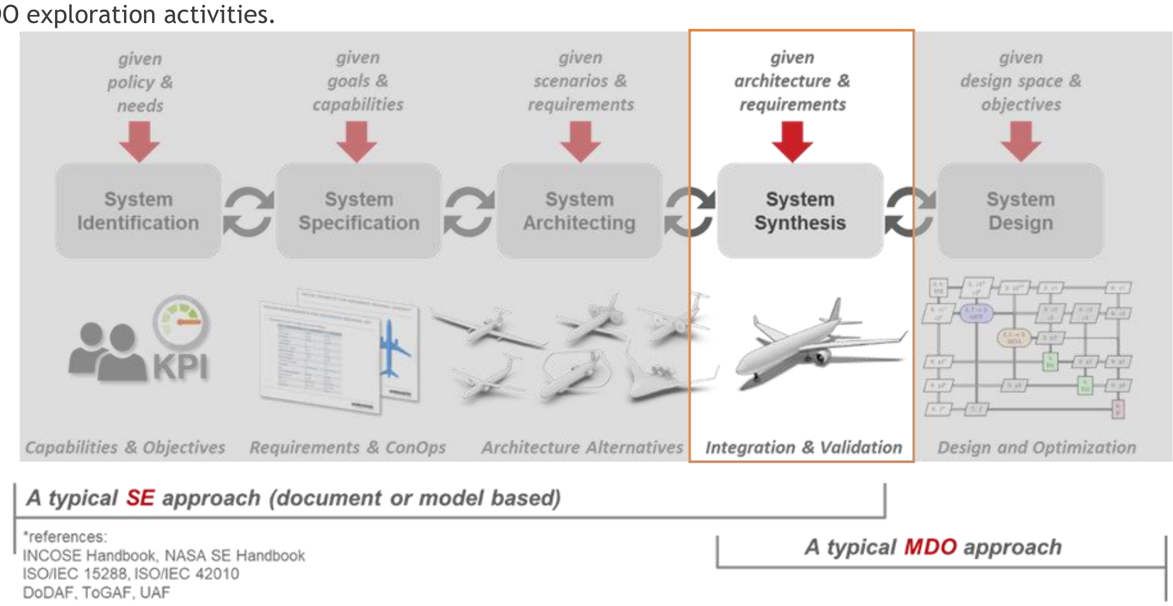
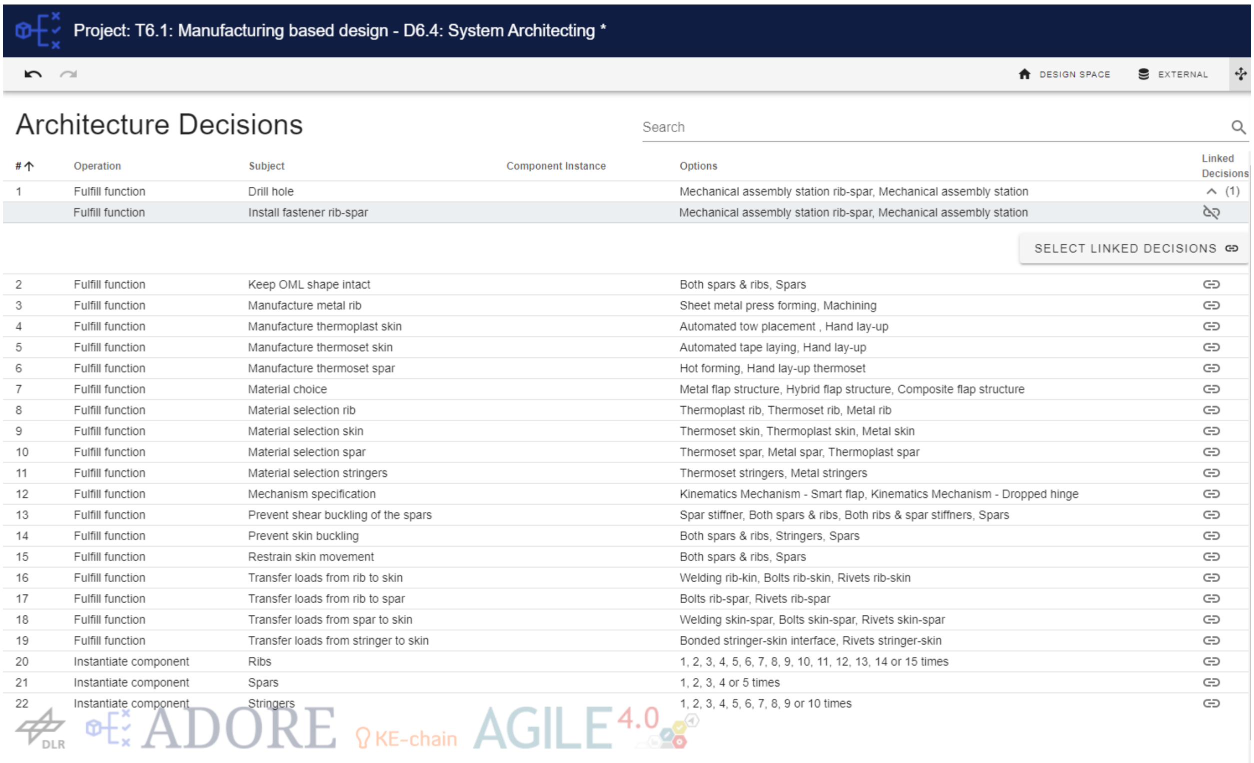


Figure 27 AGILE 4.0 Step IV: Integration & Validation

Once the system of interest and the enabling system were modelled, several architecture decisions could be identified as shown in Figure 28. These architecture decisions have automatically been determined by ADORE. Note that one linked decision has been added to the architecture decisions: when choosing fasteners as assembly method, the drilling of the hole and the installation of the fastener will always be performed at the same assembly station. Therefore, these two decisions have been linked. As soon as an assembly station for one of the two functions (drill hole or install fastener) is chosen, the assembly station for the other function is fixed to the same assembly station.


Project: T6.1: Manufacturing based design - D6.4: System Architecting *

DESIGN SPACE EXTERNAL

Architecture Decisions

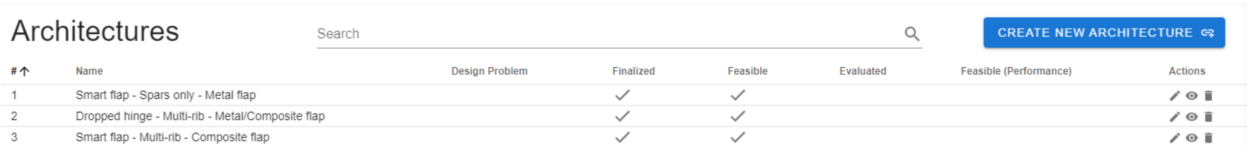
Search

#	Operation	Subject	Component Instance	Options	Linked Decisions
1	Fulfill function	Drill hole		Mechanical assembly station rib-spar, Mechanical assembly station	(1)
	Fulfill function	Install fastener rib-spar		Mechanical assembly station rib-spar, Mechanical assembly station	
2	Fulfill function	Keep OML shape intact		Both spars & ribs, Spars	
3	Fulfill function	Manufacture metal rib		Sheet metal press forming, Machining	
4	Fulfill function	Manufacture thermoplast skin		Automated tow placement , Hand lay-up	
5	Fulfill function	Manufacture thermoset skin		Automated tape laying, Hand lay-up	
6	Fulfill function	Manufacture thermoset spar		Hot forming, Hand lay-up thermoset	
7	Fulfill function	Material choice		Metal flap structure, Hybrid flap structure, Composite flap structure	
8	Fulfill function	Material selection rib		Thermoplast rib, Thermoset rib, Metal rib	
9	Fulfill function	Material selection skin		Thermoset skin, Thermoplast skin, Metal skin	
10	Fulfill function	Material selection spar		Thermoset spar, Metal spar, Thermoplast spar	
11	Fulfill function	Material selection stringers		Thermoset stringers, Metal stringers	
12	Fulfill function	Mechanism specification		Kinematics Mechanism - Smart flap, Kinematics Mechanism - Dropped hinge	
13	Fulfill function	Prevent shear buckling of the spars		Spar stiffner, Both spars & ribs, Both ribs & spar stiffners, Spars	
14	Fulfill function	Prevent skin buckling		Both spars & ribs, Stringers, Spars	
15	Fulfill function	Restrain skin movement		Both spars & ribs, Spars	
16	Fulfill function	Transfer loads from rib to skin		Welding rib-kin, Bolts rib-skin, Rivets rib-skin	
17	Fulfill function	Transfer loads from rib to spar		Bolts rib-spar, Rivets rib-spar	
18	Fulfill function	Transfer loads from spar to skin		Welding skin-spar, Bolts skin-spar, Rivets skin-spar	
19	Fulfill function	Transfer loads from stringer to skin		Bonded stringer-skin interface, Rivets stringer-skin	
20	Instantiate component	Ribs		1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 or 15 times	
21	Instantiate component	Spars		1, 2, 3, 4 or 5 times	
22	Instantiate component	Stringers		1, 2, 3, 4, 5, 6, 7, 8, 9 or 10 times	

SELECT LINKED DECISIONS

Figure 28: AC1 Architecture choices

Several architecture instances have been formulated by making a decision for the different architecture choices. The results are shown in Figure 29. In this case, three architectures have been generated. The first one is a smart kinematic flap which is completely made out of metal and uses the multi-spar concept. This means that no ribs are present in this flap. The second architecture is a dropped hinge flap, manufactured from both metal as well as composite using the multi-rib concept. The third architecture is again a smart kinematics flap. In this case the flap uses the multi-rib concept and is produced using only composites.


Architectures

Search

CREATE NEW ARCHITECTURE

#	Name	Design Problem	Finalized	Feasible	Evaluated	Feasible (Performance)	Actions
1	Smart flap - Spars only - Metal flap		✓	✓			
2	Dropped hinge - Multi-rib - Metal/Composite flap		✓	✓			
3	Smart flap - Multi-rib - Composite flap		✓	✓			

Figure 29: AC1 Architecture instances

All the parameters needed for the architecture optimization are set. Several design competences are needed for the optimization of these architectures.
Figure 30 shows part of the design competences in KE-chain.

The system architecture can be linked to the design competences using MultiLinQ. With MultiLinQ, one can check whether all the quantities of interest that were defined within the system architecture are covered by the design competences included in the optimization problem using the compliance matrix. The compliance matrix for AC1 is shown in
Figure 31.

Design competences overview

Below you find an overview of all design competences in the scope of this design study

ADD EDIT DELETE

Design competence	Function description	Model version	Input description	Output description	Input data	Output data	CMDOWS file	Import option
AMload	Generate the loads for the flap	1.0	Loadcase, overall aircraft design incl. flap geometry	Pressure and forces	AMload-input_TGVG15e.xml	AMload-output_A1hMNvm.xml		CPACS
Aerodynamic Analysis	Evaluates the aerodynamic performance of the flap	1.0	2D cross sections of the wing and flap, flight conditions	Aerodynamic data	Aerodynamic_Analysis-input_OTEjr1R.xml	Aerodynamic_Analysis-output_DlkXAD5.xml		CPACS
Landing performance tool	Evaluates the landing performance of the aircraft	1.0	Aerodynamic data	Landing performance	Landing_performance_tool-input_pLJ05ZL.xml	Landing_performance_tool-output_X9ZxidF.xml		CPACS
Initiator	First estimation of outer geometry, masses and performance of the aircraft	1.0	Top level aircraft requirements	First estimation of outer geometry, masses and performance	Initiator-input_KGFakXl.xml	Initiator-output_2IN2K14.xml		CPACS
Multi-Disciplinary Modeler - MDM	Moveable generator for flaps	1.0	Flap outer geometry, hinge line & position	IGES files with geometry, XML with detailed part description	Multi-Disciplinary_Modeler_-_MDM-input_9Uwr1LV.xml	Multi-Disciplinary_Modeler_-_MDM-output_ns3pQIW.xml		CPACS
Proteus	Determines the required thicknesses of the internal structure	1.0	Internal stresses and strains, material database	Thickness of the internal structure	Proteus-input_3FBarsz.xml	Proteus-output_9dqWE6o.xml		CPACS
CATMAC	Calculates costs of the flap	1.0	Manufacturing and assembly details, rate database	Costs	CATMAC-input_WojOU1I.xml	CATMAC-output_FZStGxQ.xml		CPACS
Production rate tool	Calculates the production rate of the flap	1.0	Manufacturing and assembly details	Production rate	Production_rate_tool-input_crFQTuY.xml	Production_rate_tool-output_fJS7GvS.xml		CPACS

Figure 30: AC1 Design Competences as visualized in KE-chain

The rows in
Figure 31 indicates the different Quantities of Interest's (QoI's) that were assigned to the system architecture using ADORE. The columns indicate the design competences that are present in the MDAO workflow. As one can see, the QoI's are calculated by four design competences: CATMAC, MDM, Production rate tool and Proteus (description of these design competences is provided in Figure 30). The other tools are required to verify the requirements, however they do not calculate any of the QoI's assigned in ADORE.

		Tools									
Components	**QOIs**	AMload	Aerodynamic Analysis	CATMAC	Constraint	Initiator	Landing performance tool	Multi-Disciplinary Modeler - MDM	Objective	Production rate tool	Proteus
Flap structure	Flap structure cost			✓							
Flap structure	Flap structure weight							✓			
Kinematics Mechanism	Mechanism Cost			✓							
Kinematics Mechanism	Mechanism weight							✓			
Machining	Machining production rate									✓	
Mechanical assembly station	Mechanical assembly station production rate									✓	
Mechanical assembly station rib-spar	Mechanical assembly rib/spar production rate									✓	
Metal rib	Rib thickness							✓			
Press forming	Press forming production rate									✓	
Ribs	Rib Pitch							✓			
Ribs	Rib Reserve factors										
Skin zones	Skin Zone reserve factor										
Skin zones	Skin zone stack										
Spars	Spar reserve factors										
Thermoplast rib	Rib Stack							✓			
Thermoset rib	Rib Stack							✓			

Figure 31: AC1 Compliance matrix

2.5 System Design

The last step of the AGILE4.0 MBSE-MDO Framework is the system design. Several activities are performed in this step and addressed below: Workflow implementation and execution, Optimization, Trade-off and Verification & Validation.

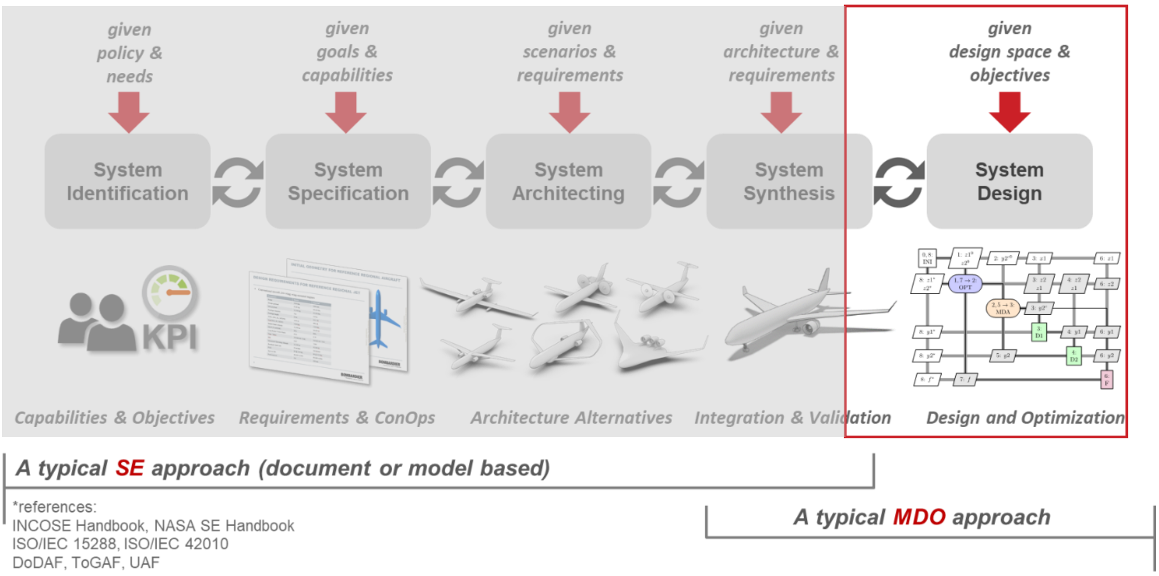


Figure 32: AGILE 4.0 Step IV: System Synthesis.

2.5.1 Workflow implementation and execution

In Figure 33, the XDSM obtained from KADMOS and VISTOMS is shown. It must be noted that in reality some of the design competences are combined in a single tool, this will become clear in the actual materialized workflow.

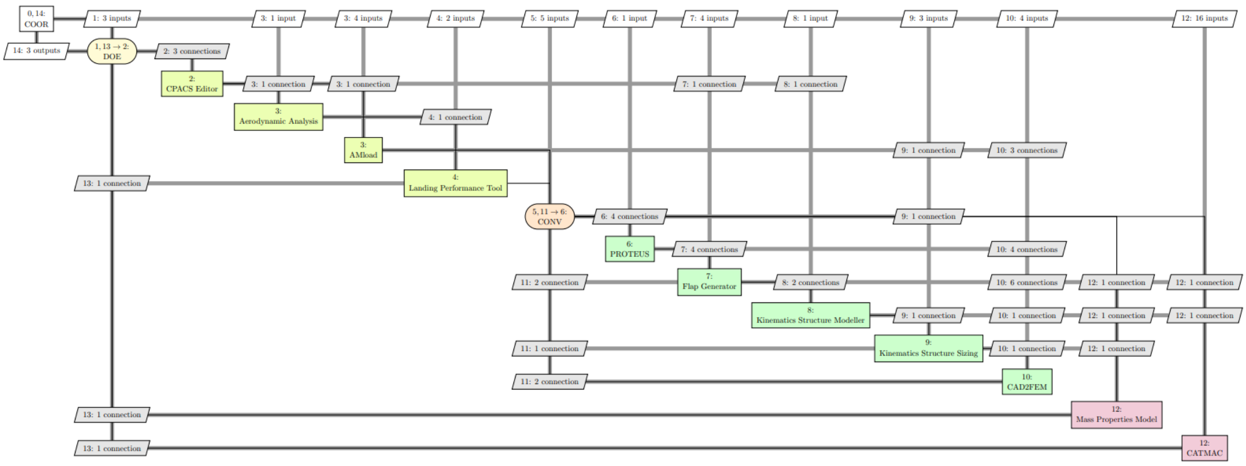


Figure 33: AC1 XDSM Flap + Production System

In Figure 34, the workflow implementation in RCE is shown. It can be seen that in contrast to the XDSM (as shown in Figure 33), no converger loop is included in the workflow. Instead, it has been decided to include the MDM tool twice in the workflow. In addition, the 'landing performance' and 'aerodynamic analysis' competences are combined into the 'PYNLL' tool. Also, the 'Flap generator', 'Kinematics structure modeller', 'Kinematics structure sizing' and 'CAD2FEM' competences are all included in the 'MDM' tool.

It can be seen that before any tool is called, some scrips are executed, these scripts map the design variables -which do not have a direct place in the CPACS schema- to the CPACS standard, such that the tools can make use of the standard CPACS schema. An example of this is the flap translation, which is given as a fraction of the flap chord, however, in CPACS an absolute value must be specified. Three tool instances are remotely called upon using BRICS, the first is NLR's tool: 'AMload' and GKN Fokker's tool 'MDM' is called twice.

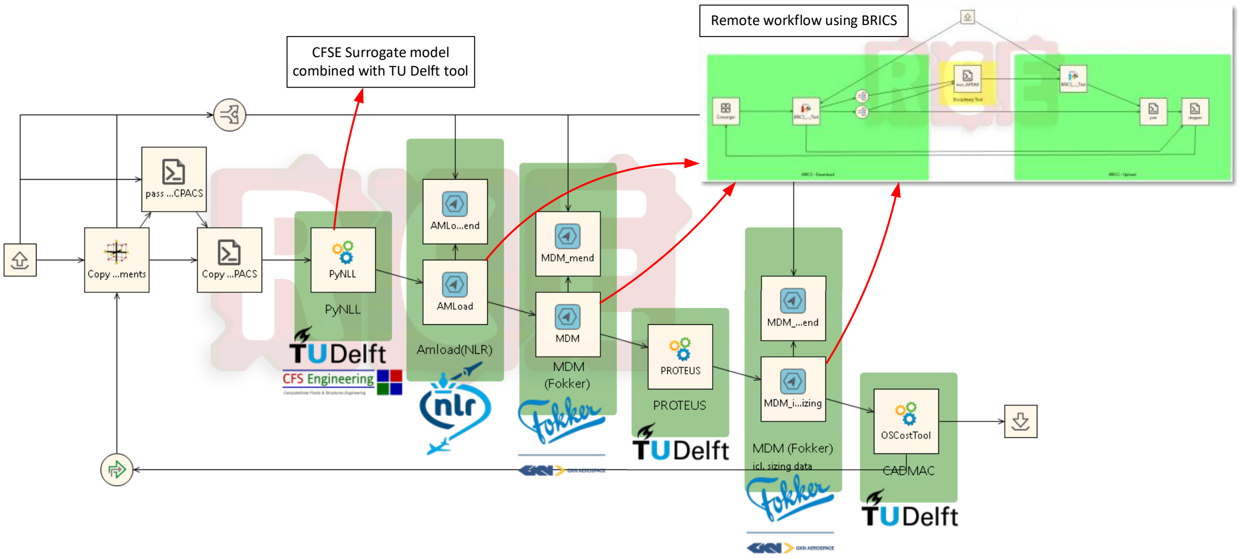


Figure 34: AC1 DoE workflow implementation in RCE including all involved partners

For the workflow several tools are used each with a specific functionality and playing specific role in the workflow. These are:

1. **PYNLL**: Aerodynamic analysis tool, calculates the wing 3D Cl_{max} in landing configuration based on the wing geometry, flap geometry and flight conditions. Tool uses the high fidelity aerodynamics surrogate to obtain 2D lift polars of sections along the wing span. Based on the 3D Cl_{max}, an estimation of the landing distance can be calculated
2. **AMload**, a loads analysis tool, determines the loads exerted on the flap in certain flight conditions.
3. **MDM** including CAD2FEM, MDM is a tool that generates a model of the flap that can be used by other tools. It is coupled to CAD2FEM, which transforms the model from MDM into a FE model, which stored in the form of a BDF file. MDM can also estimate the weight of the flap.
4. **PROTEUS**, a sizing tool, based on a FEM model it determines the required thickness of the flap skin.
5. **CADMAC**, an open source tool that calculates the recurring cost of manufacturing the individual parts in the flap.

2.5.2 Optimization

Regarding the optimization approach, the combination of a relatively long MDA time and potential license issues prompted the selection of an off-line optimization process. Therefore, it was decided to build a Design Of Experiments (DoE) using the AC1 workflow, which would then be used to perform the optimization process using NLR RSM and optimization algorithms, without the need for further calls to the workflow.

2.5.2.1 RSM building

Due to the inability to automate the high fidelity aerodynamic analysis a surrogate model was created for the expected input ranges related to the DOE settings in Table 1. NLR provided support during the task of selecting the configurations to be computed and integrated into the workflow. Information about RSM toolboxes and optimization algorithms used in the project can be found in D5.1 [5], D5.2 [6] and D5.4 [7].

2.5.2.2 Design of Experiment

A Design of Experiments using the workflow described in the previous section has been performed. In Table 1, the variables and their function are presented.

Table 1: DOE variables overview

Variable	Role	Range	Description
Flap chord	*Design variable*	*0.15 - 0.35 chord*	*The flap chord length is specified as a ratio? of the local wing chord. This variable determines the size of the flap.*
Flap translation in landing configuration	*Design variable*	*0.3 - 0.8 chord*	*The flap translation is measured in ratio of the wing chord, a higher number means more translation and more lift increase*
Rib pitch	*Design variable*	*150-1000 mm*	*Rib pitch is the minimal distance between the ribs in the flap, a smaller rib pitch leads to more ribs and vice versa.*
Mechanism type	*Design variable*	*Dropped hinge or Smart flap*	*As described above the mechanism type determines the total flap weight and cost*
Flap system total weight	*Quantity of Interest*		*The flap system total weight is the weight of the flap plus the kinematic system, meaning the hinges, beams bearings etc.*
Flap system total cost	*Quantity of Interest*		*The flap system total cost is the cost of the flap plus the kinematic system, meaning the hinges, beams bearings etc. Only mono-part cost is considered*
Landing distance	*Quantity of Interest*		*The landing distance at Maximum Landing Weight with flaps extended in landing condition.*
Minimal reserve factor of skin	*Constraint*	*>1*	*The structure of the flap is not allowed to fail therefore reserve factors must be higher than 1. Because of the availability of analysis tools, the constraint is limited to the skins. This constraint is handled within the MDO evaluation, and therefore need not be included explicitly in the top-level optimizations.*

2.5.2.3 Surrogate modelling on DOE data sets (NLR support from WP3)

The DOE data set described above was obtained from sequential randomized DOE's: in different areas of the design domain different DOE approaches (like partial central composite designs, box-behnken designs, latin-hypercube sampling (LHS) designs) were combined into an overall DOE data set. The overall data set comprises:

- 41 points for Dropped Hinge Flap (DHF)
- 36 points for Smart Flap (SMF)

For both flap mechanism types, all the 3 design variables are varied within their ranges (chord ϵ [0.15,0.35], trans ϵ [0.3,0.8], pitch ϵ [150,1000] mm). The categorical variable 'flap mechanism type' is non-trivial to include directly in the optimization. Because this variable only has 2 possible values (DHF and SMF), it is more efficient to consider separate optimization problems for each of the flap mechanism types. Therefore also separate surrogate models are created for the data sets of each of the flap mechanism types. The resulting DOE data sets for the DHF and SMF are illustrated in the Figure 35.

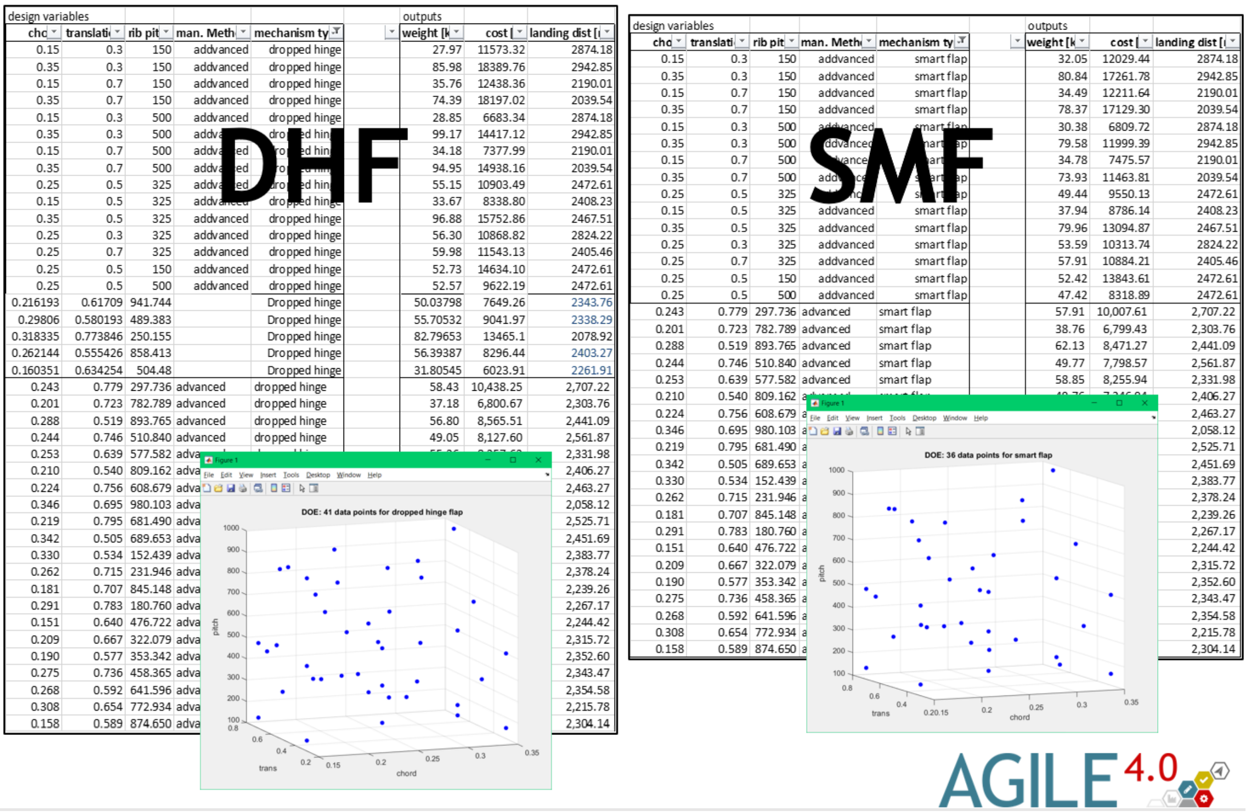


Figure 35: Illustration of the resulting DOE data sets for the DHF and SMF.

In the optimization, the 3 main outputs are considered:

- flap weight: driven by structural design
- flap cost: driven by manufacturing
- a/c landing distance: driven by flap aero-performance

For the surrogate models various methods are evaluated, a.o.:

- Scattered-interpolant (SCI)
- Radial-basis functions (RBF)
- Generalized-regression nets (GRN)
- Feed-forward neural nets (FFN)
- Gaussian-process regression (GPR) (kriging)

For the DHF, the GPR surrogate models showed best accuracy: the mean and max values of the absolute percentage errors of predictions on the DOE data set:

- weight: [mean, max]: [7.8%, 19.7%]
- cost: [mean, max]: [5.4%, 17.2%]
- landing:[mean, max]: [0.4%, 1.7%]

To assess the accuracy of the surrogate models in the whole design domain, the error values in the DOE data sets are interpolated in the whole domain. For the DHF, the percentage errors estimations on a 4000pt LHS dataset in the whole design domain are (see Figure 36):

- weight: percentage error ϵ [-49%, +45%]
- cost: percentage error ϵ [-14%, +30%]
- landing: percentage error ϵ [-1%, +8%]

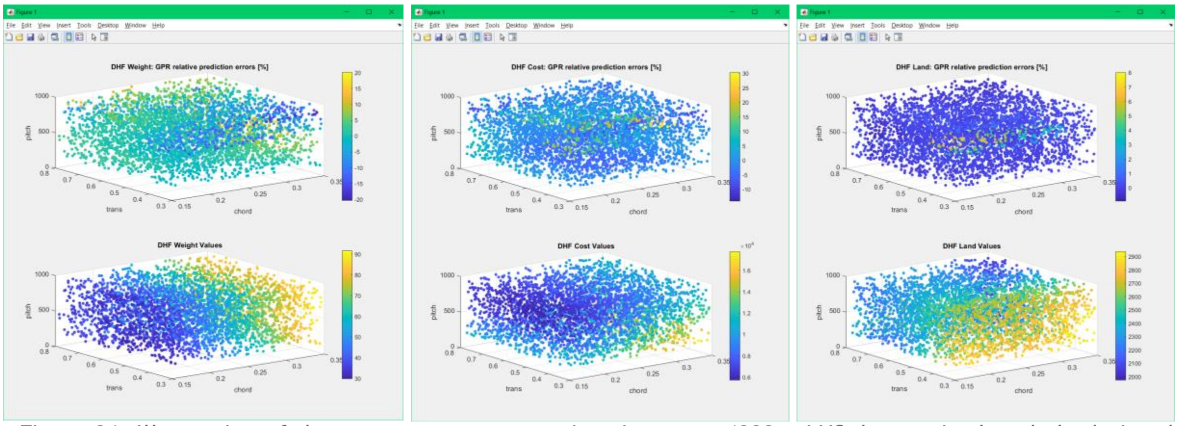


Figure 36: Illustration of the percentage errors estimations on a 4000pt LHS dataset in the whole design domain for the DHF.

For the SMF also the GPR surrogate models showed best accuracy: the mean and max values of the absolute percentage errors of predictions on the DOE data set:

- weight: [mean, max]: [7.8%, 19.7%]
- cost: [mean, max]: [5.4%, 17.2%]
- landing:[mean, max]: [0.4%, 1.7%]

- For the SMF, the percentage errors estimations on 4000pt LHS dataset in design domain are (see Figure 37):
  - weight: percentage error ϵ [-35%, +38%]
  - cost: percentage error ϵ [-26%, +21%]
  - landing: percentage error ϵ [-1%, +12%]

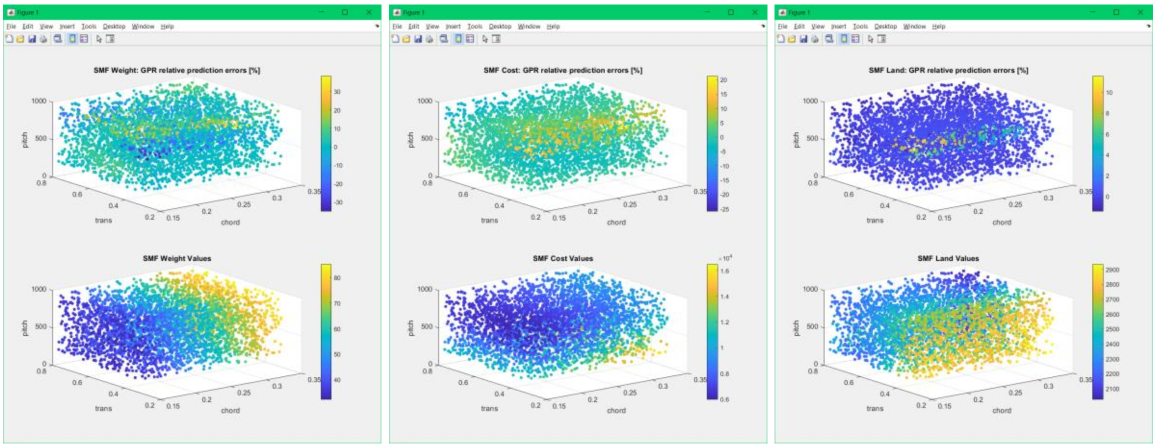


Figure 37: Illustration of the percentage errors estimations on a 4000pt LHS dataset in the whole design domain for the SMF.

With the selected methods, the surrogate models evaluations are very fast. Typically for multi-objective optimizations in the order of 1e5 function evaluations are required. With the selected methods these 1e5 evaluations can be run in just few seconds on a standard PC.

2.5.2.4 Surrogate-based optimization (NLR support from WP3)

Several optimization evaluations have been performed with the surrogate models for the DHF and SMF quantities of interest. First some Pareto ranking evaluations were done on random search data sets in the design domain, in order to determine the regions of interest.

Subsequently several multi-objective optimizations (MOO) using NSGA2 (non-dominated sorting genetic algorithm) search were performed for more detailed / coordinated and better targeted search. In these MOO evaluations, the minimum weight and cost are used as objectives, and the landing field length of less than 2500m is used as non-linear constraint function.

First for the DHF, this MOO evaluation (NSGA2 weight-cost Pareto front for land<2500) is done in the large design space (with lower- and upper bounds: lb,ub=[0.15,0.3,150],[0.35,0.8,1000]). The population size is 1000 and the number of generations needed for convergence of the Pareto front is 125, with a total number of objectives and constraint function evaluations of 125001. The resulting Pareto front has 350 points (green dots in plots in Figure 38).

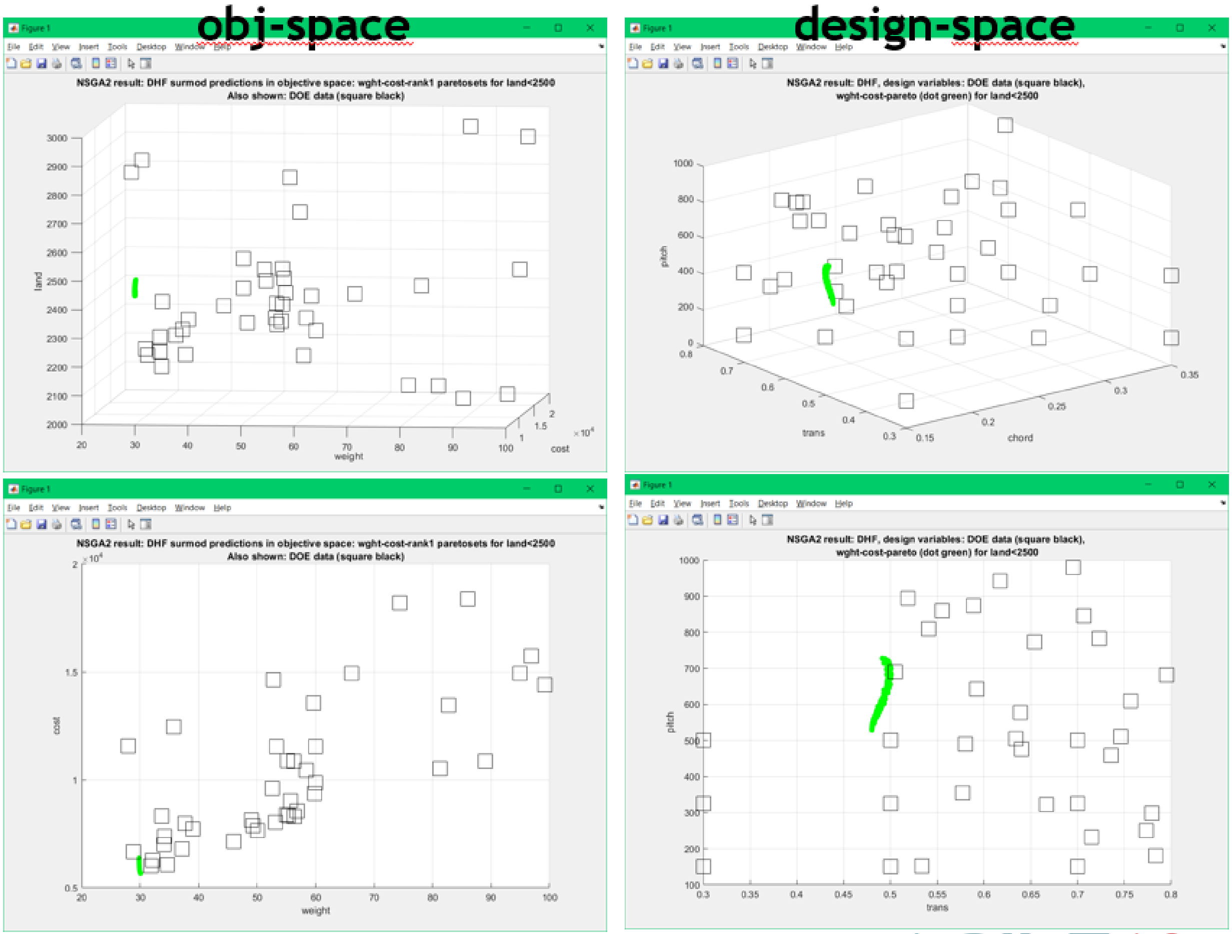


Figure 38: Illustration for the DHF of the Pareto front (green dots) and the original DOE design points (black squares) in the 3D weight-cost-landing-objective space (left) and the 3D chord-trans-pitch-design space (right).

Similarly, for the SMF an analogous MOO evaluation was performed, yielding a slightly different Pareto front. The population size is also 1000 and the number of generations needed for convergence of the Pareto front is 132, with a total number of objectives and constraint function evaluations of 132001. The resulting Pareto front has 350 points (green dots in plots in Figure 39).Figure 39: Illustration for the SMF of the Pareto front (green dots) and the original DOE design points (black squares) in the 3D weight-cost-landing-objective space (left) and the 3D chord-trans-pitch-design space (right).

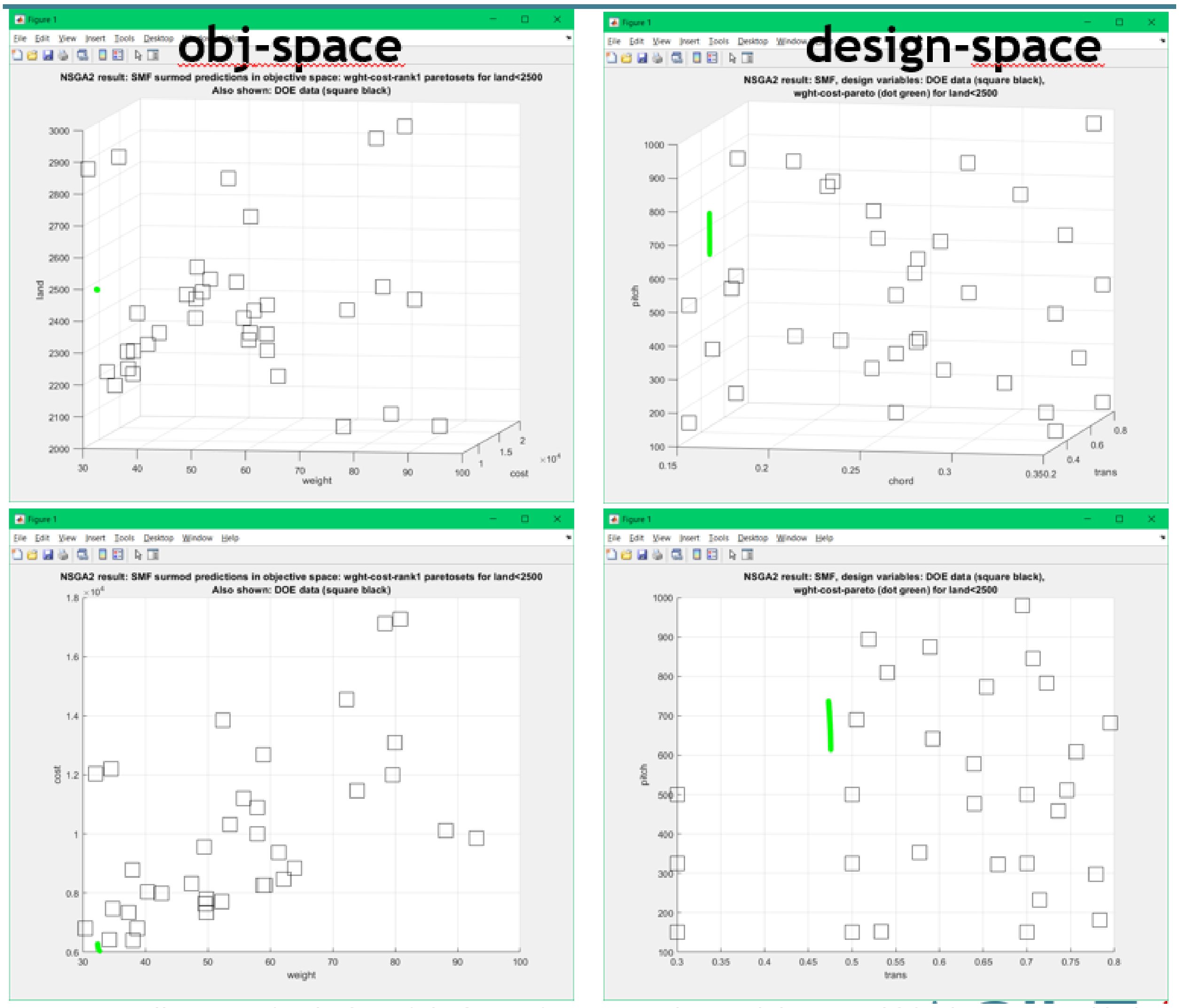


Figure 39: Illustration for the SMF of the Pareto front (green dots) and the original DOE design points (black squares) in the 3D weight-cost-landing-objective space (left) and the 3D chord-trans-pitch-design space (right).

To determine the overall optimum design, we compare the Pareto fronts of the DHF and the SMF (Figure 40).

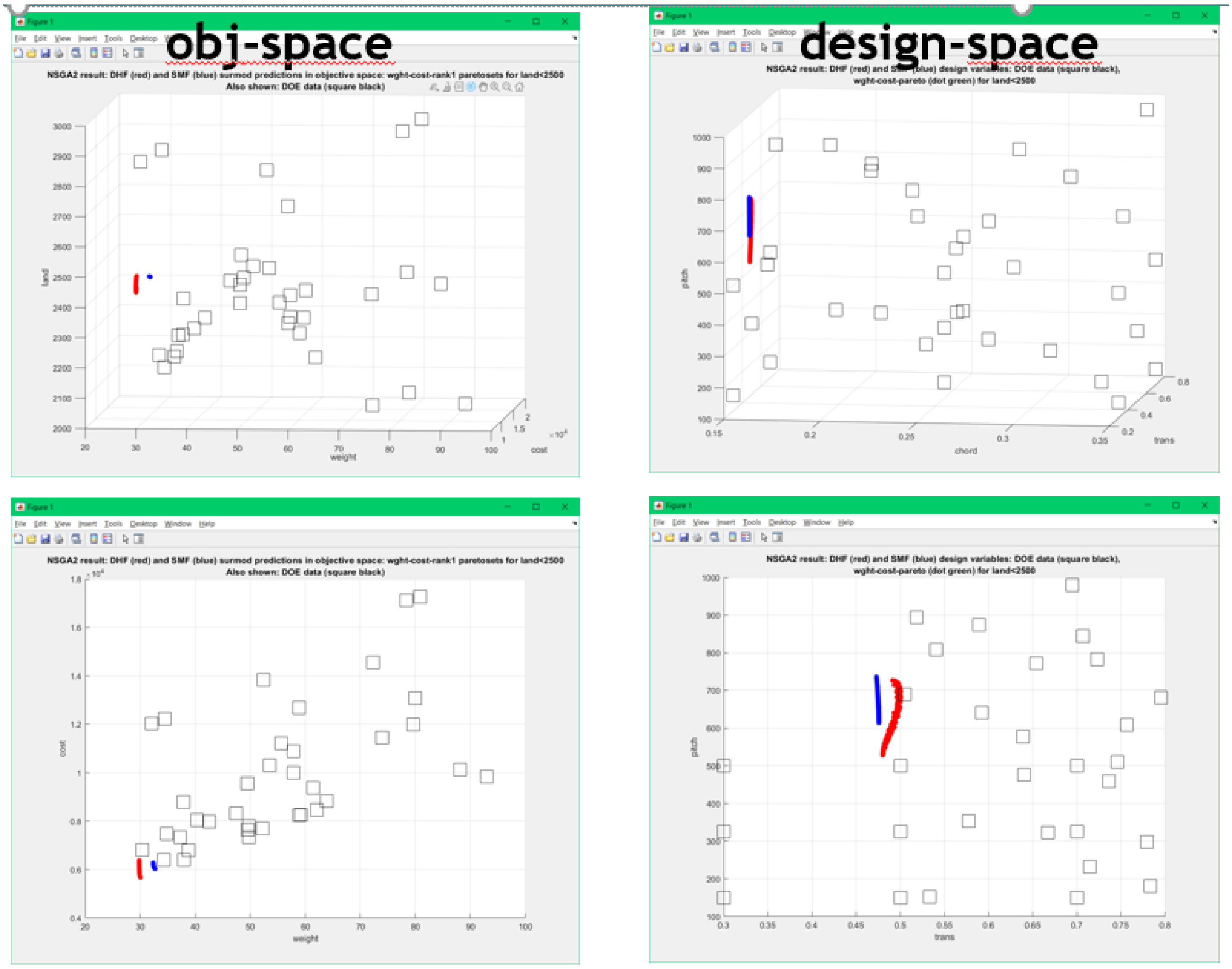


Figure 40: Illustration for the Pareto front data points for the DHF (red dots) and for the SMF (blue dots). Plots are given for the 3D weight-cost-landing-objective space (left) and the 3D chord-trans-pitch-design space (right).

Obviously, The DHF results clearly dominate the SMF results: the DHF Pareto points have lower values for both weight and cost than the SMF Pareto points. In design space, the Pareto points for both flap mechanism types are close together, all close to the lower bound for the chord and trans values of about 0.48 and pitch of around 650mm.

2.5.3 Trade-off

A value driven trade-off study considering mass, cost and landing distance criteria was performed using DLR's VALORISE software. Two scenarios are considered, the value settings used are shown in
Figure 41 and
Figure 42. For each design point, a value metric is aggregated based on these settings. It can be seen that in scenario 1, all criteria have the same weight and the 'utility curves' are linear and can be considered a base-line case. In scenario 2, more weight is given to the landing distance and cost criteria and the utility curves are changed to meet the decision makes preferences. For example, the mass utility curve results in less penalty for a heavier flap up to a certain point.

In Figure 43 and Figure 44 the value is plotted against mass and cost respectively for both scenarios. It can be seen that in case of scenario 1, the highest value options also correlates to the lowest cost and mass options, in other words, no Pareto front is formed (there are 2 Pareto point in the value-cost graph, but these points are very similar in the design space). This is the behaviour as expected from the results presented in the previous section. Based on this study, design #13 would be selected. Looking at the results of scenario 2, it can be seen that in terms of value, some different designs become interesting. Still design #13 scores well, but design #20 and #41 are now higher in value despite a larger mass and cost. This is due to a good landing distance performance, and adequate cost and weight performance.

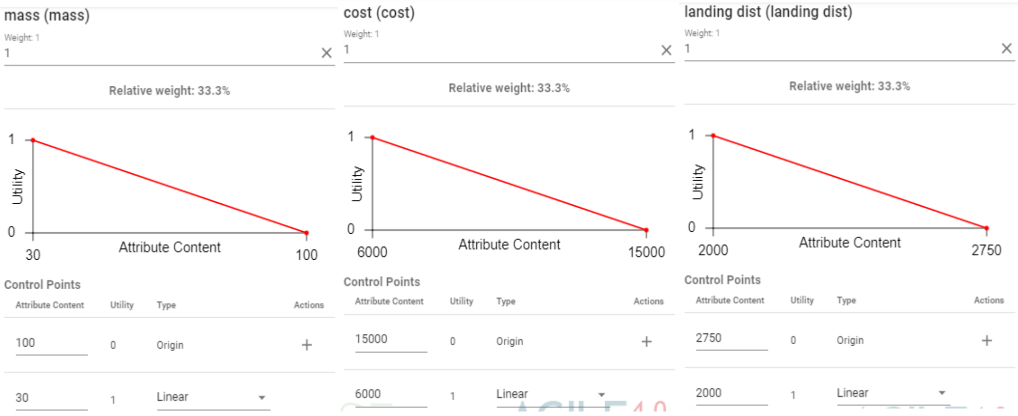


Figure 41: Valorise settings for Scenario 1.

A summary of the design variables and objective values corresponding to the three discussed designs is given in Table 2 and in Figure 45, a picture of the three flap designs as created by MDM is shown. It can be seen that design #13 correlates to a small chord, large translation dropped hinge, agreeing with the findings in the previous section. #20 and #41 however, have a large chord and large translation, leading to higher mass and cost but improving the landing performance. In this case both a dropped hinge or a smart flap mechanism could be selected, where the dropped hinge is lighter, the smart flap is cheaper. Interestingly, all designs have a similar rib pitch of around 800mm, this is bit higher than the suggested optimal value of 650mm in paragraph 2.5.2.4. This could be due to the fact that in some cases a different rib pitch might lead to the same amount of ribs.

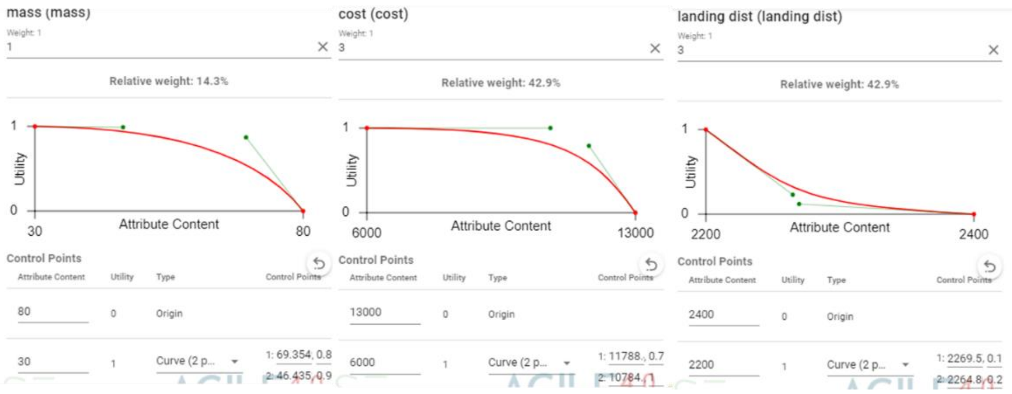


Figure 42: Valorise settings for Scenario 2.

Table 2: Design variable and objective values for design #13, #20 and #41

Design #	Chord fraction	Translation fraction	Rib pitch [mm]	Mechanism Type	Mass [kg]	Cost [$]	Landing distance [m]
#13	0.181	0.707	845.148	Dropped hinge	32.12	6259.28	2239.26
#20	0.308	0.654	772.934	Dropped hinge	59.80	9346.91	2215.78
#41	0.308	0.654	772.934	Smart Flap	63.93	8835.43	2215.78

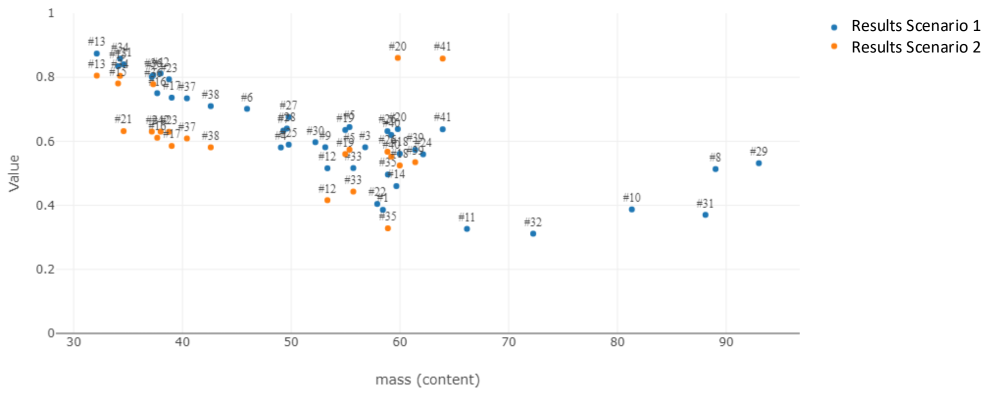


Figure 43: Valorise results for Scenario 1 and 2, Value vs mass [kg]

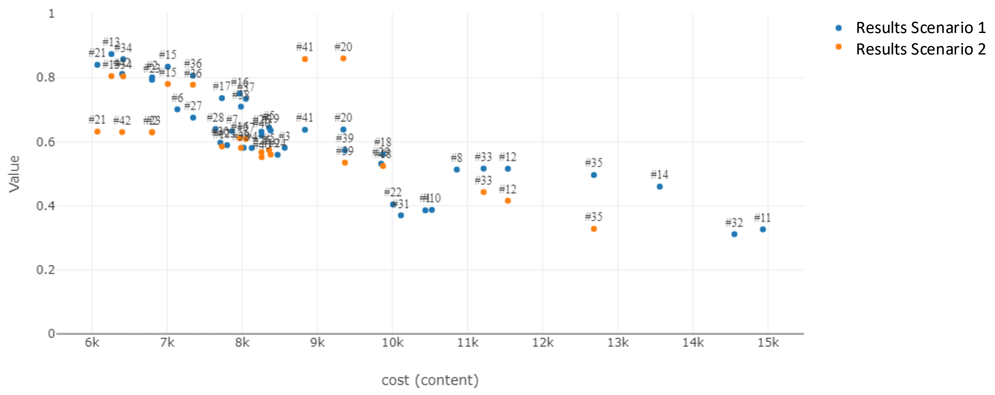


Figure 44: Valorise results for Scenario 1 and 2, Value vs cost [$]

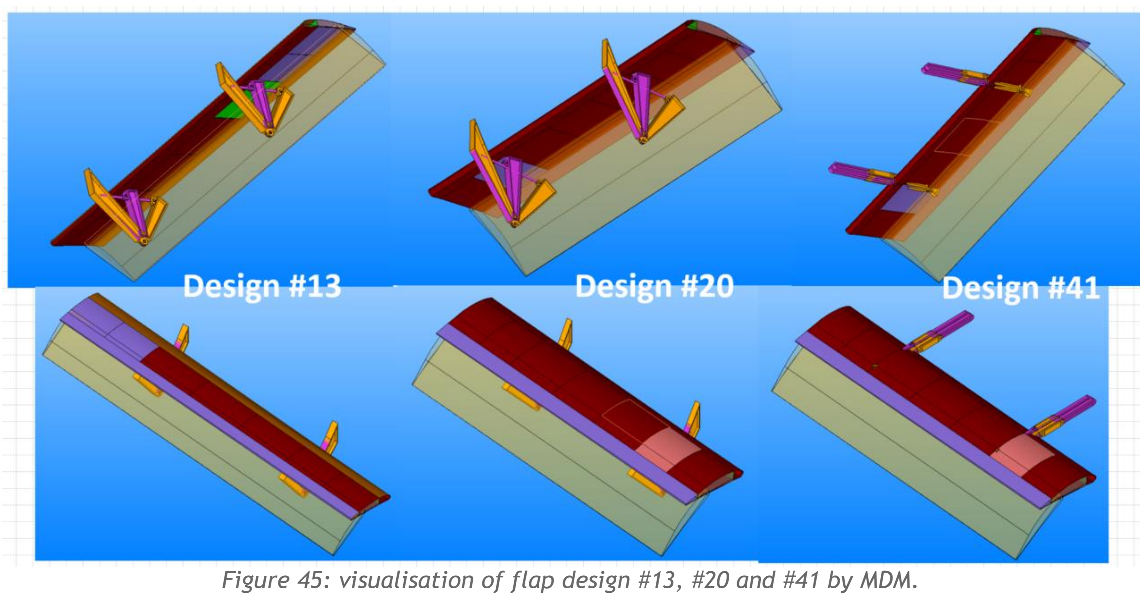


Figure 45: visualisation of flap design #13, #20 and #41 by MDM.

2.5.4 Verification and Validation

Once the interesting solutions are identified, it is important to check the solution meets the requirements and it is therefore valid. In KE-Chain, a CPACS results file can be coupled to a workflow and the requirements (as specified in Section 2.2) can be verified using the RVF. In Figure 46 the results of this action are shown corresponding to design #41. It can be seen that for this design not all the requirements are met. The reason is that for some of the requirements no feasible solution could be found and some of the constraints have been relaxed during the execution of the MDO workflow. In addition, some requirements have not been verified as no suitable design competence was available.

Requirement	ID	Text	Type	Validation	Compliance value	Compliance margin (%)
Reserve factors	R-0003	The flap structural elements shall have reserve factors higher than 1	Performance	Valid	1.11318	11.32
Aircraft landing distance	R-0018	The aircraft shall have a maximum landing distance of 1400 meters during nominal landing conditions	Performance	Invalid	1913.1322365813576	-36.65
Aircraft cruise speed	R-0020	The aircraft shall fly at Mach 0.78 maximum during cruise	Performance	Invalid	0.78	0
Aircraft range	R-0021	The aircraft shall have a range of at least 1890 km with maximum payload	Performance	Not started		
Aircraft passengers	R-0022	The aircraft shall have a maximum number of passenger of 90	Design constraint	Invalid	90	0
Aircraft maximum payload	R-0023	The aircraft shall have a maximum payload of at least 15000 kg	Design constraint	Invalid	11500	-23.33
Flap manufacturing costs	R-0028	The flap shall be manufacturable for less than $80k at shipset 100	Design constraint	Valid	8835.43	88.96
Flap weight	R-0029	The flap shall weight less than 40kg	Design constraint	Invalid	63.93216896966142	-59.83
Hinge brackets costs	R-0042	The machined hinge brackets shall cost less than $10000 each	Design constraint	Not started		
Flap production rate	R-0004	The flap shall have a production rate of maximum 10 shipsets per month.	Performance	Not started		
Rib pitch	R-0001	The flap shall have a rib pitch of minimal 250 mm	Design constraint	Valid	772.9339984	209.17

Figure 46: Requirement verification of AC1 for design #41.

2.5.5 AC conclusions

In AC1 manufacturing has been taking into account by including manufacturing cost in the MDO workflow. AC1 has been defined using all the tools and methods that are available in the OCE. This means that within AC1 all the Agile 4.0 steps have been conducted using tools from the OCE. By doing this it have been shown that these tools can be used in a realistic use case. It has also been shown that the tools in the OCE give meaningful results that help in defining and setting up MDO workflows.

With the defined workflow a flap for a 90 seat regional jet has been designed. In the application case, 2 different kinematic concepts have been considered the dropped hinge and the smart flap. The resulting flap designs have characteristics that were traded. The trade conducted was flap performance, meaning landing performance and weight and manufacturing cost. Based in the trade parameters used different flaps configurations prove to be the cheapest and/or have the most value.

3 Application Case 2

Application case 2 aims at concurrently linking aircraft design, manufacturing and supply chain in the early phase of aircraft development. The AC2 framework is shown in Figure 47.

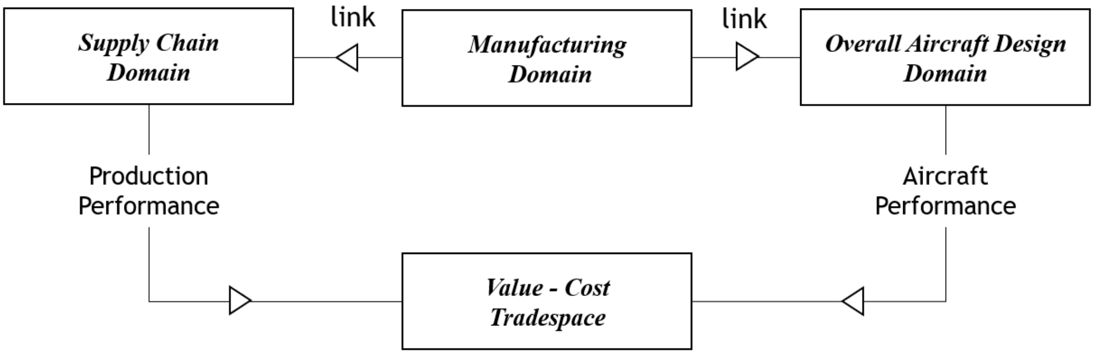


Figure 47: AC2 framework

Three domains characterize this application case:

- **Manufacturing (MfG)/strategy domain** including the set of materials, manufacturing and assembly processes selected for the aircraft component.
- **Supply chain (SC) domain** encompassing all the production aspects, from the characterization of the multiple enterprises involved in the supply chain (experience, reliability, etc.) to the logistic and transportation concepts necessary to transport goods from production to assembly sites.
- **Overall Aircraft Design (OAD) domain** focusing on the evaluation and assessment of the overall aircraft performance based on the selected materials, manufacturing and assembly processes.

The methodology ends with the value-cost tradespace in which the main attributes of the OAD and SC domains are aggregated in a value to perform several trade-off studies. The concurrent three-domains methodology has been applied in the AC2 at the design, manufacturing and supply chain of an horizontal tail plane (Figure 48). More details can be found in [2].

Figure 48: Application Case 2 focuses on the design, manufacturing and production of the HTP

In the following sections all the steps of the AGILE4.0 MBSE-MDO Framework will be addressed in details to demonstrate how the MBSE and MDO technologies have been leveraged by this application case to allow the concurrent coupling of design, manufacturing and supply chain domains.

3.1 System Identification

The first step of the AGILE4.0 MBSE-MDO framework is the system identification. In this step, the scenarios are modelled.

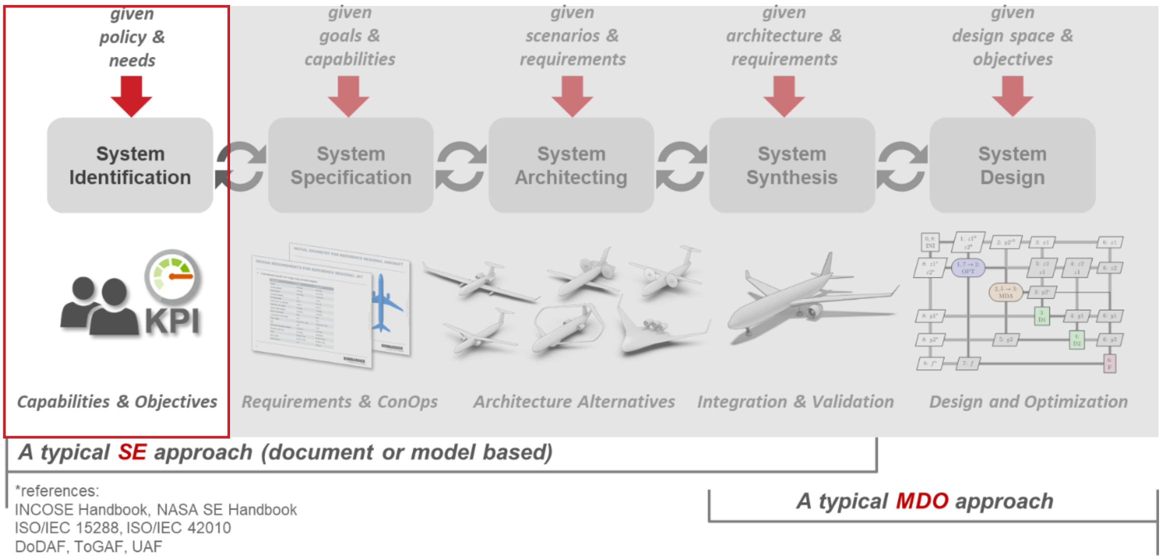


Figure 49: AGILE 4.0 Step I: System Identification.

The scenario is the step-by-step descriptions of how the system should operate and interact with its users and external interfaces. The scenario representative for the AC2 concerns the production of the HTP. It is assumed that the HTP production involves the OEM and national/international suppliers (could be Tier I, Tier II). First, the HTP requirements are fixed by the OEM. Then, the choice to outsource the HTP production to suppliers is based on strategic considerations related to the OEM own capacity/capability. In this scenario, the OEM-Strategy department decides to outsource the HTP and be responsible only for the aircraft assembly. The HTP requirements are provided by the OEM to suppliers, responsible for the HTP production. Particularly, an OEM need is to have an HTP with a specific number of Non-Conformities (NCs). Therefore, the HTP produced by suppliers has to perform a test. If the number of NCs not exceed the number fixed by the OEM, suppliers can release the HTP to the OEM. The OEM is finally responsible to assembly the HTP within the whole aircraft. This scenario has been modelled through the OCE.

All the information has been first collected in KE-chain and then visualized in Capella by using the Sequence Diagram [OES]. This diagram is reported in Figure 50. The system of interest is the HTP, the stakeholders involved are the OEM and the suppliers. Actions are represented by yellow boxes that follow the timeline; data exchanged among stakeholders are modelled as interactions (arrows in the model). The occurrence of the actions modelled in this scenario enable the validation of the OEM need related to the number of HTP NCs. In case this scenario will not be validated, the HTP will not be released by suppliers and further activities from their side will be necessary.

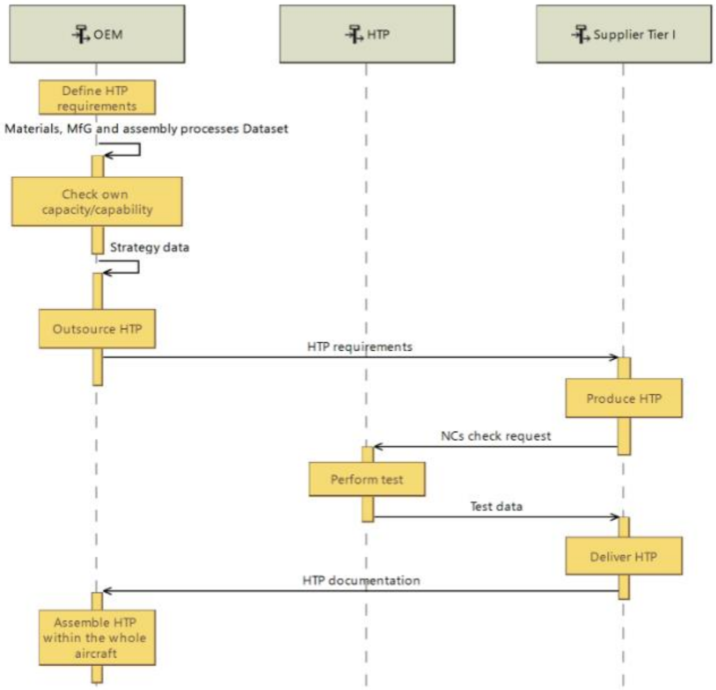


Figure 50: Use-Case 2 "Scenarios view" realized through the Sequence Diagram [OES] in Capella

3.2 System Specifications

The second step of the AGILE4.0 MBSE-MDO framework is the system specification dealing with the modelling of stakeholders, needs and requirements.

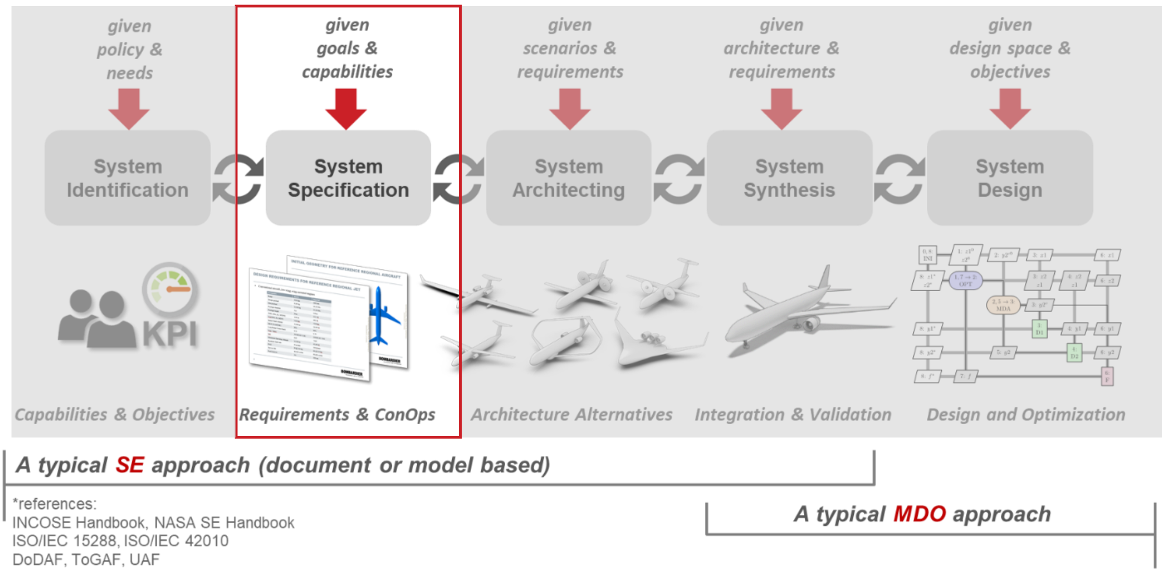


Figure 51: AGILE 4.0 Step II: System Specification.

First, stakeholders, needs and requirements have been collected in Excel Tables, as reported in Figure 52 and Figure 53.

Stakeholders	Needs	ID
Airline	Operating aircraft for the end of the year XXXX (market entrance date)	09
	Aircraft able to take off/land in as many airports as possible	19
	Low operational cost aircraft (efficiency, fuel consumption,)	43
	Safety and reliable aircraft	44
	Low cost aircraft	45
Passengers	Arrive to the destination quickly	16
	Stay confortable	17
	Low cost to travel	42
	Being safe	28
Regulation Authority	Safe aircarft operation	33
	Comply with certification campain	34
	Comply with environmental standards	11
OEM - Sales	The aircraft has to be competitive in the market	07
	Possibility to sell in dollar	04
	To sell a large volume of aircraft	24
	To increase clients database	25
OEM - Purchasing	Suppliers with complementary competences (dual sources avaliability)	02
	Suppliers collocated in geographic strategic location	03
	Suppliers with experience in development similar products	29
	Proposals with lowest costs	35
	Suppliers with owned manufactruing development resources	47
	Proposals delivering solution according to OEM necessity dates	36
	Suppliers with minimized risks	31
OEM - Controlling and Finance	The aircraft has to be delivered on time	06
	The aircraft break-even shall be fast	01
	Higher profit per aircraft than the market	46
OEM - Production/Engineering	Performant Aircraft	08
	The manufacturing process shall be lean	37
	Maximizing asset use	38
	Well designed Horizotnal tail plane	52
OEM -Manufacturing	Low Manufacturing Costs	49

Figure 52: Stakeholders and Needs for UC 2 collected in Excel

System: Aircraft											
ID	Requirement statement	Type	Parent Source	Means of Compliance	Author	Stakeholders	Version	Verification	Validation	Priority	Consequences
04	The aircraft shall entry into service in 2030*	Design (constraint)	N_09 N_06	Flight test	PD	OEM-Contr/Fin. Airline	0.1	Yes	Not started	1	Financial penalty
02	The aircraft shall fly at Mach XX during cruise	Performance	N_16	Aerodynamic analysis	PD	Airline, Pax	0.1	Yes	Not started	1	Performance not achived imply financial penalty
06	The aircraft shall have the sale price of maximum XX $ in the market	Design (constraint)	N_04 N_07 N_24 N_35	Costs analysis	PD	OEM - Sales/Purch.	0.1	Yes	Not started	1	Loss of competitiveness in the market
03	The aircraft shall have technologies with maturity TRL 6*	Design (constraint)	N_08	OAD analysis	PD	OEM-Prod/Eng.	0.1	Yes	Not started	1	Loss of competitiveness in market, financial penalty
13	The aircraft shall take off with the TOFL of maximum 1500 m during the take-off condition flight	Performance	N_19	OAD analysis	PD	Airline	0.1	Yes	Not started	1	The aircraft could be not able to take off in some airports
14	The aircraft shall have the design range of 3500 km	Design (constraint)	N_08	OAD analysis	PD	Airline	0.1	Yes	Not started	1	Loss of competitiveness in the market
07	The aircraft shall have the surface roughness of maximum XX ± XX µm during the entire aircraft life cycle	Design (constraint)	N_30	Aerodynamic analysis	PD	OEM-Purch/Qual.	0.1	Yes	Not started	3	Quality level decrease: performance decrease, loss of competitiveness in market
08	The aircraft shall land with the LFL of maximum 1400 m during the landing condition flight*	Performance	N_19	OAD analysis	PD	Airline	0.1	Yes	Not started	1	The aircraft could be not able to land in some airports
17	The aircraft shall have the passengers number of maximum 90 in every flight	Transportability	N_43	OAD analysis	PD	Airline	0.1	Yes	Not started	1	Waste of money, profit loss; financial penalty
20	The aircraft shall have the cabin lenght of 34 m	Design (constraint)	N_08	OAD analysis	PD	Passengers	0.1	Yes	Not started	1	Less space could imply less confort for the passengers
32	The aircraft shall have the unit cost of maximum XX $ in the market*	Design (constraint)	N_45	Costs analysis	PD	Airline	0.1	Yes	Not started	1	Loss of compititiveness in the market
33	The aircraft shall have the level noise emission of maximum XX during take off	Design (constraint)	N_11	Noise analysis	PD	Airline/Reg. Aut.	0.1	Yes	Not started	1	Non friendly-enviromental aircraft, aircfrat performance not matched, financial penalty
34	The aircraft shall be easy accessible in case of maintenace assessment	Design (constraint)	N_21 N_22	Inspections	PD	Maintenance	0.1	Yes	Not started	3	Aircraft cost maintance increase
36	The aircraft shall comply the CS - 25 regulation*	Functional	N_34 N_44 N_02	Flight test	PD	Airline/Reg. Aut.	0.1	Yes	Not started	1	Aircraft is not allowed to fly
37	The aircraft shall have the CO2 emission of maximum XX kg for the entire life cycle*	Design (constraint)	N_11	Simulation	PD	Reg. Aut.	0.1	Yes	Not started	1	Financial penalty
38	The aircraft shall provide a fast break-even*	Functional	N_01	Costs analysis	PD	OEM-Contr/Fin. Shareholder	0.1	Yes	Not started	1	Gain reduction and low return of shareholder's investments
54	The aircraft shall have the certification cost of maximum XX $ during the certification phase	Design (constraint)	N_45	Costs analysis	PD	Airline	0.1	Yes	Not started	3	Aircraft cost certification increase with the increase of the whole aircraft cost
63	The aircraft shall fly safetely	Functional	N_33	Simulation	PD	Reg. Aut.	0.1	Yes	Not started	1	Non-certifiability of the aircraft
101	The aircraft shall have profit margin 20% higher than the competitors in the entrance market	Suitability	N_07	Costs analysis	Emb.	OEM-Sales	0.1	Yes	Not started	2	Gain reduction and low return of shareholder's investments

Figure 53: UC 2 Aircraft Requirements collected in Excel

These tables have been then uploaded on the OCE, in KE-chain. An example of the stakeholders' model realized through the OCE is shown in Figure 54.

Stakeholder	ID	Linked to needs	Needs	Parent stakeholder
OEM-Quality	ST-0003	Yes	N30 | N53	OEM
OEM-Purchasing	ST-0002	Yes	N2 | N3 | N29 | N35 | N47 | N36 | N31	OEM
OEM-Controlling and Finance	ST-0001	Yes	N6 | N1 | N46	OEM
Passengers	ST-0008	Yes	N16 | N17 | N42 | N28	
Regulation Authority	ST-0009	Yes	N33 | N34 | N11	
OEM Production/Engineering	ST-0010	Yes	N8 | N37 | N38 | N52	OEM
OEM - Technological Development	ST-0011	Yes	N39 | N40	OEM
OEM - Planning	ST-0012	Yes	N5 | N18	OEM
Suppliers Tier II	ST-0004	Yes	N15 | N24 | N27	
Shareholders	ST-0005	Yes	N32	
Funding Agencies	ST-0006	Yes	N41 | N23	

Figure 54: UC 2 Aircraft Requirements in OCE (KE-chain)

Examples showing the needs and requirements model in KE-chain are reported in Figure 55 and Figure 56.

Need	ID	Text	Stakeholder	Linked to requirements?	Derived requirements
N6	N-0001	The aircraft has to be delivered on time	OEM-Controlling and Finance	Yes	R4, R69, R84
N1	N-0002	The aircraft break-even shall be fast	OEM-Controlling and Finance	Yes	R38
N46	N-0003	Higher profit per aircraft than the market	OEM-Controlling and Finance	No	
N2	N-0004	Suppliers with complementary competences (dual sources avaliability)	OEM-Purchasing	Yes	R36, R18, R66
N3	N-0005	Suppliers collocated in geographic strategic location	OEM-Purchasing	Yes	R19
N29	N-0006	Suppliers with experience in development similar products	OEM-Purchasing	Yes	R83
N35	N-0007	Proposals with lowest cost, time, risk	OEM-Purchasing	Yes	R6, R74, R75, +4
N47	N-0008	Suppliers with owned manufactruing development resources	OEM-Purchasing	Yes	R5

Figure 55: Use-Case 2 Needs set collected in OCE (KE-chain)

Requirement	ID	Text	Priority	Type
R3	R-0001	The aircraft shall have technologies with maturity TRL 6	Low	Design constraint
R13	R-0002	The aircraft shall take off with the TOFL of maximum 1500 m during the take-off condition flight	Low	Performance
R14	R-0003	The aircraft shall have the design range of 3500 km	Low	Design constraint
R7	R-0004	The aircraft shall have the surface roughness of maximum XX ± XX µm during the entire aircraft life cycle	High	Design constraint

Figure 56: Use-Case 2 Aircraft Requirements set collected in OCE (KE-chain)

Finally, the use-case model realized in KE-chain (including stakeholders, needs and requirements) has been exported and imported in Papyrus for visualization. In Papyrus, the stakeholders' hierarchy is visualized in a diagram shown in Figure 57. Since OEM plays an important role among all the stakeholders, several OEM departments have been considered in this AC. For each OEM department, the OEM has been identified as parent stakeholder.

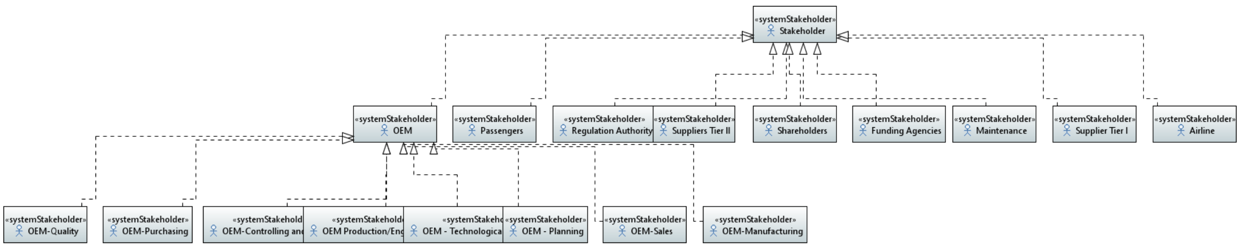


Figure 57: Use-Case 2 "Stakeholders Hierarchy view" in Papyrus

Stakeholders 'needs identified in KE-chain are visualized in Papyrus diagrams. Specifically, in Papyrus there is the possibility to visualize the needs of a specific stakeholder. An example concerning the needs of the OEM-Sales department is reported in Figure 58. The last one (N7) is about the possibility to have a competitive aircraft in the market, which is one of the key points for this AC.

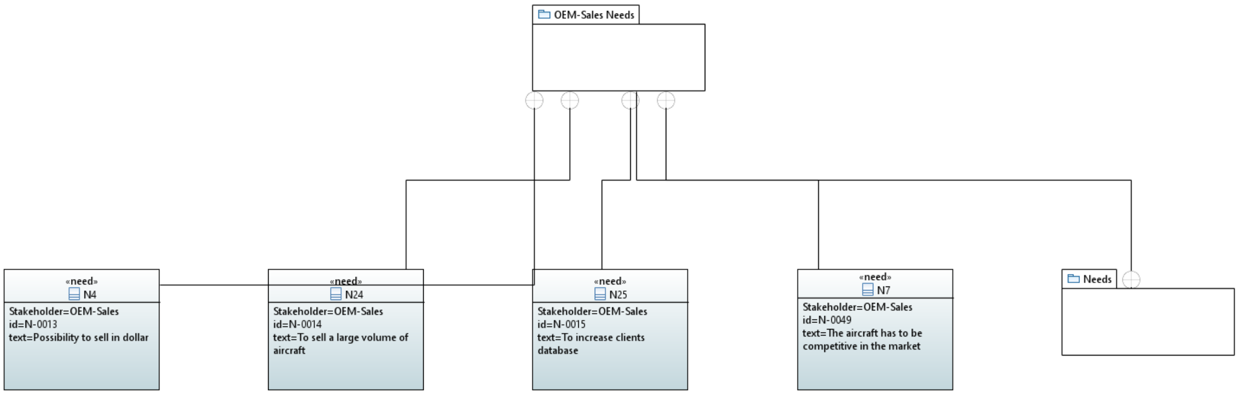


Figure 58: Use-Case 2 OEM-Sales Department "Needs view" in Papyrus

Finally, an example of the HTP requirements set visualized in a Papyrus diagram is reported in Figure 59. As shown in Figure 59, HTP requirements refer to the HTP performance as well as to its cost production.

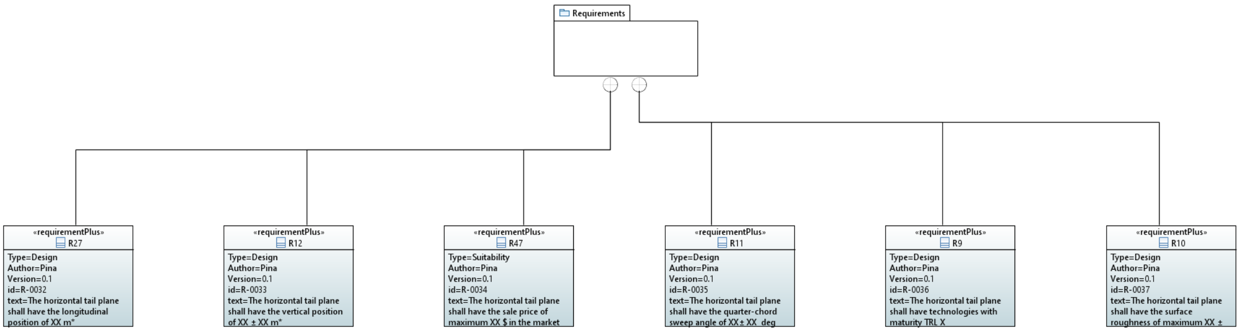


Figure 59: Use-Case 2 HTP "Requirements List View" in Papyrus

The complete set of the HTP requirements include more than the requirements shown in the figure. The model has been simplified to provide an example.

3.3 System Architecting

After the system specification step addressed in the previous section, in the AGILE4.0 MBSE-MDO Framework there is the system architecting step, which is the focus of this section. Reader can find more details in [9].

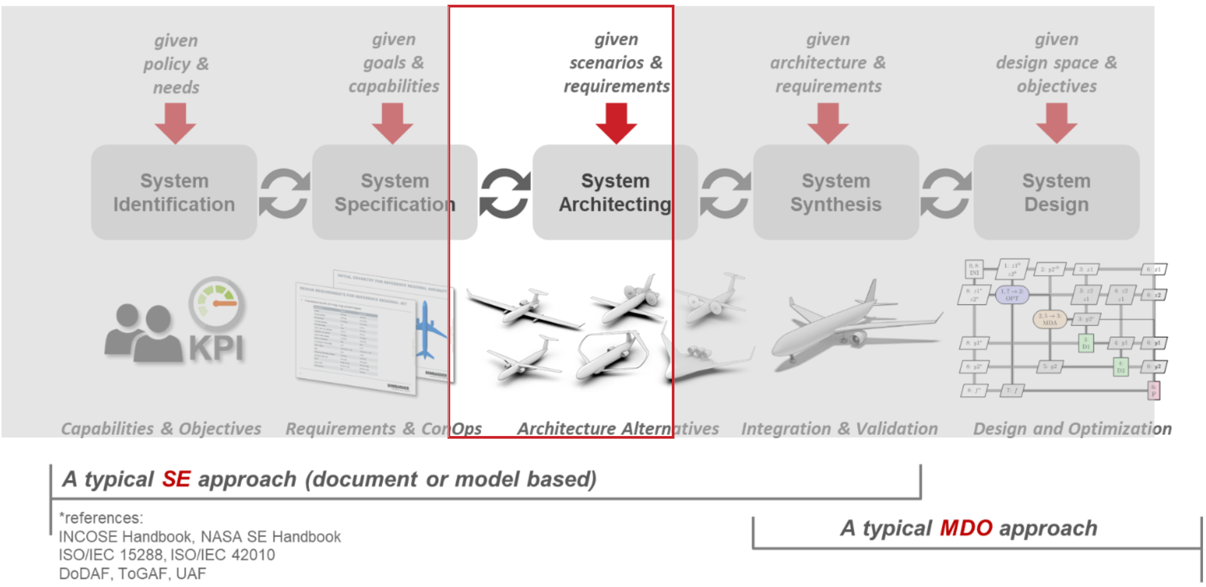


Figure 60 AGILE 4.0 Step III: System Architecting.

The AC2 architecture coupling the system of interest (HTP) with the enabling systems (manufacturing and supply chain) is reported in Figure 61. The architecture has been modelled in the OCE using ADORE.

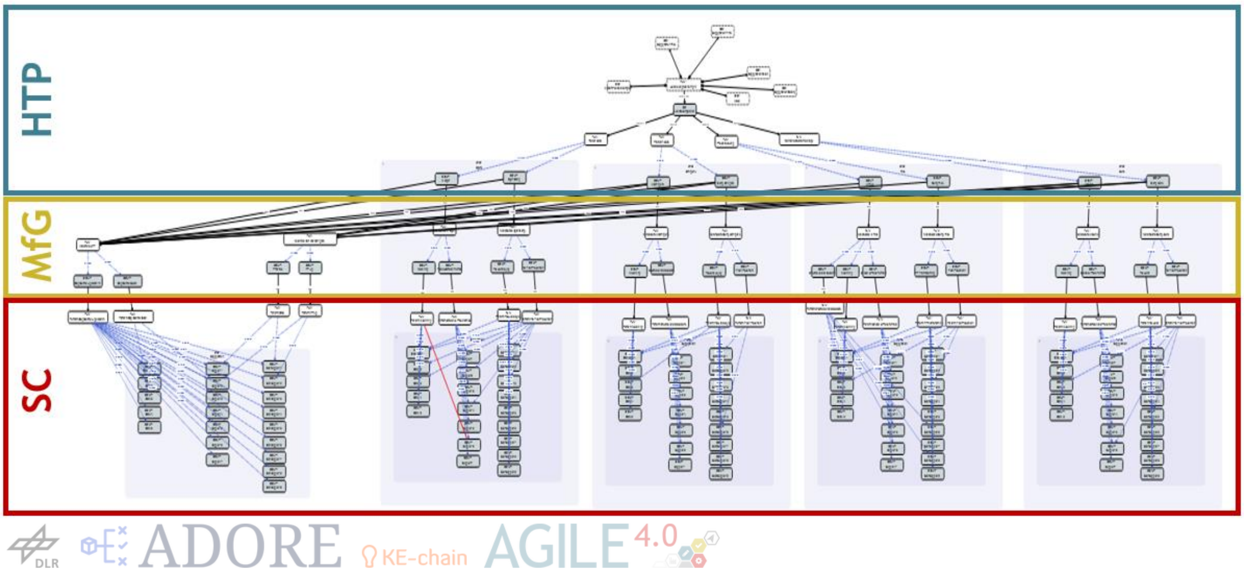


Figure 61: AC2 architecture in OCE-ADORE coupling the horizontal tail plane, manufacturing and supply chain systems

The architecture starts with the boundary function "*Handle longitudinal flight*" fulfilled by the **HTP system** and particularly by its components: **spars**, **skins**, **stringers** and **ribs**. In fact, to guarantee the longitudinal flight, the spars have to resist to loads, the stringers to transfer loads, the ribs to prevent the buckling and the skins to maintain the aerodynamic shape. All these functions and components characterize the HTP architecture, highlighted by the blue box in Figure 61. Moving down in the complete architecture, the manufacturing system architecture is defined (yellow box in Figure 61).
Each HTP component can be made of different materials, e.g. aluminum, composite, titanium. For each material several manufacturing processes can be selected. An example of manufacturing processes for aluminum is the pressed and stretch formed, for composite is the automatic fiber placement. At the same time, multiple assembly processes can be selected based on the already chosen materials and manufacturing assembly.

The assembly processes to use also depends on the components that have to be put together. In this case two assembly steps (and therefore processes) have been considered: the first one coupling skins and stringers, the second one coupling spars and ribs. The **manufacturing processes** and the **assembly processes** are identified as the main components of the **manufacturing system**.

Concluding, the manufacturing and assembly processes have to be performed by enterprises having the capability of doing it. These enterprises can be Original Equipment Manufacturer (OEM) or Suppliers Tier I/Tier II. The different combinations of these enterprises represent the different supply chain architectures. Therefore, the **OEM** and **suppliers** are proposed as the main components of the **supply chain system**.
A zoom on the spar component is reported in Figure 62 to better highlights the link between the three systems architecture (HTP, MfG, SC). In ADORE all the components identified for the HTP architecture (spars, stringers, ribs and stringers) are modelled as systems. First there is the definition of the components in terms of materials. As shown in Figure 62, in the system spars (SYS: spars) there are aluminum spars (Al Spar) and composite spars (Spar Comp). Then, to these components the function "*Manufacture Component*" is linked. In this specific case, the two functions "*manufacture Al Spar*" and "*manufacture Spar Comp*" are added. These functions represent the link between the HTP architecture and the MfG architecture. In fact, to manufacture HTP components manufacturing processes are needed. Therefore in Figure 62 each function "*Manufacture component*" is fulfilled by a manufacturing processes; machining, press and stretch formed, TS Hand Layup, TS Fiber placement, which are modelled as components. The blue-dotted lines indicate the possibility to make a choice for each component with respect to the different manufacturing processes.
The function "*Perform manufacturing process*" allows to move from the MfG architecture to the SC architecture. Then, for each manufacturing process, different OEM or suppliers can be selected (as shown from the blue-dotted lines). These enterprises, however, must have the capability to perform the selected manufacturing processes. The incompatibility constraint (red line in Figure 62) can be used to specify that a specific manufacturing process cannot be performed by a specific OEM/supplier.

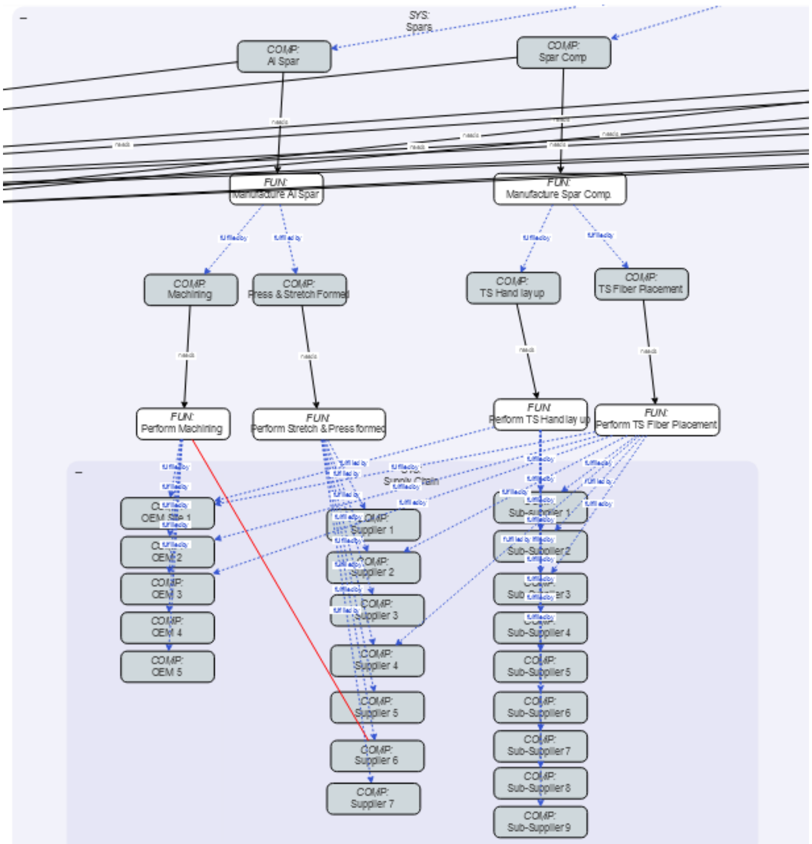


Figure 62: AC2 architecture in OCE-ADORE - zoom on the Spar component to highlight the coupling of the HTP, MfG and SC architectures

The same model illustrated in Figure 62 and previously explained is also applied to the other HTP components (stringers, skins, ribs). The difference relays in the manufacturing processes that might differ from one

component to another one. Modelling the HTP components as systems in ADORE gives the possibility to assign an instance to each system, that is the number of components (systems) characterizing the architecture. For instance, two spars characterize the HTP architecture. Therefore, an instance equal to 2 has been assigned to the spar system in ADORE. This means that all the choices modelled in the system will be taken twice, first for the spar 1 and then for the spar 2. Similarly, it has been done for the other HTP components.
Outside of the spars, stringers, skins and ribs systems, in the MfG architecture (see the left side of the yellow box in Figure 61) are also modelled the assembly processes. In this case it´s possible to choose which assembly processes use according to the components that have to be linked together. Differently from the manufacturing processes, these assembly processes have not been implemented in a system since the decision is taken only once, i.e. in the moment that skin and stringers have to be assembled.

3.4 System Synthesis

The system synthesis step in the AGILE4.0 MBSE-MDO Framework link the MBSE upstream activities with the MDO exploration activities.

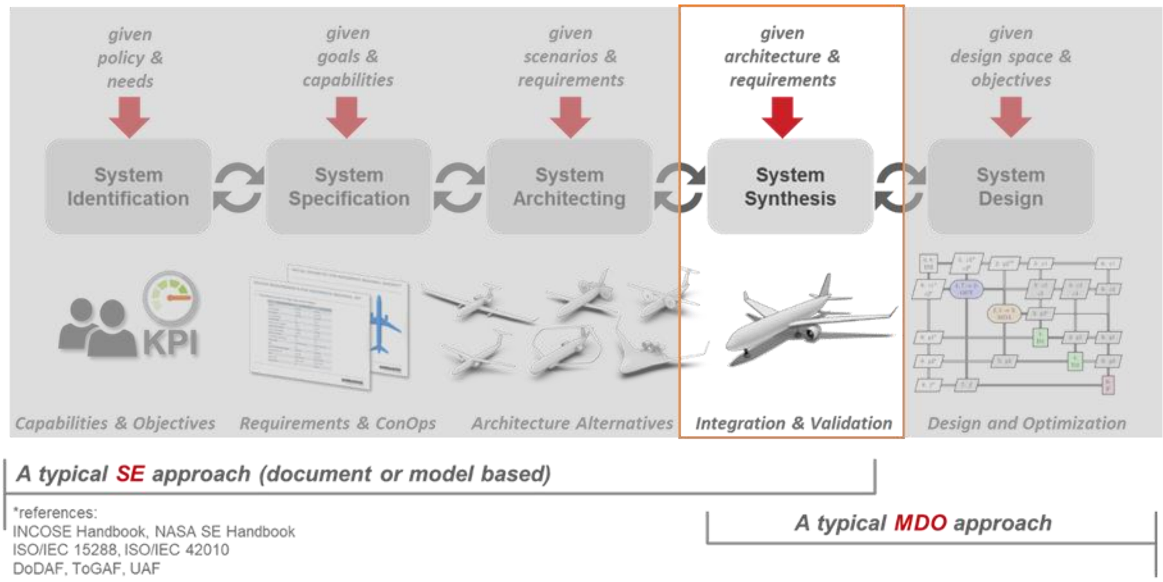
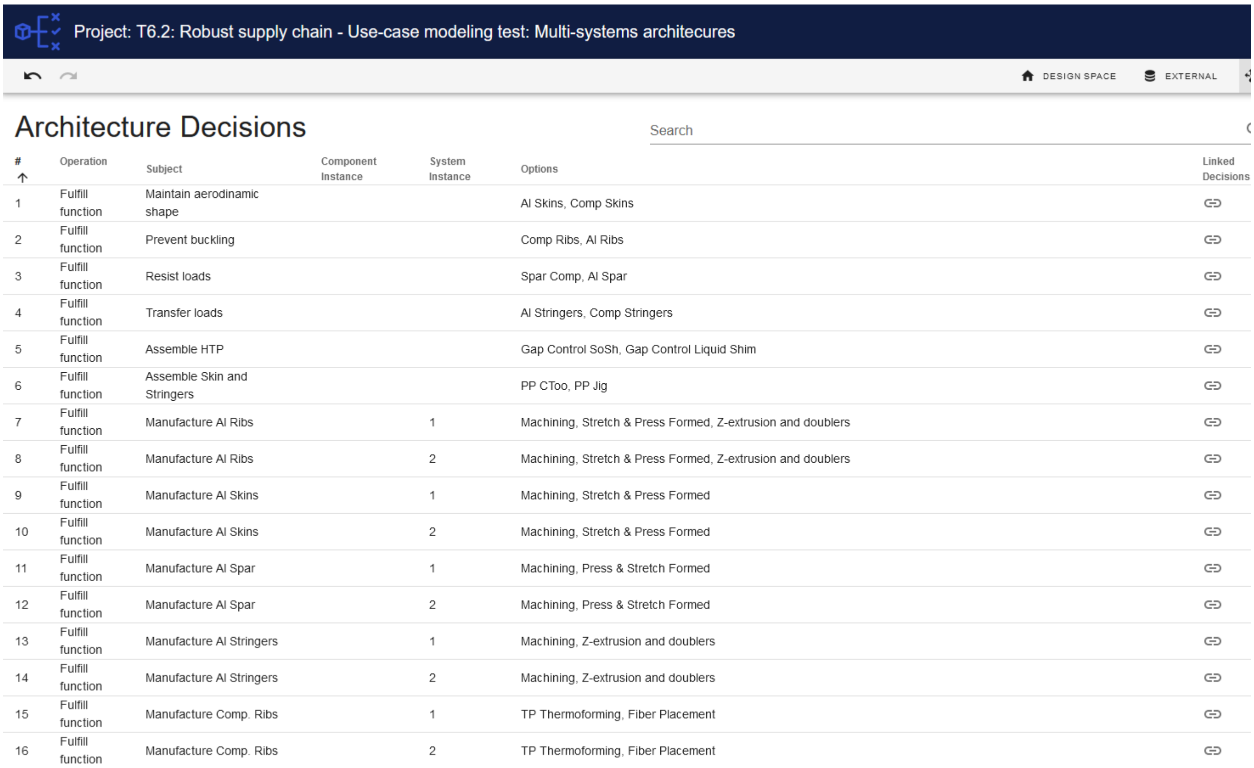


Figure 63 AGILE 4.0 Step V: System Synthesis.

As shown in the previous section, ADORE is used to generate architectures. All the possible decisions that can be taken in the complete AC2 architecture are summarized in the Architecture Decisions panel available in OCE and showed in Figure 64. The number of decisions for the AC2 is higher than 50 and only some of them are plotted in Figure 64 as example.


Project: T6.2: Robust supply chain - Use-case modeling test: Multi-systems architecures

DESIGN SPACE EXTERNAL

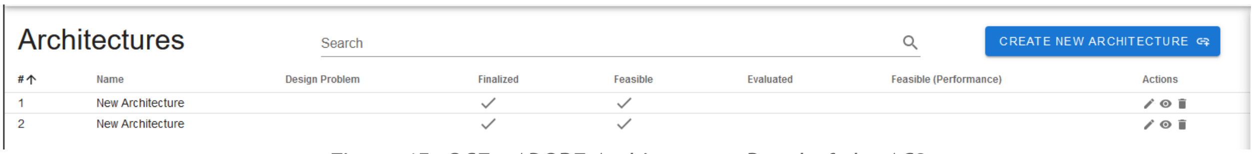
Architecture Decisions

Search

#	Operation	Subject	Component Instance	System Instance	Options	Linked Decisions
1	Fulfill function	Maintain aerodinamic shape			Al Skins, Comp Skins	
2	Fulfill function	Prevent buckling			Comp Ribs, Al Ribs	
3	Fulfill function	Resist loads			Spar Comp, Al Spar	
4	Fulfill function	Transfer loads			Al Stringers, Comp Stringers	
5	Fulfill function	Assemble HTP			Gap Control SoSh, Gap Control Liquid Shim	
6	Fulfill function	Assemble Skin and Stringers			PP CToo, PP Jig	
7	Fulfill function	Manufacture Al Ribs		1	Machining, Stretch & Press Formed, Z-extrusion and doublers	
8	Fulfill function	Manufacture Al Ribs		2	Machining, Stretch & Press Formed, Z-extrusion and doublers	
9	Fulfill function	Manufacture Al Skins		1	Machining, Stretch & Press Formed	
10	Fulfill function	Manufacture Al Skins		2	Machining, Stretch & Press Formed	
11	Fulfill function	Manufacture Al Spar		1	Machining, Press & Stretch Formed	
12	Fulfill function	Manufacture Al Spar		2	Machining, Press & Stretch Formed	
13	Fulfill function	Manufacture Al Stringers		1	Machining, Z-extrusion and doublers	
14	Fulfill function	Manufacture Al Stringers		2	Machining, Z-extrusion and doublers	
15	Fulfill function	Manufacture Comp. Ribs		1	TP Thermoforming, Fiber Placement	
16	Fulfill function	Manufacture Comp. Ribs		2	TP Thermoforming, Fiber Placement	

Figure 64: OCE - ADORE Architecture Decisions panel of the AC2 architecture

The different combinations of decisions that can be taken generate different architectures. In the AC2 several architectures have been created changing the choice of OEM and suppliers that can be selected for a specific manufacturing or assembly process. In the OCE, precisely in ADORE, all the generated architectures are listed in the architecture panel as shown in Figure 65. In the architectures panel it is also indicated if the created architecture is finalized (all the decisions are taken) and feasible.


Architectures

Search

CREATE NEW ARCHITECTURE

#	Name	Design Problem	Finalized	Feasible	Evaluated	Feasible (Performance)	Actions
1	New Architecture		✓	✓			
2	New Architecture		✓	✓			

Figure 65: OCE - ADORE Architectures Panel of the AC2

Once the architecture is defined, some quantities of interest have been defined, as shown in Figure 66. Some quantities of interest are for instance related to the supply chain system like time, quality, cost and risk. These quantities of interest have been introduced to correctly formulate the MDO design problem.

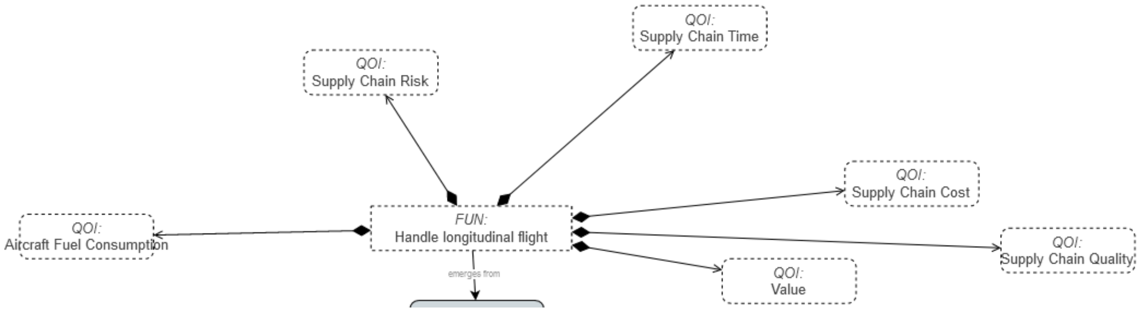


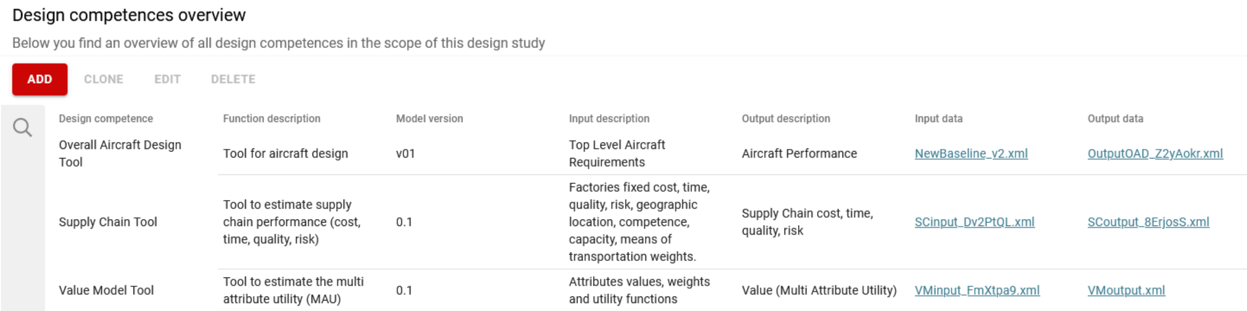
Figure 66: AC2 architecture in OCE-ADORE- Quantity of Interest (QoI)

The design problem can be set-up in a dedicated OCE – ADORE panel. Here the already introduced quantities of interest can be defined as design variables, objectives or constraints of the optimization problem. One of the design problems characterizing the AC2 aims at optimizing the cost and the value. The value is a single measure aggregated attributes (variables) of multiple domains (SC and OAD in this case). The production quantity that each OEM/supplier has to perform is used as design variable. Instead, no constraints are added in this design problem.

#	Name	Design Variables	Objectives	Constraints	Architectures	Actions
1	New Design Problem	60	2	0		

Figure 67: OCE - ADORE Design Problems Panel for AC2

All the parameters needed for the architecture optimization are set. Several design competences are needed for the optimization of these architectures. These disciplines are summarized in Figure 68.



Design competence	Function description	Model version	Input description	Output description	Input data	Output data
Overall Aircraft Design Tool	Tool for aircraft design	v01	Top Level Aircraft Requirements	Aircraft Performance	NewBaseline_v2.xml	OutputOAD_Z2yAokr.xml
Supply Chain Tool	Tool to estimate supply chain performance (cost, time, quality, risk)	0.1	Factories fixed cost, time, quality, risk, geographic location, competence, capacity, means of transportation weights.	Supply Chain cost, time, quality, risk	SCinput_Dv2PtQL.xml	SCoutput_8ErjosS.xml
Value Model Tool	Tool to estimate the multi attribute utility (MAU)	0.1	Attributes values, weights and utility functions	Value (Multi Attribute Utility)	VMinput_FmXtpa9.xml	VMoutput.xml

Figure 68: AC 2 Design competences overview in OCE (KE-chain)

At this point, MultiLinQ is used to link the architectures generated in ADORE with the MDO workflow. Based on the inputs/outputs defined for each disciplinary tool and taking as inputs the information of the architecture model, MultiLinQ is able to show which tools are used to calculate which metric. A short overview of the AC2 mapping matrix view is reported in Figure 69. The fuel consumptions is estimated by the Overall aircraft design tool, all the production aspects by the Supply chain tool while the value (i.e. the Multi Attribute Utility) by the value model tool.

Components	QOIs	Tools: Overall Aircraft Design Tool	Supply Chain Tool	Value Model Tool
Fiber Placement	pqFPIspar			
Fiber Placement	pqFPIstr			
Fiber Placement	pqFPIRibs			
Fiber Placement	pqFPISkins			
Gap Control Liquid Shim	pqGCLQmainass			
Gap Control SoSh	pqSoShmainass			
Infusion	pqInfSpar			
Infusion	pqInfStr			
Infusion	pqInfRibs			
Infusion	pqInfSkins			
Machining	pqMachning-Spar			
Machining	pqMachning-Str			
Machining	pqMachning-Ribs			
Machining	pqMachning-Skins			
PP CToo	pqPPCTooskstr			
PP Jig	pqPPJigskstr			
Press Formed	pqPFormSpar			
Press Formed	pqPFormStr			
Press Formed	pqPFormRibs			
Press Formed	pqPFormSkins			
	Aircraft Fuel Consumption			
	Supply Chain Cost			
	Supply Chain Risk			
	Supply Chain Time			
	Value			

Figure 69: AC2 Mapping matrix view obtained by using MULTILINQ

3.5 System Design

The last step of the AGILE4.0 MBSE-MDO Framework is the system design. Several activities are performed in this step and addressed below:

- Workflow implementation
- Workflow execution
- Optimization
- Trade-off
- Verification & Validation

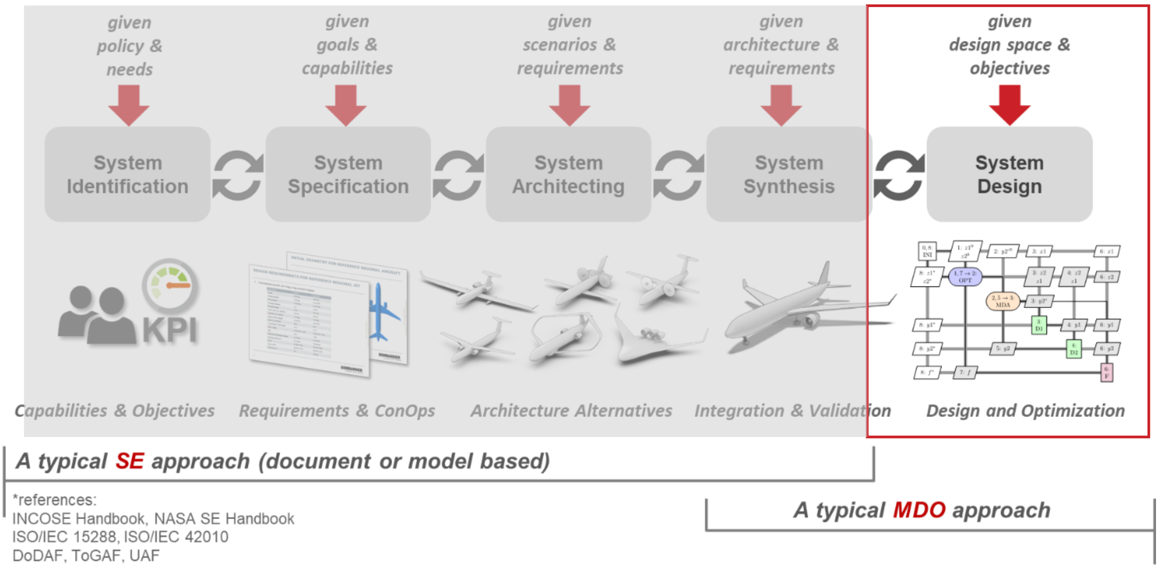


Figure 70: AGILE 4.0 Step VI: System Design.

3.5.1 Workflow implementation and execution

Several technologies have been adopted to implement the workflow: CPACS, MDAx and disciplinary competences. In Figure 71 the XDSM workflow including manufacturing, supply chain and overall aircraft design disciplines is shown. Most of the competences have been deployed by DLR by leveraging knowledge from specialists, especially for the supply chain model. It is worthwhile to underline that other workflows have been implemented only considering competences coupled in pair: manufacturing and supply chain, manufacturing and overall aircraft design (OAD) [10]. As example, only the complete XDSM workflow, coupling the three competences is reported in this section. In the next section, the three cases are instead addressed.

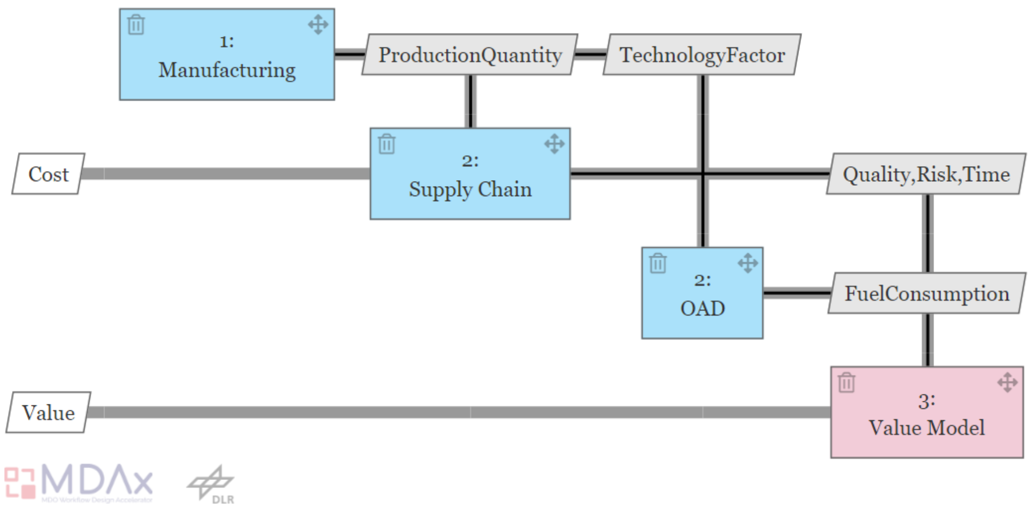


Figure 71: XDSM Workflow including Manufacturing, Supply Chain and Overall Aircraft Design competences obtained by using MDAx

Once the workflows have been set-up by using MDAx, they have been exported and run in RCE as shown in Figure 72, Figure 73 and Figure 74. Particularly, Figure 72 illustrates a workflow including manufacturing and overall aircraft design tools. Without optimization, this workflow allows to identify the best aircraft configuration in terms of fuel consumption based on the different manufacturing choices (materials and processes).

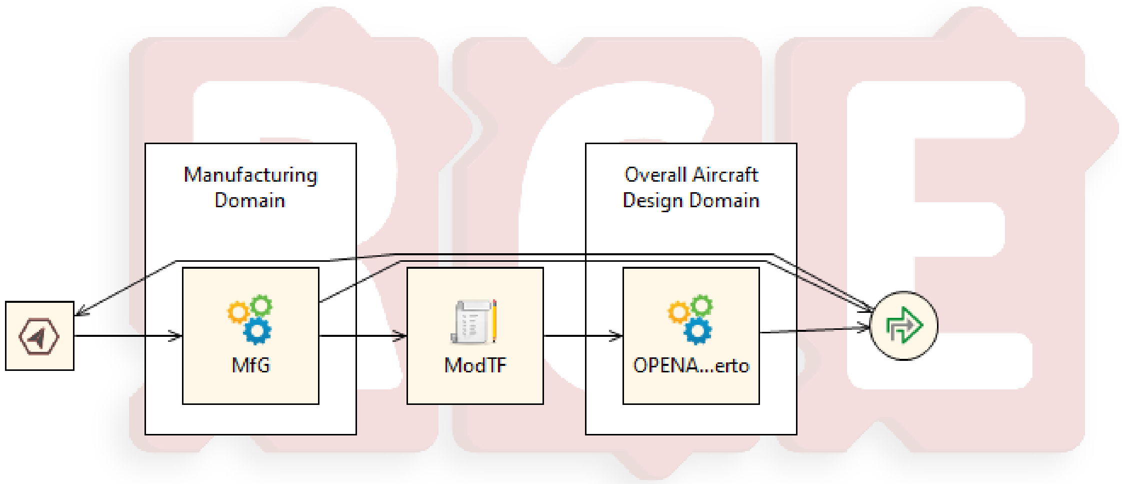


Figure 72: Executable Workflow including Manufacturing and Overall Aircraft Design tools run in RCE

Figure 73 represents a workflow including manufacturing and supply chain tools. Without optimization, this workflow allows to identify the best supply chain architecture for the production of a specific HTP.

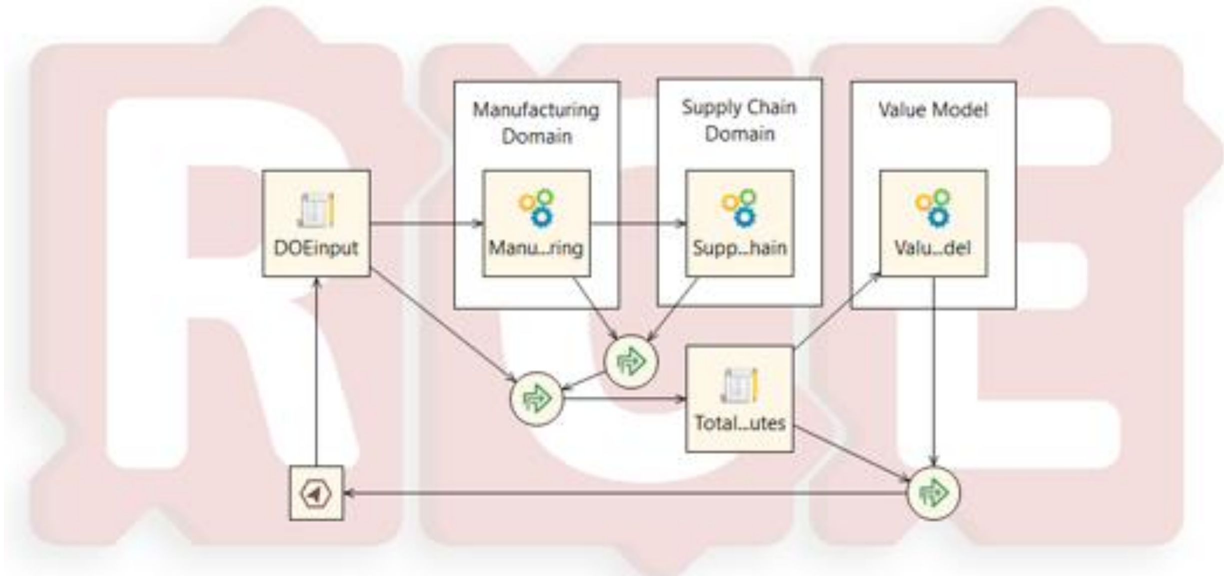


Figure 73: Executable Workflow including Manufacturing and Supply Chain tools run in RCE

Finally, Figure 74 shows a workflow including manufacturing, overall aircraft design and supply chain tools. Without optimization, this workflow allows to identify the global optimum in terms of manufacturing, design and supply chain variables.

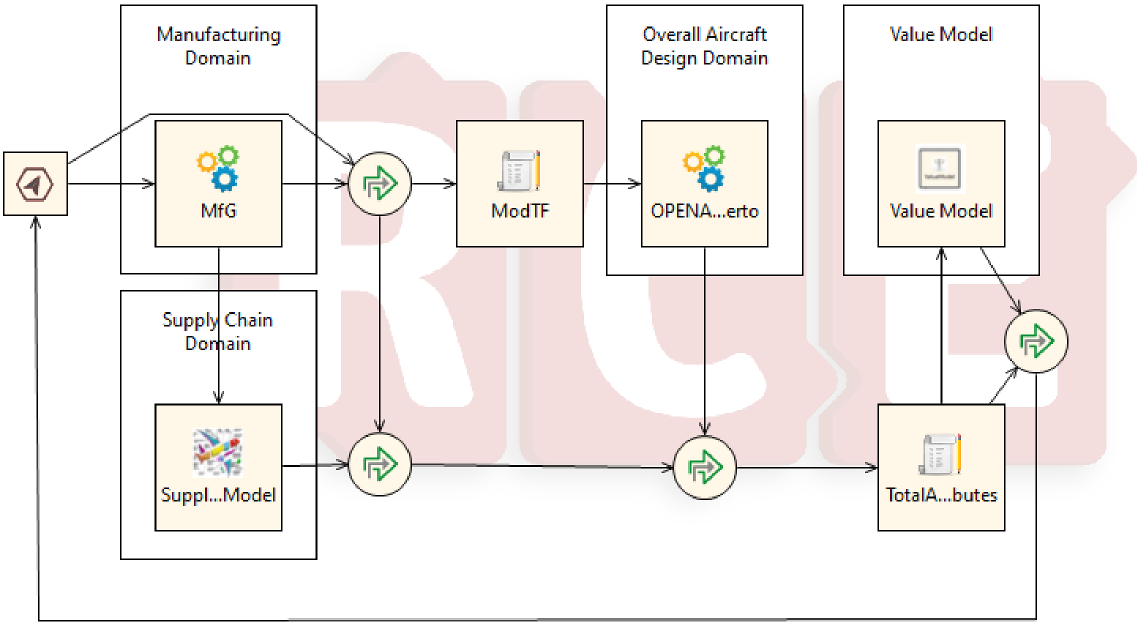


Figure 74: Executable Workflow including Manufacturing, Supply Chain and Overall Aircraft Design tools run in RCE

In all the cases, the BRICS component  has been used to add the optimization algorithms, provided by the French aerospace centre ONERA. A design optimization campaign has been addressed in this application case and in the next sub-section one of the MDO problem is presented in terms of results as one of the interesting cases in terms of supply chain optimization.

3.5.2 Optimization

As already explained in the previous section, a design optimization campaign has been addressed for this application case in order to identify the global optimum. In this section, more details on one of the MDO problems aiming at identifying the optimum supply chain architecture for a specific HTP configuration is described. The workflow run for this MDO problem is the one shown in Figure 73.

Particularly, two optimization strategies have been analysed, as reported in Figure 75. The first one, in red, addressing a 4-objectives optimization aiming at minimizing cost, time and risk and maximizing quality; the second one, in dark green, addressing a 2-objectives optimization aiming at minimizing cost and maximizing value. In both cases, a remote optimization has been run since ONERA has the required optimization capability (as explained in the previous section). By assuming linear utility curves and same weights for all the attributes, it has been demonstrated that the two optimization strategies lead to the same results, particularly the 2-objective pareto-front is contained among the 4-objectives pareto-front. Therefore, the value model allows to simplify, in this case, the visualization of a 4-objectives pareto-front [3].

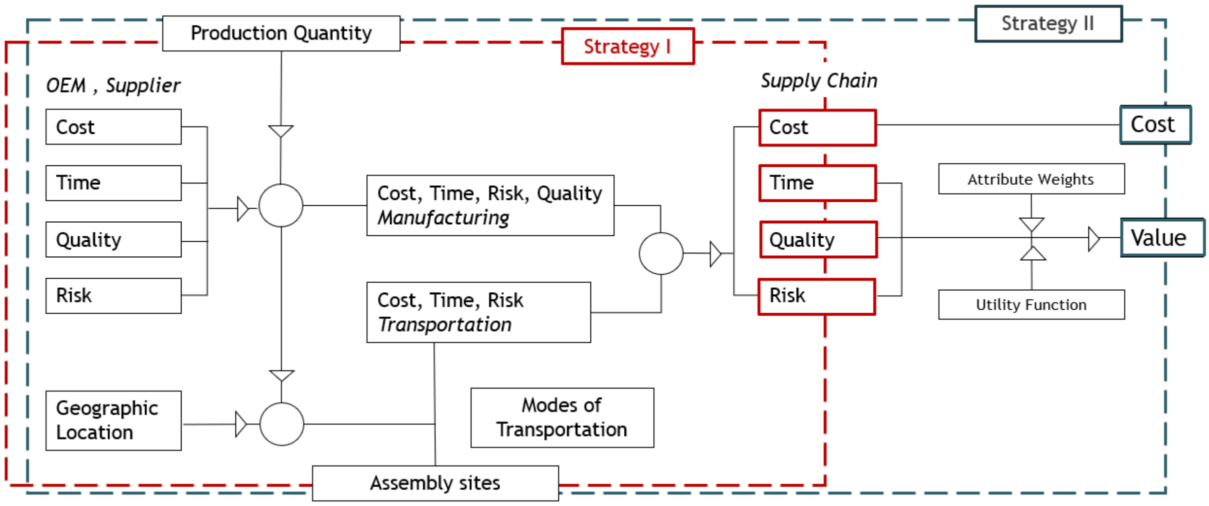


Figure 75: Two optimization strategy remotely run by executing RCE workflow (see Figure 73)

As example, the results of the MDO problem following strategy I have been here reported. In this case the design variables are the:

- The production quantity: how many components each enterprise has to produce
- The Assembly sites: which enterprise is responsible for the HTP components assembly

No constraints are considered in this MDO problem. Details on the MDO problem variables are reported in Figure 76.

HTP Components	Production quantity	N° Components	N° Production sites	N° Assembly sites
Skins	0 - 1	0/2	13	4
Stringers	0 - 1	0/30	13	
Spars	0 - 1	0/2	14	9
Ribs	0.3 – 0.7	6/14	10	

Figure 76: MDO Problem Variables

The value-driven pareto-front related to this MDO problem is reported in Figure 77 in which the solutions with the highest and lowest value are highlighted (respectively solution 1 and 3). It is worth to underline here, that the higher the value, the better is the solution in terms of production time, quality and risk (parameters aggregated in the value). Therefore, they represent the best and worst supply chain architecture to adopt to produce the selected HTP configuration, in this case, mainly made by aluminium. The solution 3 is, however, also the solution with the lowest cost. This is mainly related to the enterprises characterizing this solution, thus to the lowest fixed and manufacturing cost. In terms of transportation cost, solution 3 has higher cost since higher is the number of travelled kilometres (see Figure 78). Thus, the trade-off in terms of value and cost.

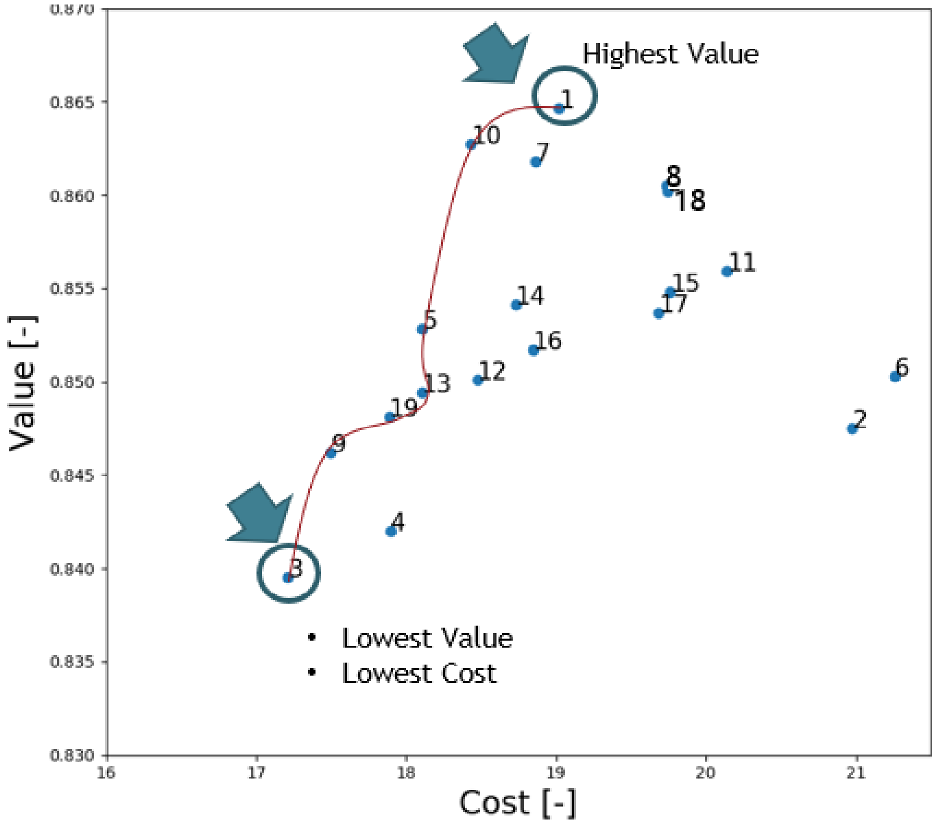


Figure 77: Value-driven Pareto-Front

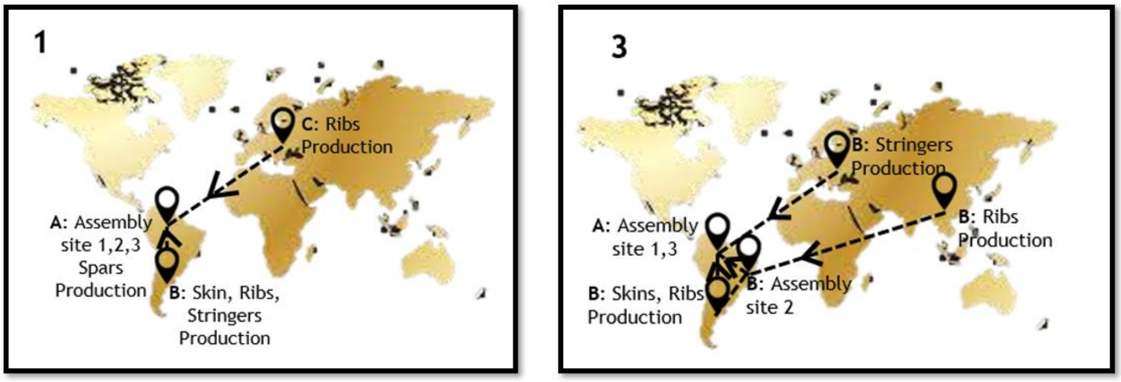


Figure 78: Supply Chain Architecture characterizing Solution 1 and 3 of the Value-Driven Pareto-Front (Figure 77)

3.5.3 Trade-off

In the application case 2, the value model theory has been used as mean to simplify the multi-criteria decision-making process and thus easily perform the trade-off activities. In fact, the trade-off is between value and cost. However, since in the value several criteria (or attributes) are aggregated (for instance production time, quality and risk), it is important to catch decision maker´s preferences in order to perform the right the trade-off study. More details are provided in this sub-section. VALORISE, the DLR internal tool has been used to support this value-driven decision-making activity.
The case of interest is again the one showed in the previous sub-section: in the optimized pareto-front (see Figure 77), the best solution for the decision-maker has to be identified. As best solution is meant here the

solution perfectly matching the decision maker´s preferences, qualitatively illustrated in Figure 79. For the case under analysis, as explained in the previous section, in the value only the production time, risk and quality are aggregated. Therefore only these attributes are of interest of the example here-addressed.

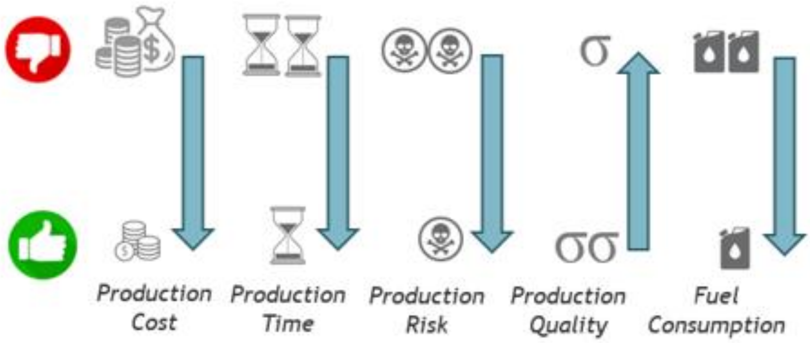


Figure 79: Decision Maker´s Qualitative Preferences

These qualitative preferences have been translated in analytical curves, through the utility functions of the value model theory [8], by using VALORISE. Thus a comparison between the previous pareto-front (see Figure 77) and the new one obtained by changing the utility curves in order to match decision maker´s preferences is reported in Figure 80. The main difference between the blue points (previous pareto-front here called "Analytical Tradespace") and the yellow points (new pareto-front here called "DM Tradespace – 1") relays in the utility curves adopted. In the first case there is the assumption of linear utility curves and same weights for all the attributes. In the second one, non-linear utility curves are assumed but still same weights for all the attributes. As consequence, the analytical tradespace based on linear utility curves is not influenced by decision maker´s preferences. Instead, the DM Tradespace – 1 is affected by decision maker´s since non-linear utility curves are exactly expressing decision maker´s preferences.

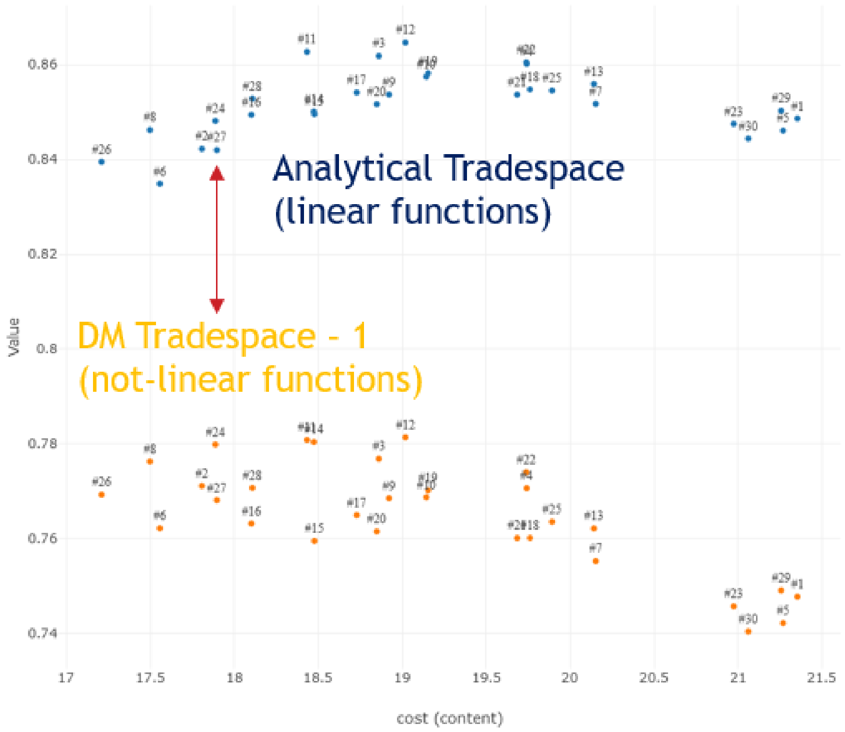


Figure 80: Value-driven Pareto-Front Comparison obtained by using VALORISE

Zooming on the two value-driven pareto-front, in Figure 81, it is possible to recognize how to the pareto-front changes based on the decision-maker´s preferences: solutions 5 and 13 are not part of the pareto-front anymore while solution 12 is now accounted. Solution 1 still remains the solution with the highest value, which in this case also the “best solution” for decision maker, meaning that it perfectly matches decision maker´s expectation in terms of production time, risk and quality, aggregated in the value.

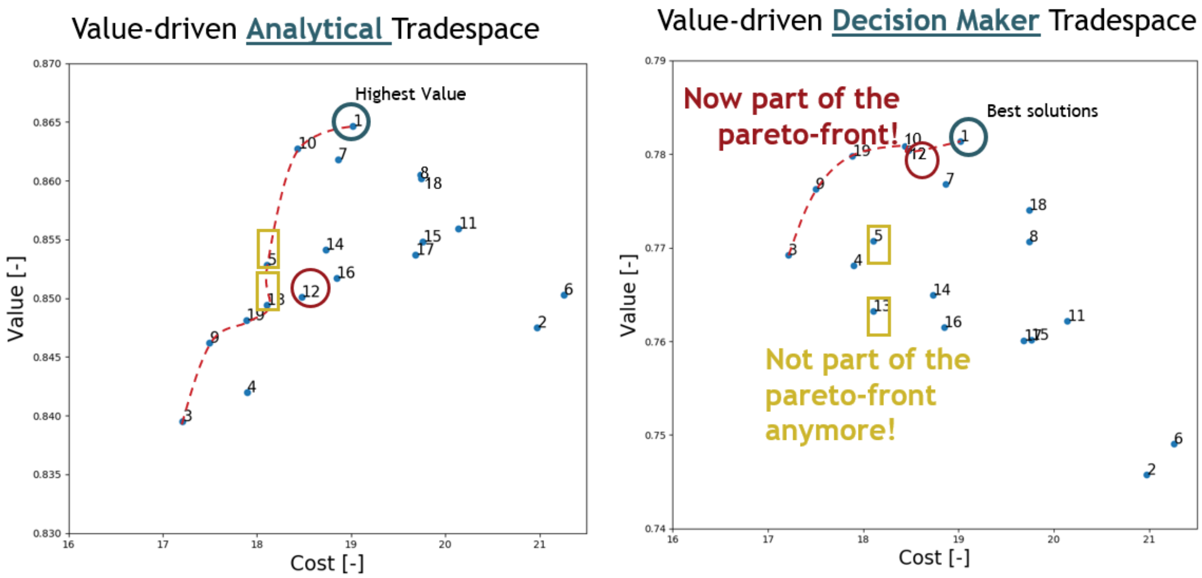


Figure 81: Zoom on the Value-driven Pareto-Front Comparison

3.5.4 Verification and Validation

Once the best solution is identified, it is important to check the solution is verifying requirements and it is therefore valid.
Through the RVF, it is possible to automatically check if requirements are met or not. In Figure 82 it is just reported one example of verified requirement, which therefore valid. It is about the LFL (Landing Field Length) that the aircraft shall have. In this way, it is also possible to check the influence that different HTP configurations, made by different materials, manufacturing and assembly processes, have on the whole aircraft performance.

R8	R-0005	The aircraft shall land with the LFL of maximum 1400 m during the landing condition flight*	Performance	Valid

Figure 82: Example of Requirements verification done through the RVF

3.5.5 AC Conclusions

In conclusions, the main challenge for application case 2 has been the concurrent coupling of multiple domains (or systems), in the specific the manufacturing, supply chain and overall aircraft design domains. Some of the MBSE and MDO technologies supported the concurrent coupling of multi-systems. However, further improvements are still needed due to complexity of relationships existing among these systems and the huge amount of data charactering the individual domain/system. The value model theory, particularly the Multi-Attribute Utility theory, has been adopted as means to enable the concurrent coupling. It has been a powerful means to simplify the visualization of a 4-objectives optimization in case of linear assumptions as well as for catching decision-maker´s preferences so simplifying the multi-criteria decision-maker process. Further activities might be done also in this direction exploration how other theories can support the concurrent coupling of multiple domains.

4 Conclusion and outlook

In industry, manufacturing aspects form an important aspect in considering the properties of a system design. Whether it is the cost of manufacturing a system or the value of its manufacturing supply chain, manufacturing aspects form an important part in deciding which systems design is best. With application cases 1 and 2 it has been shown that manufacturing aspects can be included the multi-disciplinary analyses and optimizations of complex systems.
It has also been shown in Application cases 1 and 2 that, when following a pre-determined process, the Agile 4.0 process, a MDO workflow can be set up. It has also been proven that this can be done with model based tools and methods fitting within the MBSE paradigm. These tools and methods have been enabled by the OCE in the Agile 4.0 project.

In the future, a methodical way of defining a systems design will become more important as design lead times are reduced and system requirements are stretched. As was shown, these requirements can now also include manufacturing requirements. The next step will be to leverage these developments to enable truly sustainable aircraft system design, which does of course also include the manufacturing system for the aircraft and aircraft components designed.

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