DELIVERABLE D 8.5

UPGRADE DRIVEN STREAM MDO FRAMEWORK DESCRIPTIONS AND TRADE OF RESULTS

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GLOSSARY

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

1 EXECUTIVE SUMMARY

1.1 Introduction

The deliverable 8.5 will present and describe the results of the two application cases of the WP8 obtained by executing the AGILE 4.0 framework (A4F).

The main objectives, reflecting the AGILE4.0 framework steps, are:

1. System Identification, KPI and main objectives.
2. System Specification, stakeholders involved, their needs and associated requirements.
3. System Architecting, applied to System of Interest (SoI) and second system of interest.
4. System synthesis base on alternative possible architecture-
5. System design, optimization, trade-off, and verification

The A4F involved steps are depicted in Fig. 1.

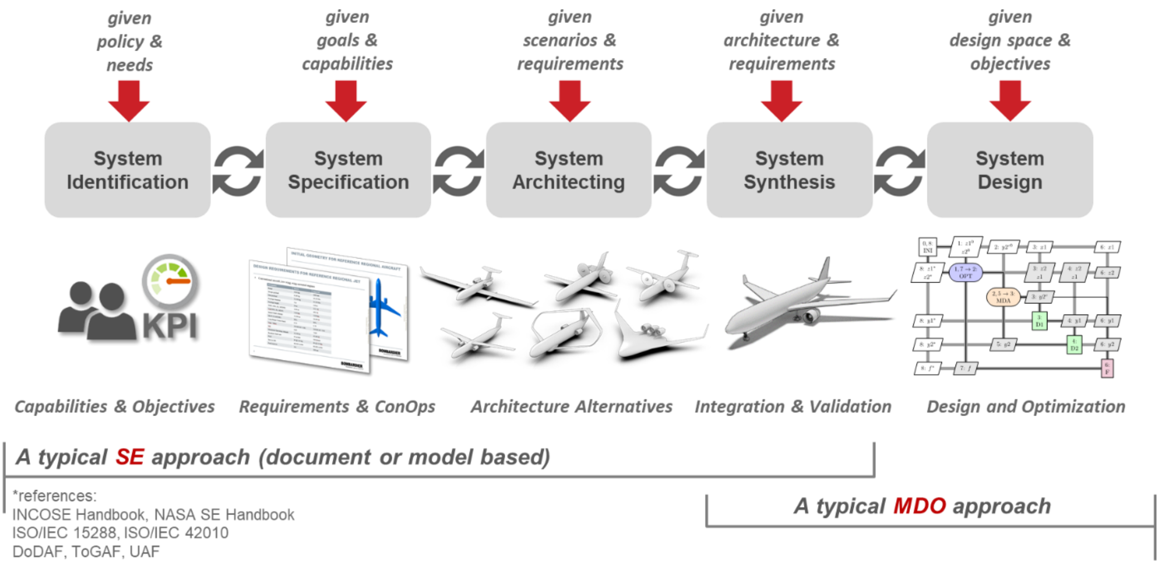


Fig. 1: AGILE 4.0 Overall Steps

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/ac6-retrofitting/ (AC6) and https://www.agile4.eu/ac7-family-concept/ (AC7).

1.2 Brief description of the work performed, and results achieved

The deliverable D8.5 describes the main achievements of application cases 6 (AC6) and 7 (AC7) obtained using the technologies developed in the framework of AGILE4.0 project. All the steps depicted in Fig. 1 have been set-up in the development process of the retrofitting of an existing 90 passengers' regional aircraft (AC6) and the design of a business-jet aircraft family (AC7). Results enables

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 M34 (end July 2022). This is mainly due to technologies release delay and COVID 19 pandemy.

1.3.2 Corrective actions

The correction action was to shift the Deliverable D8.5 due date to M40 (December 2022), contextually with the project extension.

2 APPLICATION CASE 6

The AC6 deals with the retrofitting of an existing 90-pax regional jet aircraft. The reference aircraft (baseline), already existing, was based on the results achieved in AGILE project[1], whose Top-Level Aircraft Requirements (TLARs) are summarized in Tab. 1. This airplane is powered by two turbofans with a by-pass ratio of 5.4 (like a General Electric CF34 engine) and is equipped with a conventional On-Board-System (OBS) architecture (see Fig. 2). The overall aircraft configuration, in terms of external shape, structural layout, passenger layout, landing gear, extensively studied in AGILE project, has been assumed frozen and the airplane design out of the scope of the present deliverable.

Tab. 1: AC6 Top Level Aircraft Requirements

Regional 90 pax turbofan aircraft		
	Metric	Imperial
Range	3500 km	1890 nm
Design Payload	9180 kg	20220 lb
PAX	90 pax @ 102 Kg	90 pax @ 225 lb
MLW (%MTOW)	90%	
Long Range Cruise Mach (LRC)	0.78	0.78
Initial Cruise Altitude (ICA)	11000 m	36000 ft
Maximum Operating Altitude	12500 m	41000 ft
TOFL (ISA, SL, MTOW)	1500 m	4921 ft
LFL (ISA, SL, MTOW)	1400 m	4593 ft
Fuselage length	34 m	111.5 ft
Powerplant:	2 Turbofans, BPR = 5.4, EIS 2010	
On-board-System Architecture	Conventional	

Fig. 2: Application Case 6. Engines and OBS highlighted.

The AC6 main aim was to evaluate the impact on recurring and non-recurring costs due to a retrofitting operation, while obtaining a sensible improvement on fuel consumption and pollutant and noise emissions.
The involved retrofitting packages were:

1. The *Engine Retrofitting*, consisting in replacing the baseline engines with an advanced Geared turbofan with a EIS2025+ technologies.
2. The *OBS architecture Retrofitting*, replacing the conventional OBS with more or all electrification of secondary systems.

[1] AGILE project website: https://www.agile-project.eu/ accessed 19/12/2022

The trade-off space envisioned by the AC6 owner LEONARDO, was focused on evaluating the "costs expenditure" (non-recurring costs) minus the "savings money" (recurring costs) with respect to cumulative emissions index (accounting for both pollutant and noise) between the baseline existing airplane after a "retrofitting operation", as depicted in Fig. 3. Less is the value of Costs-Savings (negative), higher are the savings respect to the costs. Less is the Cumulative Emission index, lower is the level of emissions (better performance).

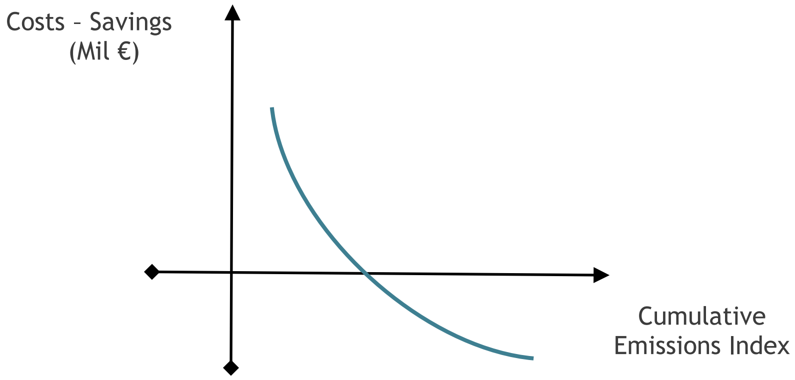


Fig. 3: AC6 main trade-off space: Costs-Savings vs Cumulative Emissions Index.

The aircraft retrofit design is performed by following the steps described in Fig. 1. The aim of these five phases is to include in the development cycle a System Engineering approach, which will lead the typical multidisciplinary design and optimization activity.
The first three steps concern the MBSE approach, which allow to perform the Systems Engineering Product Development process through modelling. Indeed, first phase concern modelling of the scenario in which the activity is performed. The stockholders' actions and interactions are here defined, specifying the steps required to realize final product and its influence on to the involved stakeholders. The second phase aims to define the involved stockholders' needs and requirements. They can be modelled according to the MBSE approach, generating rational statements which make easy their fulfilment verification. The third phase concerns the system architecture modelling. A model of the systems under analysis is generated, describing how each systems' components fulfil the requirements. Here, different solutions can be modelled, each one is generated through a decision-making process. The last two phases concern the MDAO process. The first one is mainly focused on the definition of the system to be analysed. This step is performed through previously described decision-making process. The second phase concerns design and optimization of the defined systems. The systems are here designed and analysed through the definition of a MDAO workflow in which only the involved disciplines are included. After the execution of these steps, requirement verification methods, decision-making modelling, verification, and validation processes can be performed to select the best solution and verify if the previously defined requirements are satisfied. These operations are made possible thanks to all the steps which characterize the MBSE approach. The results achieved through each one of the steps introduced in Figure 1 and the subsequent verification process are presented in the following sections.

2.1 System Identification

The AC6 System of Interest (SoI) is represented by a conventional regional jet 90 passenger aircraft with conventional OBS architecture and 2010 reference engine architecture, as described into D8.1 [1].

The AC6 2nd System or enabling system is represented by a retrofitting solution obtained by AC 6 SoI. Two retrofitting packages are considered: advanced powerplant and OBS electrification installation, leading to different enhanced platforms and multiple architectures.

The focus is on improving fuel efficiency, noise, emissions, maintenance, weight, and costs characteristics of the retrofitted aircraft, trading-off on capital costs and costs saving.

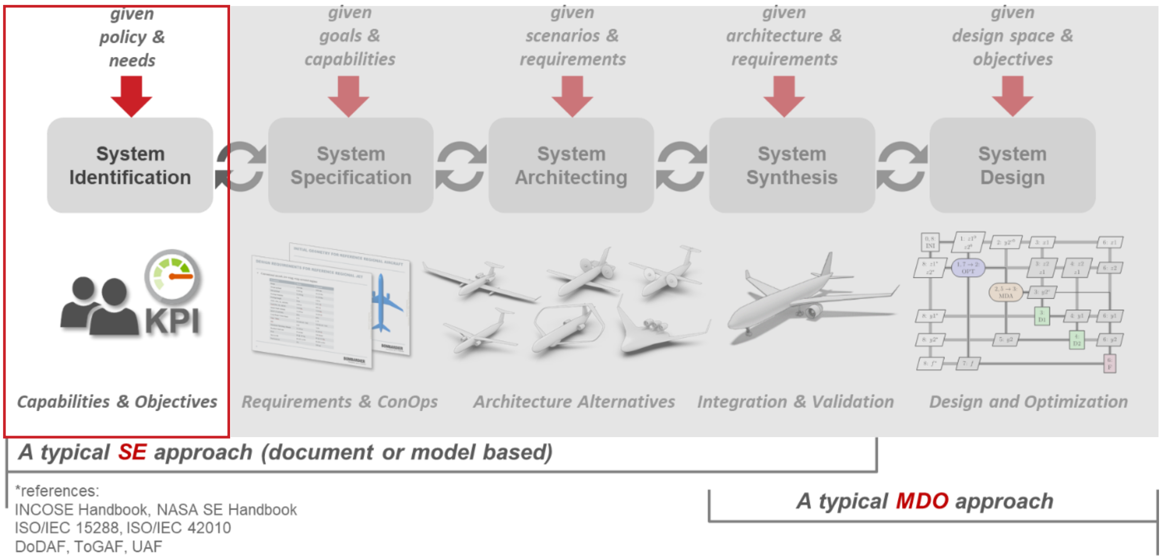


Fig. 4: AGILE 4.0 Step I: System Identification.

The first step concerns the system identification and scenario modelling, see Fig. 4. This task is performed using the OCE with Capella [2], a model-based engineering public domain tool which allows to model different scenarios into the OCE framework. An example of feasible scenario is the "*Environmental Restriction*" introduced by Governments and received by Regulations Authority. This generic restriction can represent prohibition or limitations of flying for pollutants aircraft, pressing the Airliners to quickly upgrade their existing fleets. The Airlines will request to the aircraft OEM a solution to reduce emissions whom, due to the tight deadline, will opt for a retrofitting activity. Innovative equipment (engine and OBS) will be acquired from tiers one suppliers (or OEM), which will develop and test their products before selling them to aircraft OEM. Once verified the availability and the characteristics of the innovative equipment, aircraft OEM will definitively start the retrofitting process. The retrofitting activities will be designed and then performed, installing on the aircraft the new components. Then, a certification phase is required, involving the certification authorities. After the aircraft upgrade is completed and the type certificate is released by the authorities, airliner will be able to offer their passengers a greener and more comfortable flight. Reduction of air emissions will be reported to the Governments, reduction of noise emission will be appreciated by passengers. In addition, the aircraft upgrade could also modify the ticket price. This is another fundamental aspect perceived by passengers. In Fig. 5, the "*Environmental Restriction*" scenario is illustrated. In grey are indicated all the stockholders accounted in the scenario. Arrows and boxes illustrate stakeholders' actions derived from Government's restrictions. Actions are developed vertically to indicate their location in time during the development of all the scenario. More details about scenario definition in [3].

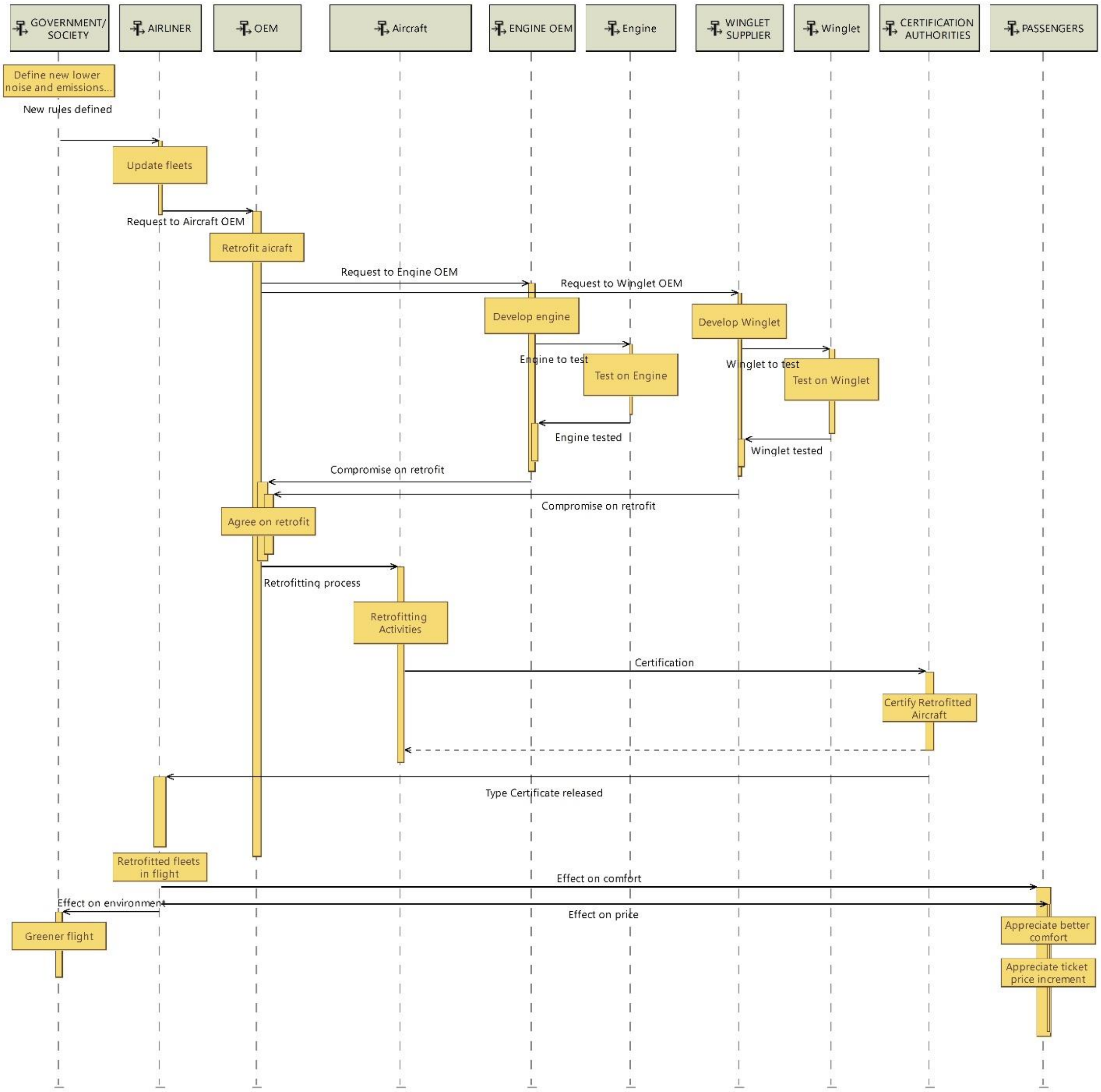


Fig. 5: "Environmental Restriction" scenario modelled through OCE.

2.2 System Specifications

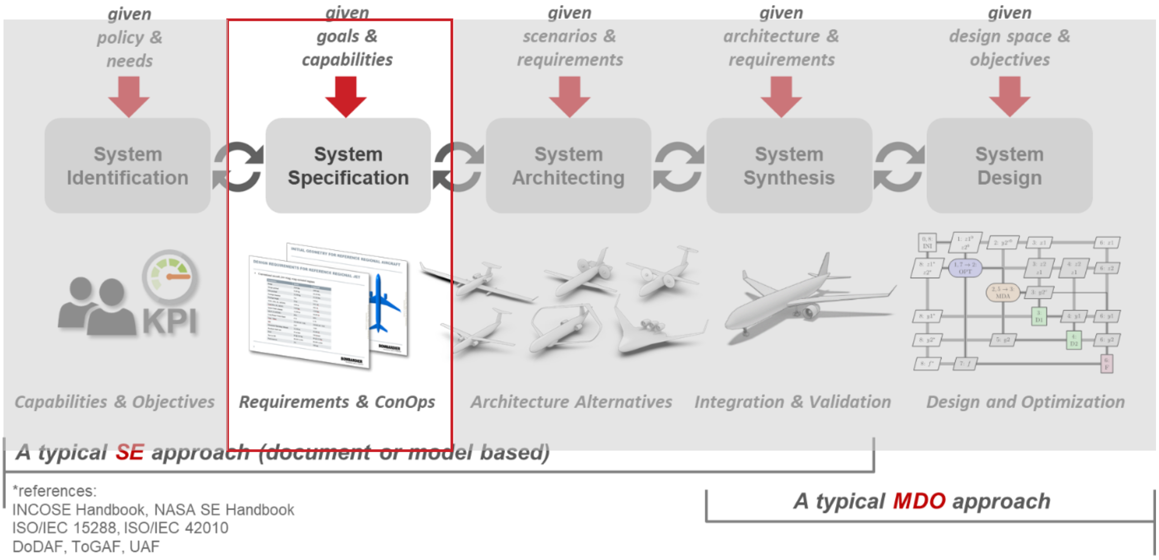


Fig. 6: AGILE 4.0 Step II: System Specification.

The second step is indicated in Fig. 6. It concerns the definition of requirements, generated considering stakeholders and their needs.

Considering the scenario represented in Fig. 5, the following stakeholders can be rationally selected:

- OEM (Original Equipment Manufacturer): they collect the needs from all the stakeholders to retrofit the aircraft accordingly. They account for new government regulation, Airliner timing and economical requirements and equipment's availability. From this information, the OEM will decide the best retrofitting level solution.
- AIRLINERS: they directly operate the aircraft to maximize their profit, ensuring passenger comfort and considering the regulation prescriptions. They will provide the fleet on which apply the operations and they will pay for the retrofitting activities.
- ENGINE OEM: it is involved as first level supplier (or more) for the engine retrofitting. It collects overall aircraft OEM requirements, trying to accomplish all tasks with an innovative product. The same happens for other OEM (e.g., OBS OEM).
- CERTIFICATION AUTHORITY: aircraft retrofitting for sure involves certification authority at several levels. Their indications will drive the upgraded aircraft design and the following testing activities.
- MRO (Maintenance, Repair, and overhaul): once aircraft is retrofitted, MRO must be considered within the process to avoid any subsequent issue. Their need will have an influence on the retrofitting solution choice, impacting aircraft and OEM activities.
- PASSENGERS: passengers as aircraft final users, are involved for comfort and emissions. Of course, they will also consider the ticket price modification made by Airliners.
- MARKET: the market forecast, especially related to the fuel price, can be seen as a stakeholder from which some specific needs could directly depend. Also, equipment price and current technology level can be considered as part of this stakeholder.
- GOVERNMENT: they are the stakeholder from which all the scenario originates, the introduced limitations will generate and affect all the actions and interactions just described.

The information, initially collected from a Brainstorming of Team of Experts and collected in a document-based format, have been developed to a model-based format in the OCE. This step has been performed through the OCE in KE-Chain [4], a web-based portal which provides centralized and integrated access to the OCE. Tab. 2 and Tab. 3 represent a summary of the needs defined for each stakeholder and requirements necessary to meet the stakeholder's need represented according to the MBSE approach. Fig. 7 represents an example of needs and requirements in a model-based format. Through Papyrus technology [5] all the requirement's info generated in this step are stored and traced. As it is possible to see, for each requirement the responsible stakeholder, the level of priority, the ID, the description, the linked need and the consequences which arise if the requirement is not fulfilled are indicated. More detail about the definition of Stockholder's needs and requirements can be found in [6] More details about MBSE schematization in [3].

Tab. 2: Needs of each stakeholder accounted.

Stakeholders	Needs
OEM	Maximize profit
	Minimize costs of production
	Minimize costs of certification
	Minimize risks (costs / benefits)
	Possibility to choose among multiple engine manufacturer
AIRLINERS	Maximize profit (minimize DOC, maximize pax load factor)
	Ensure passengers comfort also at noise level
	Minimize fuel burnt
	Minimize emissions
	Minimize taxes due to noise and emissions
	Operate in any available airport
ENGINE OEM	Need the exclusivity
CERTIFICATION AUTHORITY	Guarantee CS-25/FAR Certification
	Environmentally friendly aircraft
MRO	Easy inspection activities
	Keep the same facilities to accomplish maintenance activities
PASSENGERS	Comfortable flight also in terms of internal noise
	Affordable ticket price
	Would like to pay for a "green" flight
MARKET	Establish economic trends (fuel price)

Tab. 3: System's Requirements description.

Requirement	Description	Type
Airliner operability	The retrofitted Aircraft shall have at least the same operability of the reference aircraft	Performance
Airliner taxes	The Aircraft shall reduce taxes by a minimum of 10 % for condition: typical mission	Performance
CO2 reduction	The Aircraft shall exhibit -20% CO2 reduction during/after exposure to atmosphere for any flight conditions	Environment
Controllability and Maneuverability	The Aircraft shall ensure safe maneuverability and controllability	Functional
Cruise Mach	The Aircraft shall fly at MLR equal to 0.78 Mach for condition: cruise condition 35000 ft	Performance
CS25 compliancy	The Aircraft shall comply for condition: CS-25 regulations	Functional
Design payload	The Aircraft shall exhibit design payload in accordance with DP equal to 9180 kg for condition: design mission	Design constraint
Design range	The Aircraft shall fly at design range equal to 1890 nm for condition: design mission	Performance
DOC reduction	The aircraft shall reduce DOC by a minimum of -10 % for condition: typical range	Performance
Engine C inspection	The Engine shall reduce Engine C inspection time by a minimum of 10 % for condition: Engine C inspection	Performance
Engine EIS	The Engine shall entry into service for condition: 2025+ advanced	Functional
Engine NOX	The Engine shall exhibit -20% NOX reduction during/after exposure to atmosphere for typical mission	Environment
Engine OEM profit	The retrofitted AIRCRAFT shall increase the engine sell rate of at least 10% after engine retrofitting	Suitability
Engine SFC	The Engine shall consume at ESFC by a minimum of 0.49 lb/lbh for condition: cruise condition	Performance
Fuel burnt reduction	The Aircraft shall reduce fuel consumption by a minimum of 10 % for condition: typical mission	Performance
Fuselage commonality	The Aircraft shall respect the condition: same fuselage of reference AC	Functional
Landing Field Length	The Aircraft shall land at landing field length by a maximum of 4593 ft for condition: landing	Performance

Maintenance cost reduction	The Aircraft shall reduce at aircraft maintenance costs by a minimum of 10 % for condition: entire operative life maintenance costs	Performance
Maximum Takeoff Weight (MWTO)	The retrofitted Aircraft shall have a maximum take-off weight lower than reference aircraft for condition: design mission	Design constraint
Noise reduction	The Aircraft shall exhibit -6 db noise reduction during/after exposure to atmospheric acoustic for certification points	Environment
Number of Passengers	The Aircraft shall exhibit number of pax in accordance with PAX is equal to 90 for condition: design mission	Design constraint
OBS architecture	The OBS shall have for condition: more electric architecture	Functional
OBS architecture	The OBS shall have for condition: all electric architecture	Functional
Tail planes commonality	The Aircraft shall have for condition: same tailplanes of reference AC	Functional
Takeoff Field Length	The Aircraft shall take-off at Take-off field length by a maximum of 4921 ft for condition: take-off ISA sea level	Performance
Ticket price	The retrofitted AIRCRAFT shall have a ticket price reduction of -10% during typical mission	Suitability
Typical range	The Aircraft shall fly at typical range equal to 500 nm for condition: typical range	Performance
Wing commonality	The Aircraft shall have for condition: same wing of reference AC	Functional
Airliner taxes	The Aircraft shall reduce taxes by a minimum of 10 % for condition: typical mission	Performance

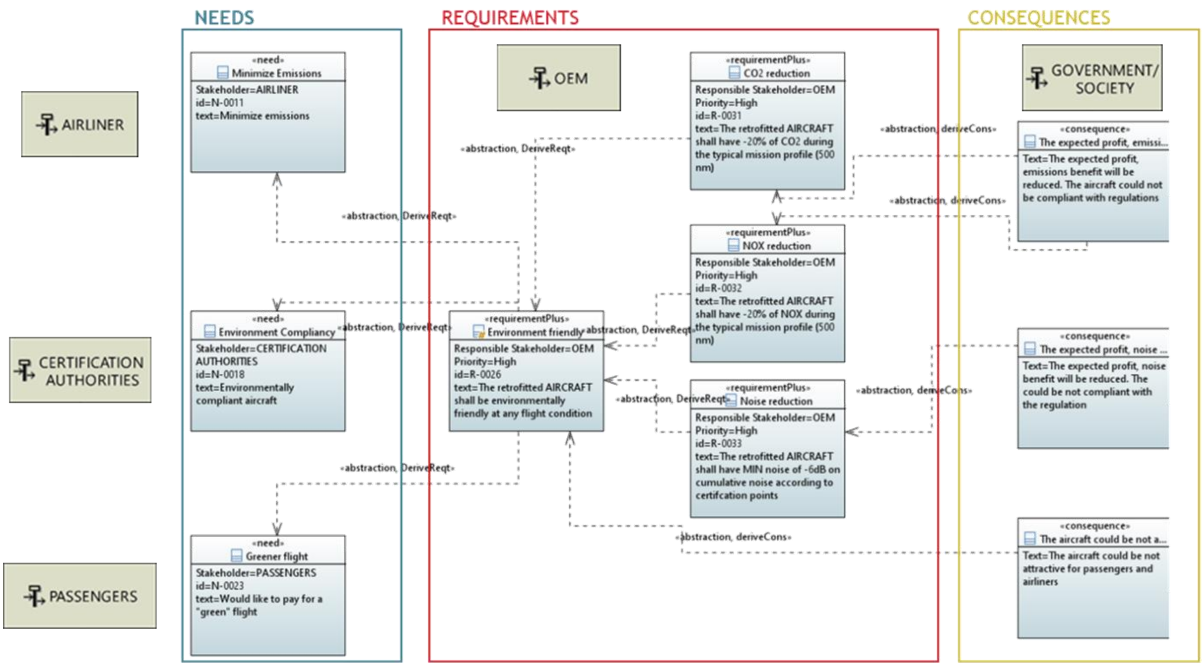


Fig. 7: System's Requirements info collected and visualized in a MBSE schema.

2.3 System Architecting

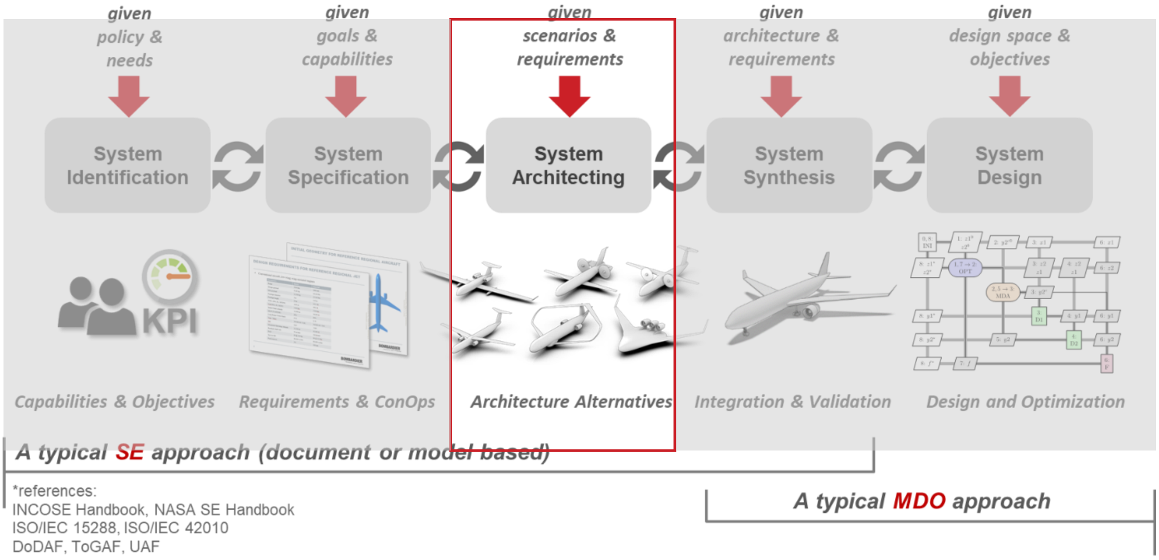


Fig. 8: AGILE 4.0 Step III: System Architecting.

The third step of the AGILE4.0 MBSE approach (Fig. 8) concerns the generation of an architecture which represent the systems that must be analysed.

Within the OCE, it has been possible to easily model a system architecture representing both the SoI and ES (Enabling System) under analysis. Starting from the functional requirement indicated in
, all the components which can belong to the baseline and final systems are introduced to the model, as element able to fulfill the specific requirement. Of course, a component will also need the fulfillment of one or more functions, which on their turn will require other components. In this way, a complex system architecture can be generated accounting for all the retrofitting aircraft solution. Indeed, through a decision panel automatically generated, it is possible to choose how to fulfill each specific requirement and consequently obtain the architecture model of the baseline aircraft or one of the upgraded solutions. In Fig. 9 an extract of the complete architecture model is represented. The model is obtained through ADORE [7], a tool connected with the OCE implemented in KE-chain which allow to generate architectures model though graphical user interface. Fig. 9 represents the model concerning the engine components, including nacelles, attachment points, starter, generator, and fuel systems. Instead, Fig. 10 represents the architecture of the OBS. Different systems are considered ranging from control systems, ice control systems and power systems. As it is possible to notice, some requirements can be fulfilled by different components. For instance, the flight control systems can be completely electric or can also be powered by hydraulic and pneumatic systems. In this and other similar cases, an architecture decision must be made. It will define which solution is considered and subsequently analyzed, as illustrated in the following paragraph. More details about systems architecture model in [8].

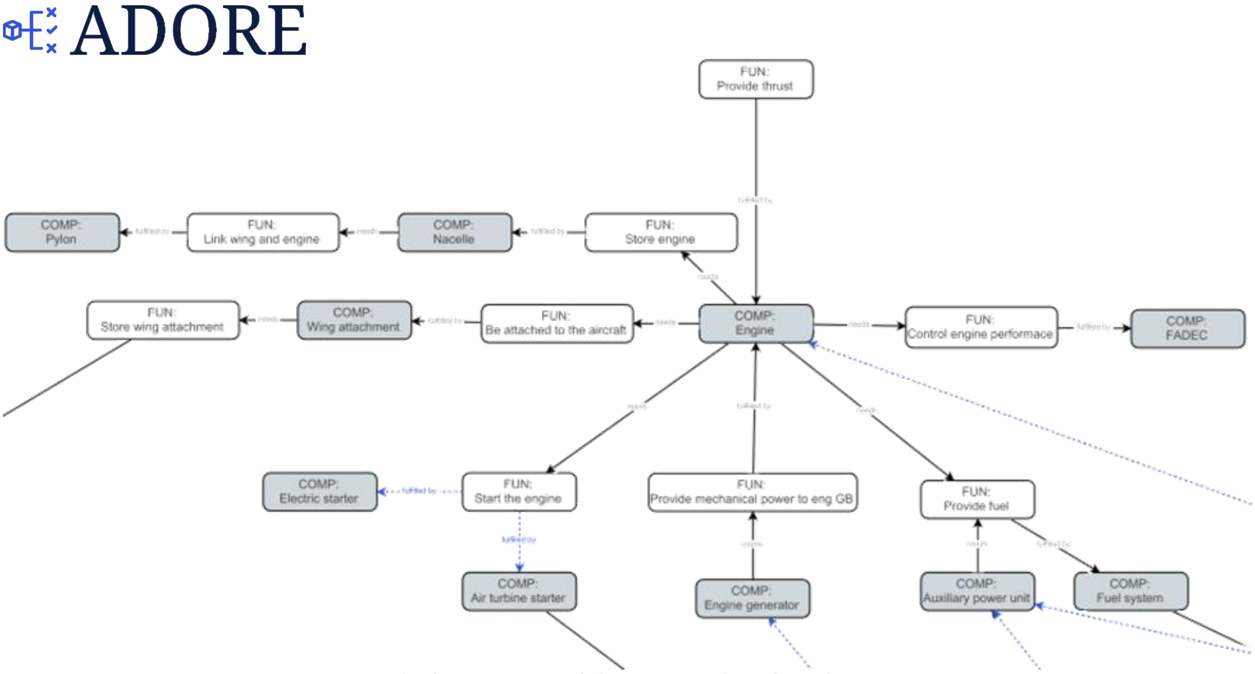


Fig. 9: Architecture Model extract related to the Engine.

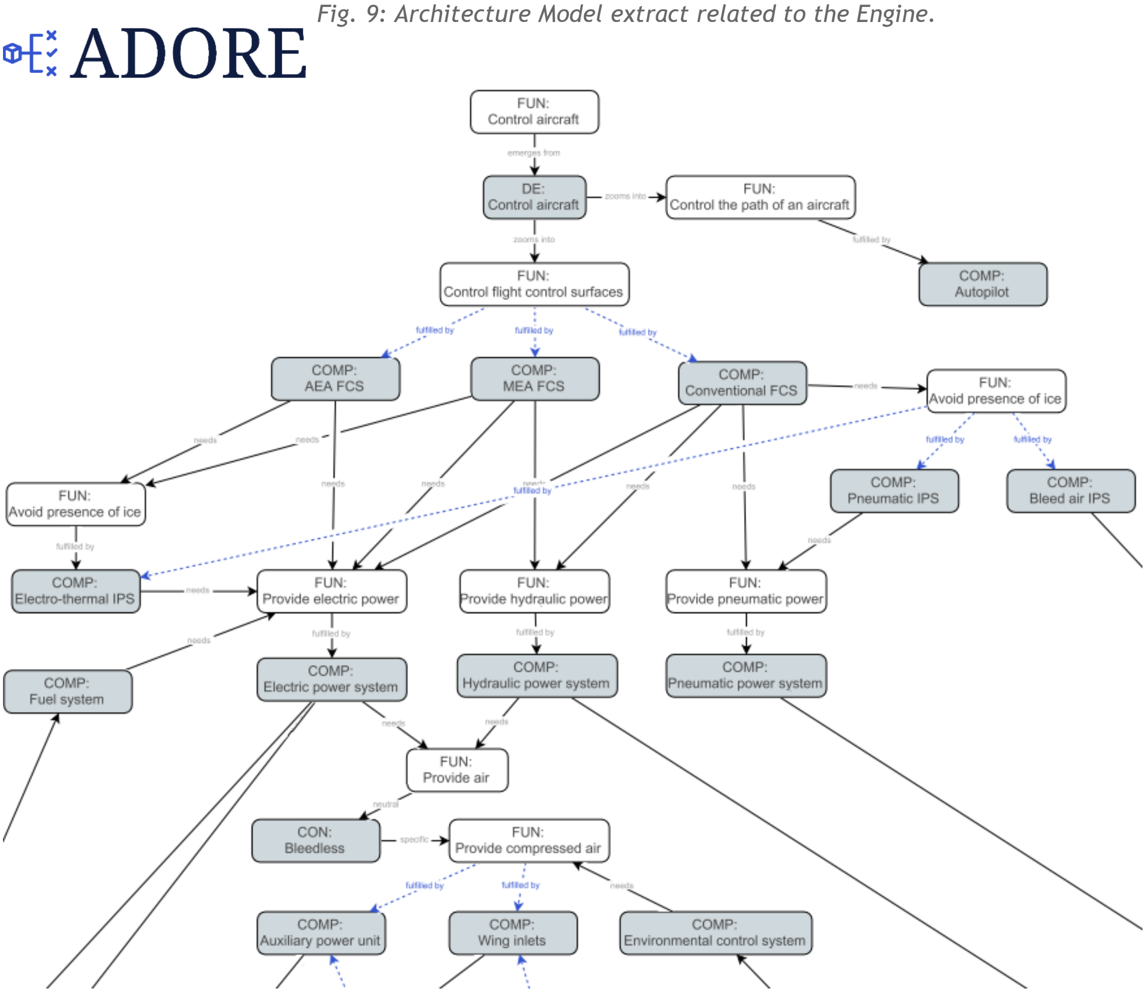


Fig. 10: Architecture Model extract related to the OBS.

2.4 System Synthesis

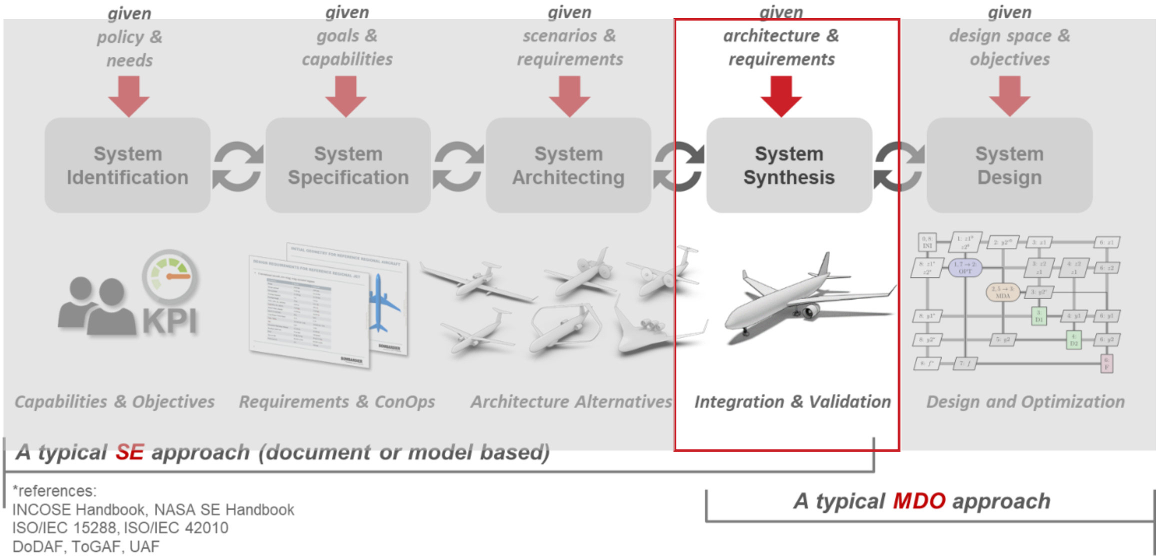
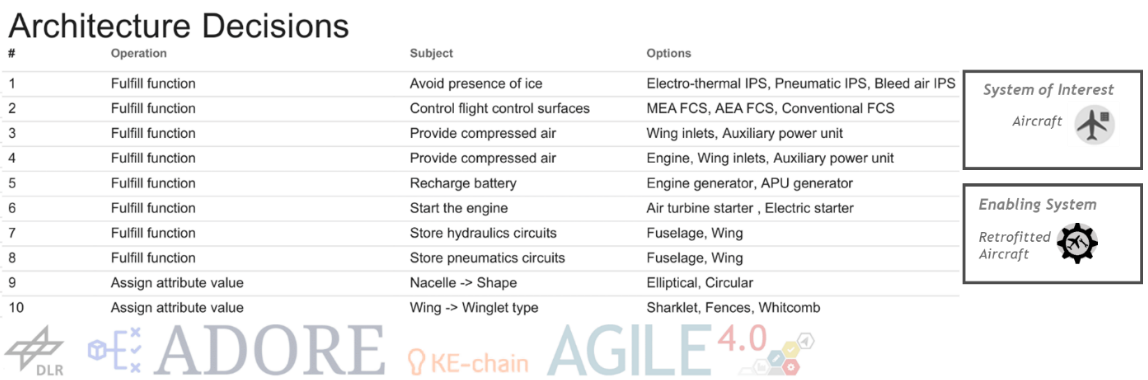


Fig. 11: AGILE 4.0 Step IV: System Synthesis.

The fourth step of the process represents the beginning of the MDAO phase (Fig. 11), during which, among feasible architectures, the systems that must be analysed is selected. This step represents the bridge between the MBSE and MDAO approach. Indeed, the connection between available disciplines and the model of the system are generated to analyse both SoI and ES. Once obtained the systems architecture model, a decision panel like the one represented in Fig. 12, is automatically generated. Indeed, when a model's function can be satisfied by more than one component, the designer must choose which elements will fulfil it. The main choices consist of OBS level of electrification (Conventional, more electric or all electric), the engine characteristics (such as its starters and nacelle geometry) and winglet type (modelled as further example). For each type of OBS, it is possible to choose a different way to provide electricity, pressurized air and so on. Also, a choice on winglet type is presented here (fence, Whitcomb, sharklet). The coherence of the decision is guaranteed by the architecture model schema: if a decision on a specific OBS architecture is made, all the other choices incompatible with that selection are automatically excluded. For instance, if an all-electric OBS configuration is choose, the ice protection system will necessary be supplied by electric power. Otherwise, if a conventional OBS configuration choice is made, the ice protection system can be powered by pneumatic energy of bleed air. Two main architectures have been generated through the decision panel illustrated in Fig. 12: the SoI and the ES. They represent the system which will designed and analysed in the final part of the MDAO process.


Architecture Decisions

#	Operation	Subject	Options
1	Fulfill function	Avoid presence of ice	Electro-thermal IPS, Pneumatic IPS, Bleed air IPS
2	Fulfill function	Control flight control surfaces	MEA FCS, AEA FCS, Conventional FCS
3	Fulfill function	Provide compressed air	Wing inlets, Auxiliary power unit
4	Fulfill function	Provide compressed air	Engine, Wing inlets, Auxiliary power unit
5	Fulfill function	Recharge battery	Engine generator, APU generator
6	Fulfill function	Start the engine	Air turbine starter , Electric starter
7	Fulfill function	Store hydraulics circuits	Fuselage, Wing
8	Fulfill function	Store pneumatics circuits	Fuselage, Wing
9	Assign attribute value	Nacelle -> Shape	Elliptical, Circular
10	Assign attribute value	Wing -> Winglet type	Sharklet, Fences, Whitcomb

Fig. 12: ADORE Decision panel. It indicates the possible choice which can be made to generate a new architecture

For each system that is generated, a table indicating the status of the connection between the MBSE architecture and the MDAO tool is generated. In KE-Chain, MultiLinQ [7] tool has been provided to accomplish this task. In MultiLinq, the system architecture model which the user wants to examinate can be imported. In the model, a quantity of interest (QOI) must be defined for each component. For instance, a QOI for the engine can be the fuel consumption or the BPR; a QOI which concerns the whole aircraft can be its total price. These QOIs are defined through ADORE, during the systems architecture definition phase. Then, the CPACS file obtained after the workflow execution must be imported. In this way, MultiLinq allows to the user to select which is the file branch linked to each QOI. The previously defined tools information is then automatically imported from the OCE. Through all these data, MultiLinq generates a mapping matrix which indicates for each QOI which is the design disciplines which takes it into account. Fig. 13 represents an excerpt of the mapping matrix obtained for the AC6 enabling system. This matrix allows the designer to understand if the system architecture model and the workflow are correctly linked to each other. Indeed, it can show if a tool is unnecessarily considered or if a component's QOI is not estimated during computations. In the example showed in Fig. 13 all competences and QOIs are linked to each other. A great part of the components is linked to OBS design disciplines; this is due to the inclusion of different aircraft system components in the Enabling System architecture, useful to characterize the differences between possible OBS levels of electrification.

MULTILINQ

		Tools								
Components	QOIs	AERO RSM	AERODYNAMICS	COSTS	ENGINE	NOISE	OBS	PERFORMANCE	SFC SENSITIVITY	Structural RSM
AEA FCS	FCS Mass						✓			
APU generator	Electrical Generation Mass						✓			
Air turbine starter	Electrical Generation Mass						✓			
Aircraft	Aircraft Price			✓						
Aircraft	Certification EPNL Noise					✓				
Aircraft	DOC			✓						
Aircraft	Design Range							✓		
Aircraft	Landing Distance							✓		
Aircraft	Maximum Take-Off Weight						✓	✓		✓
Aircraft	Retrofitting Cost			✓						
Aircraft	Take-Off Distance							✓		
Aircraft	Typical Range							✓		
Autopilot	Automatic Flight System Mass						✓			
Auxiliary power unit	APU Mass						✓			
Batteries	Electrical Generation Mass						✓			
Bleed air IPS	DeIcing Mass						✓			
Conventional FCS	FCS Mass						✓			
Electric power system	Electrical Distribution Mass						✓			
Electric starter	Electrical Generation Mass						✓			
Electro-thermal IPS	DeIcing Mass						✓			
Engine	BPR				✓					
Engine	Engine Price			✓						
Engine	Number of Compressors				✓					
Engine	TT0				✓					
Engine generator	Electrical Distribution Mass						✓			
Environmental control system	Air Conditioning Mass						✓			
FADEC	Automatic Flight System Mass						✓			
Fuel system	Fuel Mass							✓		

Fig. 13: Excerpt of Enabling System mapping matrix generated through MultiLinQ.

2.5 System Design

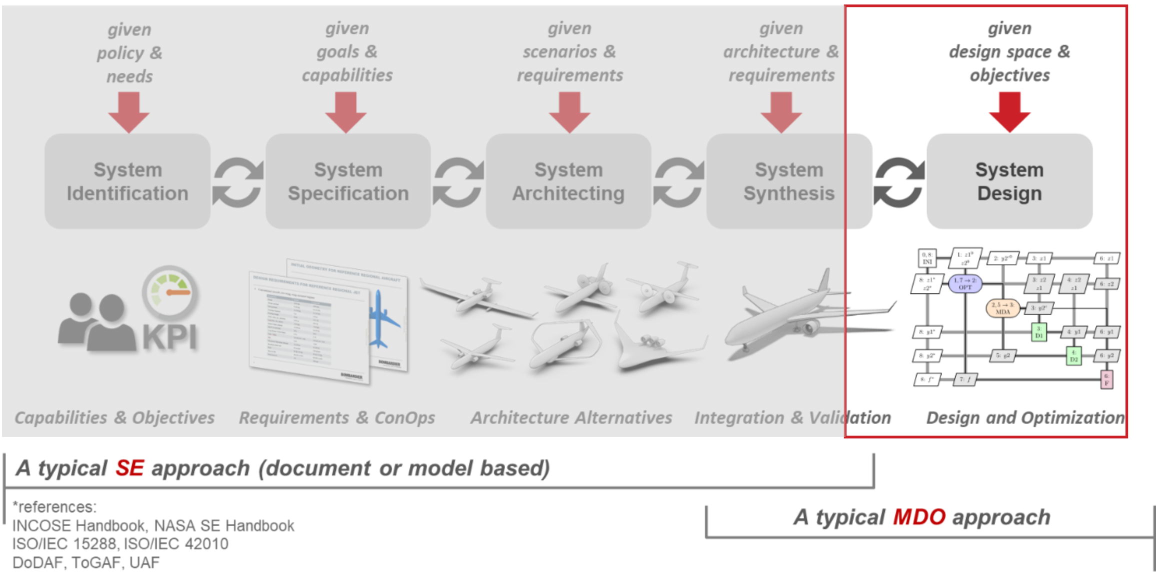


Fig. 14: AGILE 4.0 Step IV: System Synthesis.

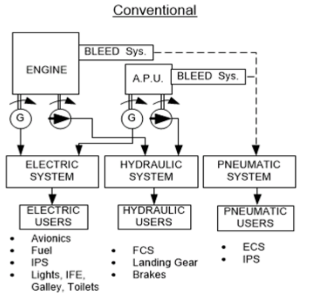
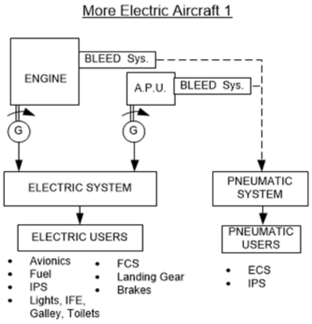
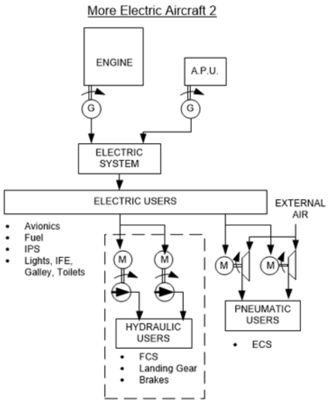
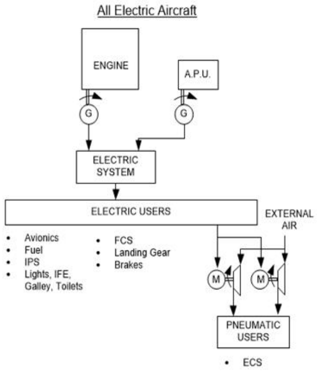
The last step of the process represents the development of the MDAO workflow and the execution of the analysis, optimization, and trade-off studies, as illustrated in Fig. 14.

2.5.1 Workflow implementation

Different MDAO problems can be addressed to design and analyse the system described in the previous section. The first step to define an appropriate workflow consists in the tool's identification. The design of a retrofitting activity is not a straightforward activity; indeed, it involves different phenomena. For instance, it is essential to analyse the impact on both performance and cost of such an operation. As made for the stakeholders, a wide range of disciplines must be considered to obtain a coherent and feasible solution. Below, the disciplinary competences involved in the MDAO workflow are briefly described. High, medium, and low fidelity analysis are performed on the aircraft-level. To save computational time and guarantee higher level of fidelity, several competences are integrated as surrogate models.

- ENGINE: the engine module is a surrogate-based tool. The main input of this tool is the engine BPR. From that, it provides the main engine characteristics such as: i) Thrust and Fuel Flow as function of Mach number, altitude, ratings for five different mission phases; ii) engine and pylon masses; iii) nacelle dimensions iv) engine list price; v) engine noise deck, expressed as 1/3 octave band in a polar arc. The engine performance data are based on GASTurb 11 [9] engine modeler, from which 4 different engine BPR (5.4, 9, 12, 15) are generated with the same top-level engine requirements; the engine acquisition price and noise deck are based on semiempirical and statistical correlations.
- AERODYNAMICS: this branch computes calculations for both low-speed and high-speed conditions. A response surface model (RSM) has been developed to account for high fidelity results in high-speed condition, CFD analysis have been computed in cruise condition for different engine position with engine on and off. A tool based on semi-empirical approaches allows to compute low-speed aerodynamics.
- ASTRID [10]: tool capable to size all on-board systems, providing their weights and bleed usages. ASTRID estimates hydraulic, pneumatic, and electric power required by each system for different phases of the mission profile. Also, secondary power (power-off-takes) impact on engine fuel flow is computed. Four different OBS architectures have been modelled, named: i) C (conventional) ii) MEA1(more electric aircraft 1) iii) MEA2 (more electric aircraft 2) and iv) AEA (all electric aircraft). A description of these architectures can be found in Tab. 4.

Tab. 4: Main characteristics of the architecture considered for OBS electrification.

OBS Architecture	Main Characteristics
	Conventional • Hydraulic actuation (FCS, LG) • Bleed system • Electrical generators and hydraulic pump • Primary electric generation 115 VAC • Electric system: 2 generators
	MEA1 • Electric actuation (FCS, LG) • Bleed system • Electrical generators • Primary electric generation 230 VAC • Electric system: 2 generators
	MEA2 • Hydraulic actuation (FCS, LG) • Bleed system removed • Electrical generators • Primary electric generation 230 VAC • Electric system: 4 generators
	AEA • Electric actuation (FCS, LG) • Bleed system removed • Electrical generators • Primary electric generation 230 VAC • Electric system: 4 generators

- PERFORMANCE & MISSION [11], [12]: this tool computes ground and in-flight performance and air emissions according to a simulation-based approach. The overall mission profile, performance, fuel consumption, flight time and gaseous emissions are computed.
- PROTEUS [13]: tool which sizes the composite wing, computing the minimum wing structural weight using aeroelastic tailoring. Aeroelastic instability, angle-of-attack, strength failure, buckling loads and laminate feasibility are considered during the optimization. This structural competence is based on a surrogate model based on a DOE high-fidelity structural analysis.

- NOISE: this competence computes the noise emissions at certification points defined by FAR 36 [14] and ICAO Annex 16 [15]. It also provides the noise margin from the certification limit. The method is based on semiempirical approaches based on ESDU methodology [16].
- COSTS: tool based on semi-empirical approaches and industrial knowledge. It computes recurring and not-recurring costs, aircraft price, direct operative costs and the costs associated to a retrofitting process. The tool is based on methodologies proposed by Kimoto et al. [17] and Association of European Airlines [18]. Moreover, an additional methodology has been implemented to estimate development, operation and equipment costs associated to a retrofitting activity. Also, the savings costs (part of direct operating costs) coming from fuel consumption reduction, maintenance costs and emission taxes are computed.

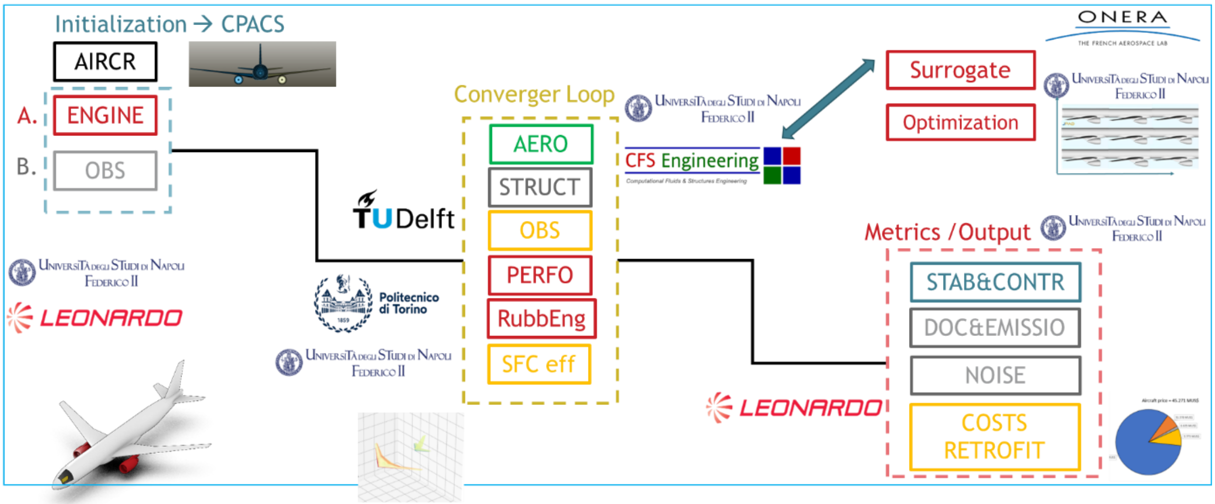


Fig. 15: MDAO workflow preliminary schematization.

Fig. 15 represents a schematization of the desired workflow. A documented based representation of the connection between disciplines and the partner involved for its execution has been achieved. All the information concerning the above-described disciplines can be insert in the OCE. Input and output of each tool must be indicated in a common parametric language. In this case, CPACS [19] files are used to describe the system under analysis and facilitates data exchange through different disciplines. Through these data, KE-Chain automatically defines an MDAO problem. The disciplines involved in the workflow are selected according to the system under analysis (SoI or ES). The computations' parameters such as design variable, constraint, objective, or quantity of interest are defined according to the requirement previously described. Fig. 16 and Fig. 17 represent the XDSM's workflow schema generate respectively for the System of Interest and for the Enabling System. Below, a brief description of both MDAO problem is provided.
The System of Interest workflow (Fig. 16) starts by defining the system aerodynamics during all mission conditions, then OBS architecture is sized according to the aircraft's weight and performance previously computed, also accounting for secondary power. Through the subsequent execution of three tools (ASTRID, Performance & Mission and SFC sensitivity), the convergence on maximum take-off weight is achieved within a *converger* loop. Also, pollutant emissions of the reference platform are computed. In conclusion, costs and price of the platform under analysis are estimated.
The Enabling System MDO workflow (Fig. 17) starts by defining the new engine characteristics, according to the innovative engine BPR selected. Then, once updated the defined solution geometries and weights, the aerodynamics are evaluated in all mission conditions. In addition, the wing structure and the OBS architecture are sized according to new aircraft's weight and performance, computed in the workflow. Through the subsequent execution of four tools (ASTRID, Performance & Mission, SFC sensitivity and PROTEUS), the convergence on maximum take-off weight is achieved within a *converger* loop. Then, pollutant and noise emissions of the designed platform are computed. In conclusion, the recurring, non-recurring and retrofitting costs required to generate such a platform are estimated. In this case, the workflow computation is driven by an optimizer, which will select the best retrofitting solution according to defined objective functions.

The main difference between the two workflows concerns the computation of additional effect required in case of aircraft retrofit. If a new engine is installed on the platform, the engine performance, geometries and weights must be computed to account for its impact on the aircraft. Analogous effect must be computed if a new OBS architecture is installed on the aircraft. A retrofitting activity will impact all previously described disciplines and will introduce the necessity to compute new wing structure, the aircraft noise and the costs required to achieve the retrofitting activity considered. This explains the higher complexity of the ES workflow with reference to the SoI one.

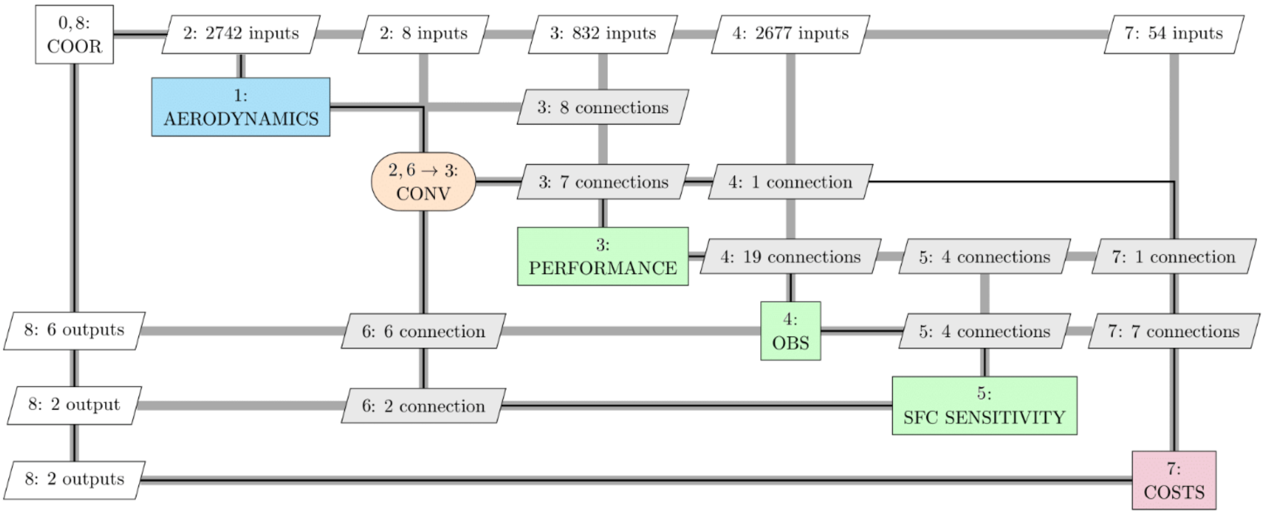


Fig. 16: MDAO XDSM of the System of Interest.

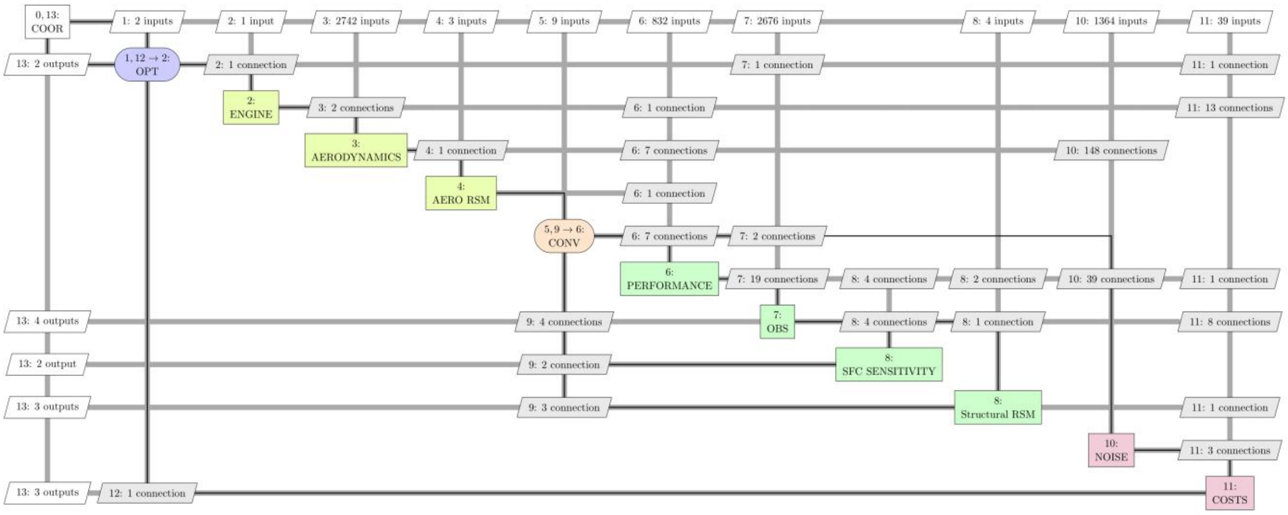


Fig. 17: MDAO XDSM of the Enabling System.

2.5.2 Workflow execution

In this section, some examples of results achieved through the execution of the workflows previously described are presented. In Tab. 5 are summarized the main assumption related to the following computations. It must be noted that table data can be used as "trade-off" parameters for an OEM to enable or not a retrofitting process. After the upgrade activities, the Enabling System will operate for **twelve** years, during which it will realize **seven flights per day** for almost every day of the year. The economic value assumed by the aircraft at the end of its life will be a percentage of the retrofitting costs. This value is mainly influenced by the new equipment installed, which will not yet be at the end of their life. The **fuel price** considered is actualized to value assumed at the beginning of year 2022 [20]. The **noise and emissions costs** are computed considering the current taxes required by Frankfurt airport [21]. These assumptions are directly linked to the scenario presented in Fig. 5, providing a deeper specification of the stakeholder characteristics. Indeed, the **number of aircraft** to be retrofitted and the typical mission data indicates that the Airliner operates with regional flights. The saving achieved through improved maintenance operations is an indicator of the MRO level of development. In conclusion, the profit margin, the learning curve rate, and the savings related to the agreement on equipment acquisition are indicators of the OEM features.

Tab. 5: Hypothesis assumed to compute the retrofitting costs and savings.

Costs Savings Analysis Hypothesis		
	Metric	Imperial
Retrofitted fleet	700 units	
Typical mission range	1333 Km	720 nm
Cruise Mach	0.78	
Cruise altitude	10973 m	36000 ft
Flight per Day	7	
Operative days per year	358 (a-b check included)	
Flight per year	2506	
Flight hours per year	3579 (block time = 1.5h)	
Years of utilization	12	
Aircraft residual value	10%	
Maintenance saving	[5 for engine alone – 10 for engine + OBS] %	
Manufacturer profit margin	7%	
Learning curve rate	0.95	
Agreement saving	50 %	
Fuel price	0.48 €/kg of kerosene / 73 $ per barrel	
Noise taxes	Frankfurt airport taxes	

The executable workflow is shown in Fig. 18. The collaborative remote execution is enabled by leveraging on technologies as RCE [22] and BRICS [23] and the CPACS common language to describe the system under analysis and facilitates data exchange [19]. Disciplinary competences are locally executed, and results automatically exchanged among distributed teams of expert. The time needed for single aircraft converged points is about 15 minutes. A DOE of 108 points was run for a total of 27 hours.

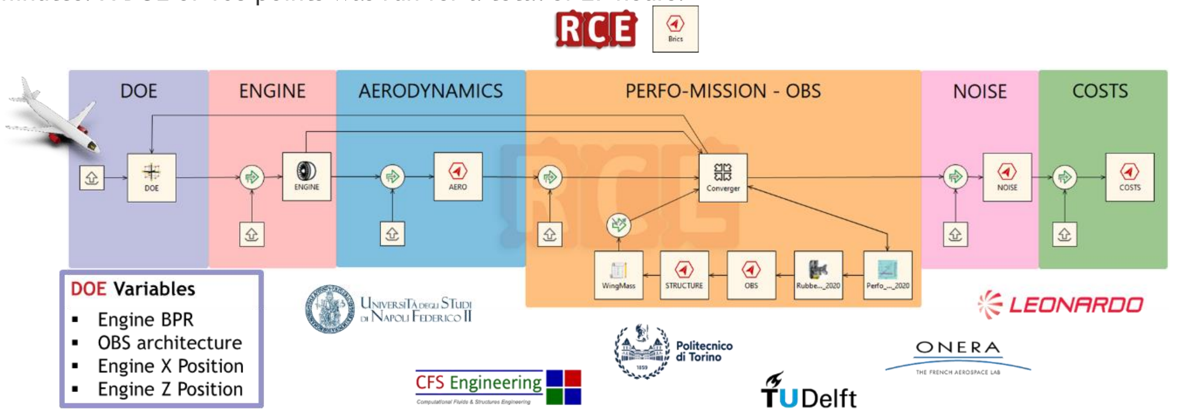


Fig. 18: Executable workflow: converged DOE

First significant result is represented by the comparison between costs to generate the Enabling Systems and the savings achieved thanks to its utilization. Capital costs are computed considering all steps from the retrofitting design phase to the final aircraft delivery, including the equipment acquisition. The savings are computed as difference between the cost required to operate the System of Interest and the one required to operate the Enabling System. In the savings are included expenditure for fuel acquisition, air and noise emission taxes and maintenance costs.

Tab. 6 summarizes the total development, conversion and equipment costs required to perform seven different refortifying activities. In case the operation includes an engine upgrade; the turbofan BPR that is considered is 15. Using these data, it is possible to see how each of the three aliquots of the cost increases by considering a more demanding retrofitting activity, which includes both engine and OBS upgrades. The development cost required to perform an engine upgrade represents the lowest value; in contrast, this kind of activity represents a large expense in terms of equipment acquisition, due to the high cost of the innovative turbofans. On the other hand, an OBS upgrade requires a higher cost for developing the retrofit and a lower cost for acquiring the equipment. More details can be found in [24].

Tab. 6: Summary of total development, conversion and equipment costs required for a single aircraft to be upgraded, computed for seven different retrofitting activities, example for engine BPR=15.

Retrofitting Activity	Development Cost (Million EUR)	Conversion Cost (Million EUR)	Equipment Cost (Million EUR)
Engine Upgrade	160.9	6.35	19.0
MEA1	182.3	5.71	7.5
MEA2	169.5	4.91	8.4
AEA	201.2	8.13	8.3
Engine Up. + MEA1	268.9	12.06	26.5
Engine Up. + MEA2	255.9	11.26	27.4
Engine Up. + AEA	287.6	14.48	27.3

In APPENDIX A a more detailed description of the data used to obtain the costs results is presented. Fig. 19 represents these costs and savings for the System of Interest and for fifteen different Enabling systems. These solutions are distinguished by engine BPR and OBS level of electrification. Data are referred for single aircraft per year of utilization. The Systems of Interest is located at the origin of the axis. Indeed, no retrofitting activity is performed on it and so no costs are required to make it operative. Since the savings are computed in comparison with the System of Interest, their value is zero. It is possible to notice how to a higher investment made to start the retrofitting activity corresponds a higher value of the savings generated. This is due to the higher level of innovative equipment introduced on the aircraft, which led to improved performance and by consequence to savings up to € 1.65 Mln per year per aircraft. The dashed line in represents the isoline in which the savings generated thanks to the aircraft upgrade match the correspondent initial investment. It means that all points positioned above this line are remunerative solution for the Airliner. Therefore, it is possible to notice how OBS electrification is not an economically convenient operation since the improved performance are not enough to compensate the initial investment. By contrast, the engine replacement represents the most economically convenient operation, generating a savings per aircraft per year which overcome the capital costs by € 0.2 Mln in case of engine BPR equal to 9. In conclusion, engine and OBS retrofit operations brings to a neutral situation, in which the savings assume value close to the capital costs. However, with this kind of retrofitting activity it is possible to achieve a reduction in fuel consumption and air emission up to 20% with reference to the System of Interest.

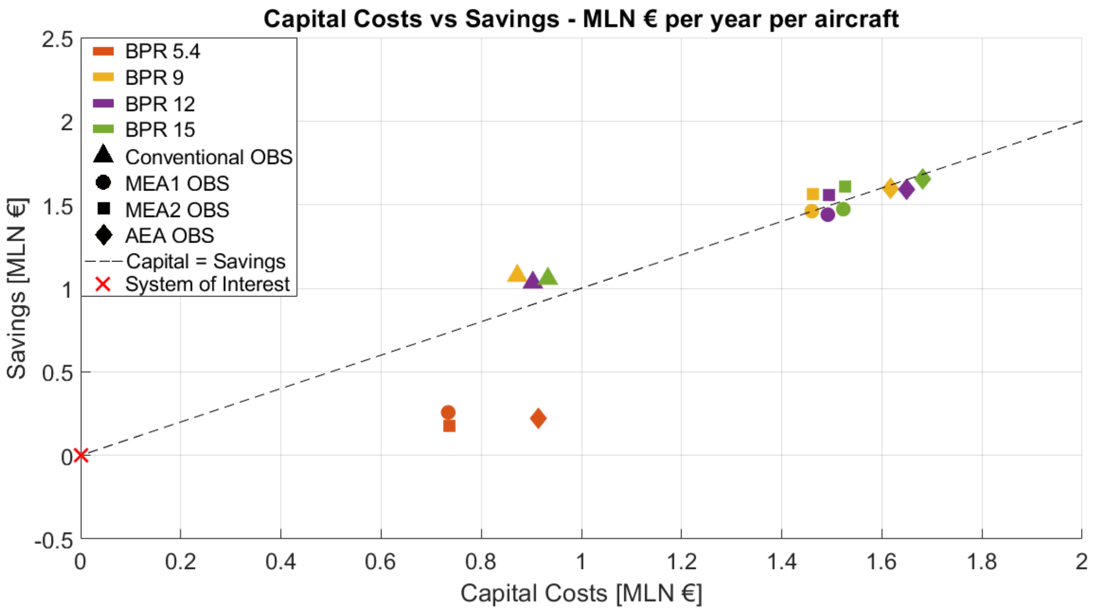


Fig. 19: Capital Costs and Savings represented for the System of Interest and different Enabling System solutions. The colour of each point represents the engine BPR, the shape (triangle, circle, square or diamond) represent the OBS level of electrification. The assumptions of the analyses are indicated in Tab. 5.

2.5.3 Optimization

The MDAO workflow presented in Fig. 18 has been also exploited to perform optimization analysis and decision-making activities. Two different optimization strategies have been performed thanks to the capabilities in the AGIL4.0 consortium:

1) Surrogate-based constrained MDO with UNINA JPAD Optimizer
2) Mixing Direct - Surrogate-based constrained MDO with ONERA SEGOMOE Optimizer

The optimization problem statement is summarized in Tab. 7. Four different optimization variables are considered: i) OBS level of electrification (categorical), ii) engine BPR (continuous), iii) engine position along fuselage direction (continuous), iv) engine position along vertical direction (continuous).

The first variable is categorical, since four different OBS architecture are considered (see Tab. 4), the others are continuous variable. The engine position variables are illustrated in Fig. 20.

Different constraints and check are performed in the optimization. Four constraints are considered: i) The ES maximum take-off weight must be equal or less the System on interest one, ii) ES take-off distance must be minor or equal than SoI one, iii) ES landing distance must be minor or equal than SoI one, iv) ES cumulative noise emitted in certification points must be lower than SoI one by 6 EPNLdB. These constraints represent the Airliner requirement which consists in enabling the new system to operate in the same airports considered before. In addition, several checks are performed for engine clearance, stability and control.

Tab. 7: Optimization problem definition; objectives, constraints, and variables.

	4 Objective Optimization
Objective functions:	*Minimize*:
	$f_1 = Costs - Savings$
	$f_2 = MTOW$
	$f_3 = CEI$
	Maximize:
	$f_4 = Max\ SAR$
Constraints:	
	w.r.t:
	$MTOW \leq 39058.50\ kg$
	$TOFL \leq 1500\ m$
	$LNFL \leq 1400\ m$
	$Cumulative\ noise \leq 263.6\ dB$
Variables:	
	by varying:
	$9.0 < BPR < 15.0$
	$-0.98 < X/C_{loc} < -0.80$
	$-0.39 < Z/C_{loc} < -0.21$
	$OBS \in$ [CONVENTIONAL, MEA1, MEA2, AEA]

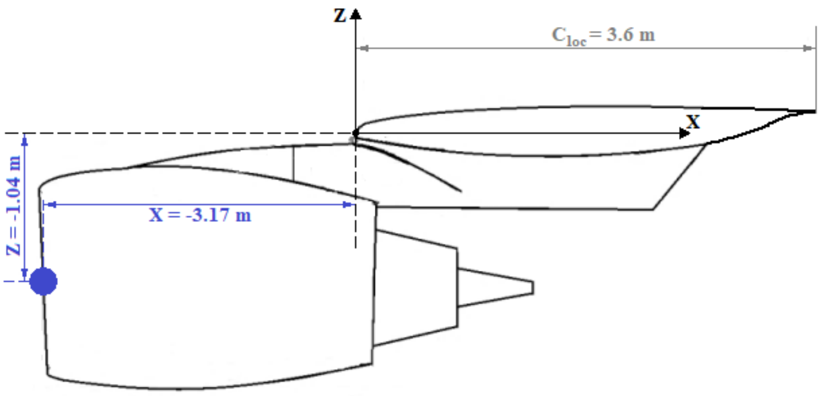


Fig. 20: X and Z axis and baseline position considered for engine attachment point.

Three or four objective functions are considered (depending on whether WTO is used are constraints or not): i) difference between capital costs and saving required to perform the retrofitting activity, to be minimized, ii) specific air range, to be maximized, iii) cumulative emission index (CEI), defined in eq. (1), to be minimized, iv) maximum take-off weight, to be minimized.

$$CEI = W_1 \frac{NOX + CO}{NOX_{SoI} + CO_{SoI}} + W_2 \frac{CO2}{CO2_{SoI}} + W_3 \frac{CNoise}{CNoise_{SoI}} \tag{1}$$

CEI in eq (1) is a weighted function of all emissions (gaseous and noise) respect to the SoI. The *NOX*, *CO*, and *CO2* represent respectively the amount of these pollutants generated during the entire typical mission. *CNoise* indicates the cumulative noise emitted accordingly regulation [15]. The subscript "*SoI*" indicates that data are referred for System of Interest. A CEI value equal to 1 means same emissions level of the SoI. A value lower than one means emissions reduction. For the following results, all the weights have been assumed equal among them (*W1*, *W2* and *W3* = 1/3).

The optimization tool used has been the JPAD Optimizer based on MOEA Framework [25], which is directly implemented in JPAD library [11] [26]. The MOEA Framework is a free and open-source Java library for developing and experimenting with multi-objective evolutionary algorithms (MOEAs) and other general-purpose optimization algorithms. Several algorithms are provided out-of-the-box, including genetic algorithms, particle swarm etc. Here the ε-NSGAII algorithm is used. ε-NSGA-II is an extension of NSGA-II that uses an ε-dominance archive and randomized restart to enhance search and find a diverse set of Pareto optimal solutions. Full details of this algorithm are given in [27].

A second optimization strategy has been followed the ONERA SEGOMOE optimizer is executed remotely, whose workflow is represented in Fig. 21. In this strategy a direct optimization is executed, by calling remotely it calls the workflow illustrated in Fig. 18. Starting from 13 points extracted from 108 DOE previously computed, ONERA algorithms enrich the database with the computation of additional 68 points. A final database composed by 81 points has been subsequently used to perform surrogate-based optimization with ONERA algorithm.

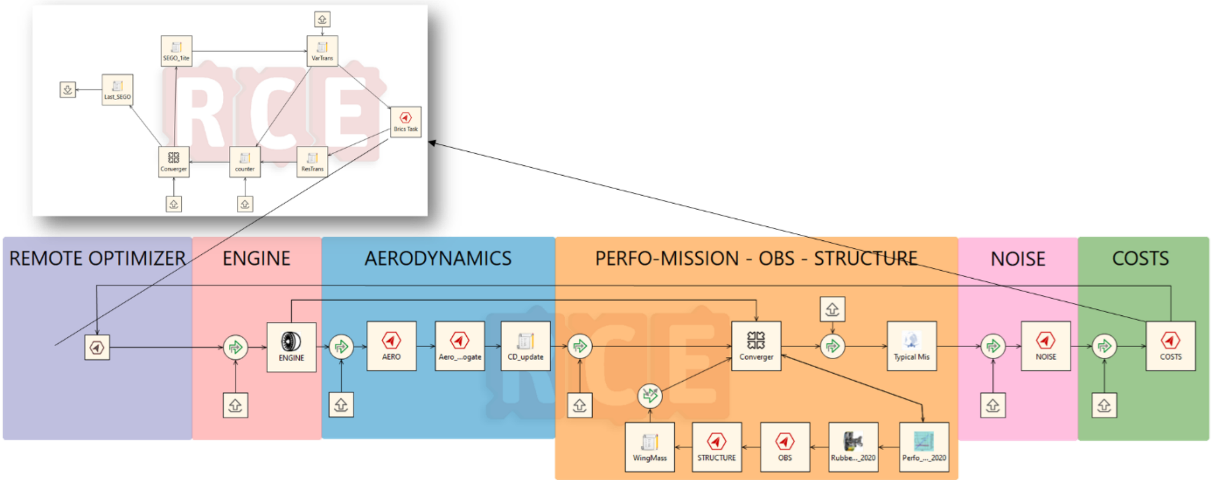


Fig. 21: Executable workflow: Remote Optimization.

2.5.3.1 Optimization Results

This subsection resumes the results of optimization previously explained. The DOE points and the pareto frontiers obtained with the two approaches are shown in Fig. 22, following described:

1) Blue circles represent the full-factorial DOE 108 points obtained running the workflow depicted in Fig. 18;
2) Red crosses represent the 81 points (13 + 68) DOE points obtained running the workflow of Fig. 21;
3) Yellow stars are the pareto frontiers obtained with UNINA JPAD Optimizer;
4) Green crosses are the pareto frontiers obtained with ONERA SEGOMOE Optimizer;
5) Finally, the red circles always represent the baseline SoI aircraft.

Within yellow and green pareto frontiers points, the best solution is up to the designer. For instance, the point with minimum difference between costs and savings (the lower one) is always an optimum point in terms of economical profit. However, it is not the best solution in terms of other variables (CEI and SAR). Indeed, to achieve a low value of the costs, several solutions which lead to significant benefits in terms of emissions, SAR and WTO may be discarded. The same happens for the points which allow to obtain the maximum benefits with respect to the other variables.
Pareto frontiers results for both optimizers are summarized in Tab. 8. The results could be summarized as follows:

A) JPAD Optimizer predicts best points in terms of “Costs - Savings” up to a value of -0.014 Mln $ /year for a conventional OBS architecture, while ONERA SEGOMOE predicts better values (less than -0.30 Mln$ / year.
B) JPAD Optimizer predicts best points in terms of SAR (specific air range) around 0.834 km/kg with higher engine bypass ration (up to 15) and AEA OBS architecture, while SEGOMOE never predicts points with engine bypass ratio higher than 13.08, do not allowing the estimation of better values of SAR (the highest for SEGOMOE is 0.815).
C) JPAD Optimizer predicts best points in terms of CEI with higher engine bypass ratio and AEA OBS architecture, equal to CEI = 0.867, while SEGOMOE lowest value is CEI = 0.878.
D) JPAD Optimizer predicts best points always with and engine X/C position = -0.8, meaning as closer as possible to the wing leading edge, while SEGOMOE predicts a variability of the engine position.
E) Both the optimizers predict best points with different Z/C position: generally, as higher is the BPR, as lower should be the engine position respect to the wing leading edge with respect to the clearance limits. This is due to an aerodynamic effect related to the engine-pylon-wing interference.
F) All the optimizers never violate the constraints.

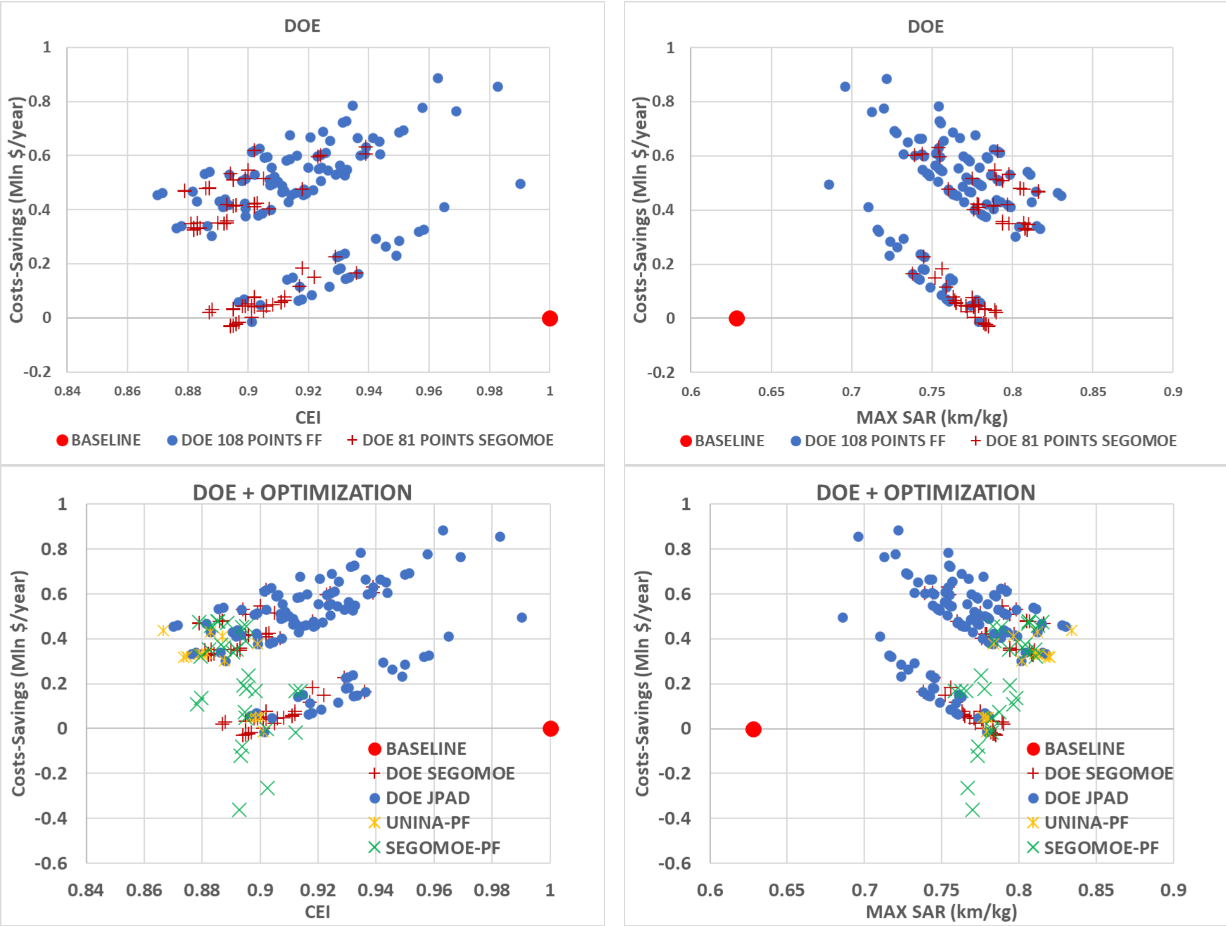


Fig. 22: DOE and Optimization results, Scenario 1(Tab. 5). DOE points computed with Full factorial and SEGOMOE approaches. Baseline aircraft red circle.

Focusing on opposite solutions on the pareto frontiers, the engine BPR and the OBS architecture may be selected exactly in a opposite direction, depending on the performance objective to be maximized: BPR = 9.0 with conventional OBS and/or BPR = 15.0 with AEA OBS architecture. A lower BPR and level of electrification (i.e. state of the art technologies) allows to reduce the retrofitting costs, allowing a moderate performance improvements. By the contrast, increasing the level of retrofitting (advanced engine and overall OBS electrification, beyond the state of the art) can drastically improve the overall performance (i.e. SAR and CEI), increasing the retrofitting costs.

As example, considering a higher BPR and level of electrification, emissions reduce (CEI passes from 1 to 0.78), MTOW slightly decreases (around -3.1% with respect to the baseline), and SAR increases (around + 25% with respect to the baseline). By the consequence costs minus savings increases up to 0.44 Mln € per year, meaning a loss for an airliner operating the aircraft for the considered scenarios.

Tab. 8 Pareto frontiers points. JPAD Optimizer and SEGOMOE Optimizer.

	Variables				Objectives				Constraints			
	OBS	Engine BPR	Engine x Position	Engine z Position	Cost - Savings	WTO	CEI	maxSAR	WTO	LD	TOD	Cnoise
	-	-	m	m	Mln $	kg	-	km/kg	kg	m	m	EpnldB
BASELINE	Conv	5.4	12.3	-1.55	0	39058	1	0.628	39058	1400	1500	269.6
JPAD predicted Pareto Front (predicted points obtained with RSM based on full-factorial 108 points)	Conv	13.42	12.6	-1.61	0.051	38828	0.9	0.777	38828	1229	1089	255.9
	Conv	14.28	12.6	-1.64	0.048	38863	0.897	0.78	38863	1243	1104	254.6
	Conv	13.87	12.6	-1.62	0.05	38849	0.898	0.778	38849	1230	1089	255.2
	Conv	9	12.6	-1.57	-0.014	38214	0.901	0.779	38214	1225	1068	263.5
	MEA1	9.16	12.6	-1.57	0.379	37978	0.899	0.783	37978	1219	1060	263.4
	MEA1	15	12.6	-1.68	0.413	38277	0.887	0.796	38277	1215	1068	253.5
	MEA2	13.64	12.6	-1.62	0.332	38731	0.88	0.812	38731	1227	1085	255.6
	MEA2	14.88	12.6	-1.67	0.318	38754	0.874	0.82	38754	1238	1095	253.8
	MEA2	14.74	12.6	-1.66	0.32	38753	0.874	0.819	38753	1227	1085	254.1
	MEA2	13.89	12.6	-1.62	0.33	38738	0.879	0.813	38738	1227	1085	255.3
	MEA2	13.27	12.6	-1.61	0.334	38718	0.882	0.81	38718	1226	1084	256.2
	MEA2	9	12.6	-1.57	0.303	38372	0.888	0.802	38372	1217	1062	263.6
	AEA	9.05	12.6	-1.57	0.432	37857	0.883	0.812	37857	1216	1057	263.6
	AEA	15	12.6	-1.68	0.439	38160	0.867	0.834	38160	1224	1074	253.4
SEGOMOE predicted Pareto Front (predicted points obtained with RSM based on optimization database)	AEA	9.01	12.4	-1.65	0.455	37663	0.895	0.783	37663	1217	1051	263.2
	Conv	10.06	12.13	-1.83	0.167	37778	0.914	0.759	37778	1229	1082	258.6
	MEA1	9	12.52	-1.31	-0.002	38791	0.902	0.782	38791	1216	1066	262.8
	AEA	11.51	12.39	-1.73	0.474	37884	0.879	0.815	37884	1224	1066	259.1
	Conv	12.93	12.5	-1.63	0.107	38333	0.878	0.796	38333	1226	1083	256.6
	Conv	12.37	12.5	-1.63	-0.361	38215	0.893	0.77	38215	1220	1055	258.2
	AEA	9.69	12.37	-1.64	0.478	37697	0.886	0.806	37697	1215	1051	262.4
	Conv	12.62	12.5	-1.63	-0.265	38188	0.902	0.767	38188	1215	1049	257.5
	Conv	13.08	12.5	-1.63	0.136	38350	0.88	0.798	38350	1229	1085	256.2
	Conv	9	12.16	-1.79	0.167	37775	0.912	0.763	37775	1229	1082	261.7
	Conv	12.16	12.5	-1.63	-0.121	38303	0.893	0.773	38303	1226	1074	258.7
	MEA2	10.19	12.2	-1.83	0.238	37756	0.896	0.775	37756	1220	1082	262.7
	MEA2	11.39	12.36	-1.67	0.361	37962	0.887	0.802	37962	1225	1079	259.2
	Conv	9.22	12.52	-1.31	-0.018	38118	0.912	0.782	38118	1225	1065	262.8
	MEA2	11.77	12.37	-1.64	0.34	38052	0.891	0.805	38052	1227	1067	258.7
	MEA2	11.44	12.4	-1.73	0.32	38084	0.88	0.811	38084	1224	1071	259.3
	AEA	11.44	12.39	-1.64	0.458	37832	0.883	0.812	37832	1222	1061	258.9
	MEA2	11.44	12.4	-1.64	0.353	38064	0.882	0.81	38064	1224	1062	259.6
	AEA	10.13	12.39	-1.66	0.454	37730	0.894	0.789	37730	1217	1053	261.7
	MEA2	11.44	12.36	-1.73	0.374	37984	0.886	0.804	37984	1222	1071	259.1
	Conv	12.13	12.5	-1.63	-0.081	38311	0.894	0.774	38311	1227	1076	258.8
	Conv	9.3	12.53	-1.65	0.048	38220	0.895	0.783	38220	1220	1082	262.7
	AEA	9.24	12.34	-1.54	0.389	37719	0.895	0.784	37719	1214	1085	262.7
	MEA2	9.83	12.36	-1.66	0.353	37740	0.892	0.794	37740	1217	1053	262.5
	AEA	9.69	12.37	-1.36	0.192	37796	0.894	0.794	37796	1216	1082	262.8
	AEA	9.86	12.37	-1.64	0.478	37708	0.885	0.806	37708	1216	1051	262.3
	MEA2	9.93	12.2	-1.76	0.176	37762	0.895	0.778	37762	1225	1082	262.8
	Conv	9.26	12.23	-1.79	0.167	37743	0.898	0.766	37743	1228	1082	262.7
	AEA	11.44	12.37	-1.63	0.47	37825	0.889	0.806	37825	1221	1081	258.7
	AEA	9.22	12.37	-1.32	0.073	37794	0.895	0.787	37794	1216	1082	262.8

To validate this PF results. A set of points have been selected from both the PF to be recomputed with workflow shown in Fig. 18. The selection criterion has been based on the value assumed by the objective function. For both optimization solutions, the two best points for each objective have been selected. Since the best points in terms of SAR usually corresponds to the best point in terms of CEI, twelve points have been selected (six for each optimization). In addition, two more points have been added to the set due to the lower value assumed by the cost minus saving objective. Therefore, fourteen points have been recomputed using the workflow illustrated in Fig. 18. The results of this validation activity are illustrated in Fig. 23. The value of the objective function predicted by the optimizer and computed with a direct analysis are illustrated. In addition, the difference between these the value is indicated. As it is possible to see, WTO, max SAR and CEI objectives are almost always well predicted by both the optimizers (Delta errors are less than 1%). By contrast, the prediction error of the difference between costs and savings overcome 10% for a set of points. This is mainly due to the high sensitivity of this objective. The difference between costs and savings changes dramatically in response to a slight variation of all the optimization variables. A wider dataset should be exploited to enhance the prediction of cost minus savings objective function.

	ID	INPUT				PREDICTED PF POINTS				COMPUTED POINTS							
		OBS	Engine BPR	Engine x Position [m]	Engine z Position [m]	WTO [KG]	Max SAR [Km/Kg]	Cumulative Emission Index	Costs-Saving [Mln€ per year per AC]	WTO [KG]	Delta [%]	Max SAR [Km/Kg]	Delta [%]	Cumulative Emission Index	Delta [%]	Costs-Saving [Mln€ per year per AC]	Delta [%]
UNINA JPAD OPTIMIZER PARETO FRONT	1	1	14.276	12.600	-1.638	38863.0	0.780	0.897	0.048	38900.352	0.096	0.778	0.213	0.894	0.259	0.056	14.2
	2	1	9.000	12.600	-1.570	38214.4	0.779	0.901	-0.014	38212.377	0.005	0.780	0.057	0.897	0.443	-0.015	9.5
	3	2	9.158	12.600	-1.573	37977.5	0.783	0.899	0.379	37961.998	0.041	0.785	0.207	0.895	0.486	0.377	0.4
	4	3	14.882	12.600	-1.673	38754.1	0.820	0.874	0.318	38700.144	0.139	0.824	0.481	0.867	0.779	0.304	4.7
	5	4	9.055	12.600	-1.573	37857.4	0.812	0.883	0.432	37846.257	0.030	0.813	0.099	0.878	0.515	0.428	0.9
	6	4	15.000	12.600	-1.684	38160.4	0.834	0.867	0.439	38140.714	0.052	0.837	0.406	0.860	0.730	0.427	2.7
ONERA SEGOMOE OPTIMIZER PARETO FRONT	7	1	12.370	12.495	-1.633	38214.7	0.770	0.893	-0.361	38731.422	1.334	0.775	0.641	0.899	0.666	0.048	860.3
	8	1	12.621	12.495	-1.633	38187.8	0.767	0.902	-0.265	38768.552	1.498	0.774	0.892	0.900	0.302	0.056	572.7
	9	2	9.004	12.519	-1.311	38791.5	0.782	0.902	-0.002	38144.543	1.696	0.766	2.127	0.910	0.836	0.454	100.5
	10	3	11.439	12.400	-1.726	38084.3	0.811	0.880	0.320	38402.814	0.829	0.803	1.072	0.886	0.708	0.346	7.6
	11	4	9.006	12.397	-1.655	37663.1	0.783	0.895	0.455	38024.225	0.950	0.795	1.490	0.892	0.407	0.494	7.9
	12	4	11.513	12.390	-1.726	37884.3	0.815	0.879	0.474	38217.502	0.872	0.807	1.047	0.884	0.555	0.492	3.7
	13	4	9.694	12.371	-1.640	37697.3	0.806	0.886	0.478	38104.296	1.068	0.797	1.101	0.891	0.643	0.502	4.8
	14	4	9.223	12.373	-1.320	37794.0	0.787	0.895	0.073	38170.789	0.987	0.784	0.346	0.900	0.579	0.542	86.5

Fig. 23: JPAD and SEGOMOE PF Validation results.

As final step, both databases illustrated in Fig. 22 have been combined to execute an optimization which considers a wider set of points. From this combined database, all the unfeasible solutions have been removed (see red points in the last column of Fig. 23); all the points which violate at least one constraint have been removed from the set. By consequence, an optimization based on **130 points** coming from both Full factorial (108) and SEGOMOE (81) selection has been computed. Tab. 9 resumes the results of this optimization and Fig. 24 an example of pareto front. As it is possible to notice, 15 points have been obtained: 4 belongs to UNINA pareto front and the remaining 11 belongs to SEGOMOE pareto front. The UNINA points are characterized by low value of CEI and high value of SAR. Indeed, more and all electric architecture and high BPR are selected. The SEGOMOE points represent several possible optimization solutions which includes retrofitting systems with low value of cost minus savings or WTO. In conclusion, the best points from UNINA set are 4 points out of the 6 re-evaluated Pareto Front points, whereas the 11 best points from ONERA are not the ones from re-evaluated Pareto Front.

Tab. 9: Pareto frontiers points achieved with combined JPAD Optimizer and SEGOMOE dataset.

ID	Variables				Objectives				Constraints			
	OBS	Engine BPR	Engine x Position	Engine z Position	Cost - Savings	WTO	CEI	maxSAR	WTO	LD	TOD	Cnoise
	-	-	m	m	Mln $	kg	-	km/kg	kg	m	m	EpnldB
BASELINE	Conv	5.4	12.3	-1.55	0	39058	1	0.628	39058	1400	1500	269.6
UNINA Pareto Front obtained from combined database	MEA1	9	12.60	-1.57	0.377	37962	0.895	0.785	37962	1219	1060	263.4
	MEA2	14.88	12.60	-1.67	0.304	38700	0.867	0.824	38700	1238	1095	253.8
	AEA	9.06	12.60	-1.57	0.428	37846	0.878	0.813	37846	1216	1057	263.6
	AEA	15.00	12.60	-1.68	0.427	38141	0.860	0.837	38141	1224	1074	253.4
SEGOMOE Pareto Front obtained from combined database	MEA2	13.27	12.36	-1.72	0.348	38405	0.881	0.810	38405	1230	1085	256.3
	Conv	14.57	12.59	-1.75	0.021	38449	0.887	0.790	38449	1231	1086	254.3
	AEA	11.68	12.36	-1.68	0.470	37815	0.879	0.816	37815	1215	1061	258.7
	AEA	9.82	12.37	-1.65	0.478	37703	0.886	0.807	37703	1212	1051	262.2
	Conv	9.09	12.59	-1.63	-0.031	37920	0.894	0.785	37920	1218	1059	263.5
	MEA1	9.08	12.42	-1.70	0.410	37679	0.902	0.779	37679	1211	1051	263.5
	AEA	11.51	12.39	-1.71	0.468	37825	0.879	0.816	37825	1215	1061	259.0
	MEA2	11.50	12.41	-1.71	0.326	38115	0.882	0.809	38115	1223	1071	259.2
	MEA2	11.35	12.38	-1.71	0.331	38103	0.883	0.808	38103	1222	1070	259.3
	MEA1	11.38	12.38	-1.70	0.414	37740	0.895	0.788	37740	1213	1057	259.2
	AEA	9.55	12.37	-1.63	0.479	37690	0.887	0.805	37690	1212	1051	262.6

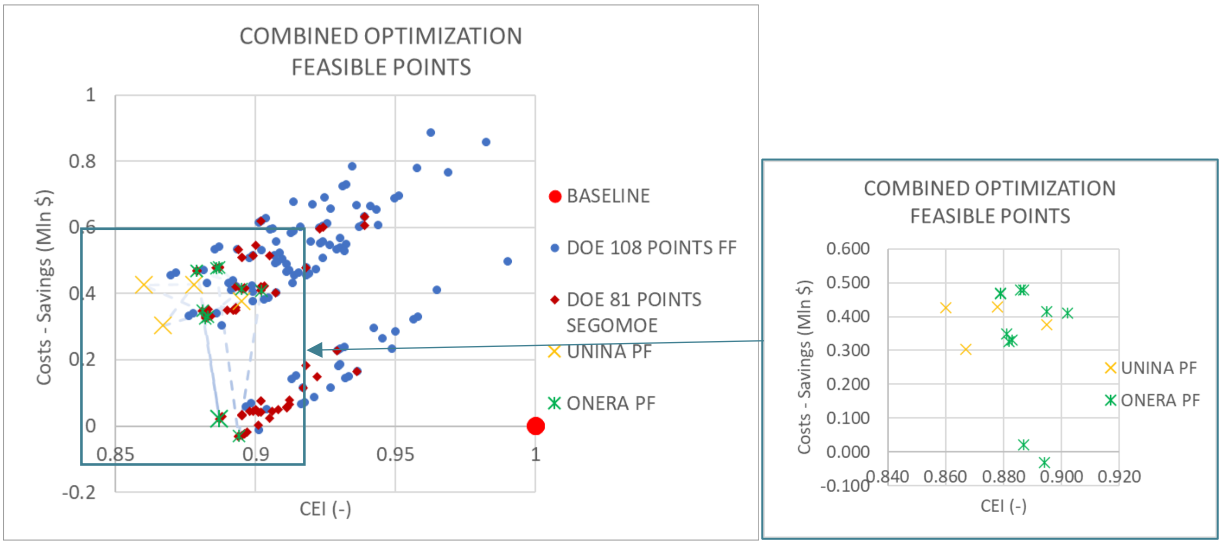


Fig. 24: JPAD and SEGOMOE FEASIBLE combined optimization results.

2.5.4 Trade-off

The main AC6 trade-off activity consists in comparing what happens on Costs-Savings and Performance (CEI, SAR, WTO and other). For a given scenario (see Tab. 5), the results and trade-off have been deeply described in section 2.5.3. Leveraging on results obtained with workflows (see Fig. 22), a datasheet enabling the trade-off space analyses has been created. The datasheet, based on all available computed data, allows to the user to:

1. Define a scenario in terms of:
   a. Number of aircraft to be retrofitted
   b. Fuel price
   c. Year of utilization after retrofitting
   d. Maintenance costs savings for Engine and OBS retrofitting
2. Custom aircraft to be evaluated in terms of:
   a. Engine BPR
   b. OBS architecture
   c. Engine X/C and Z/C position

In the following results, the mission data defined in Tab. 5 have been used for 4 different scenarios summarized in Tab. 10. In this table, all the hypothesis which have been modified with respect to Tab. 5 are indicated. Through these 4 scenarios, the fuel price and the maintenance savings generated by the introduction of new technologies are progressively increased, representing situations which are realistically possible in the next future. In Tab. 10 are also indicated the main characteristics of the customized aircraft which is represented in the following results (green filled circle). The aim of the analysis consists in representing how the objective variables are influenced by the scenarios. The effect of the scenario on the 108 points represented in Fig. 22 and on the customized point are represented in the following.
Fig. 25 represents the trade-off results achieved for the scenarios described in Tab. 10. The difference between costs and savings and CEI are represented for 110 points: the 108 points represented in Fig. 22, the customized point indicated in green and the baseline aircraft in red. The CEI is not influenced by the scenario variables. Indeed, these variables have no influence on the aircraft performance. By contrast, they have a great influence on the economical aspect. In the first scenario, only one aircraft is economically convenient. Moving toward the fourth scenario, an increasing number of points reach the negative part of the vertical axis; for these points the savings due to the retrofitting activity overcome its costs. In the fourth scenario, most of the points are economically convenient. This happens because of the increase of the fuel price and the maintenance savings. These effects increase the advantages of introducing more green technologies. In addition, is possible to see that in the first scenario there is a great economical difference between solution with conventional OBS and solution with more and all electrified OBS. This difference is greatly reduced by going toward the fourth scenario. This happens for two reasons. The increase of fuel price compensates the high expenditure required to electrify the OBS. The increase of the savings due to OBS maintenance make these solutions more profitable.

Tab. 10 Trade-off scenarios.

Trade-off Scenarios				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Retrofitted fleet	700 units	700 units	700 units	700 units
Fuel price	73 $ per barrel	**100 $ per barrel**	**100 $ per barrel**	**150 $ per barrel**
Years of utilization	12	12	12	12
Maintenance saving	[5 for engine alone - 10 for engine + OBS] %	[5 for engine alone - 10 for engine + OBS] %	[**10** for engine alone - **20** for engine + OBS] %	[**10** for engine alone - **20** for engine + OBS] %

AIRCRAFT SELECTION PANEL - CUSTOM AIRCRAFT	
BPR =	12
POSITION X =	12.55
POSITION Z =	-1.612
OBS =	MEA2

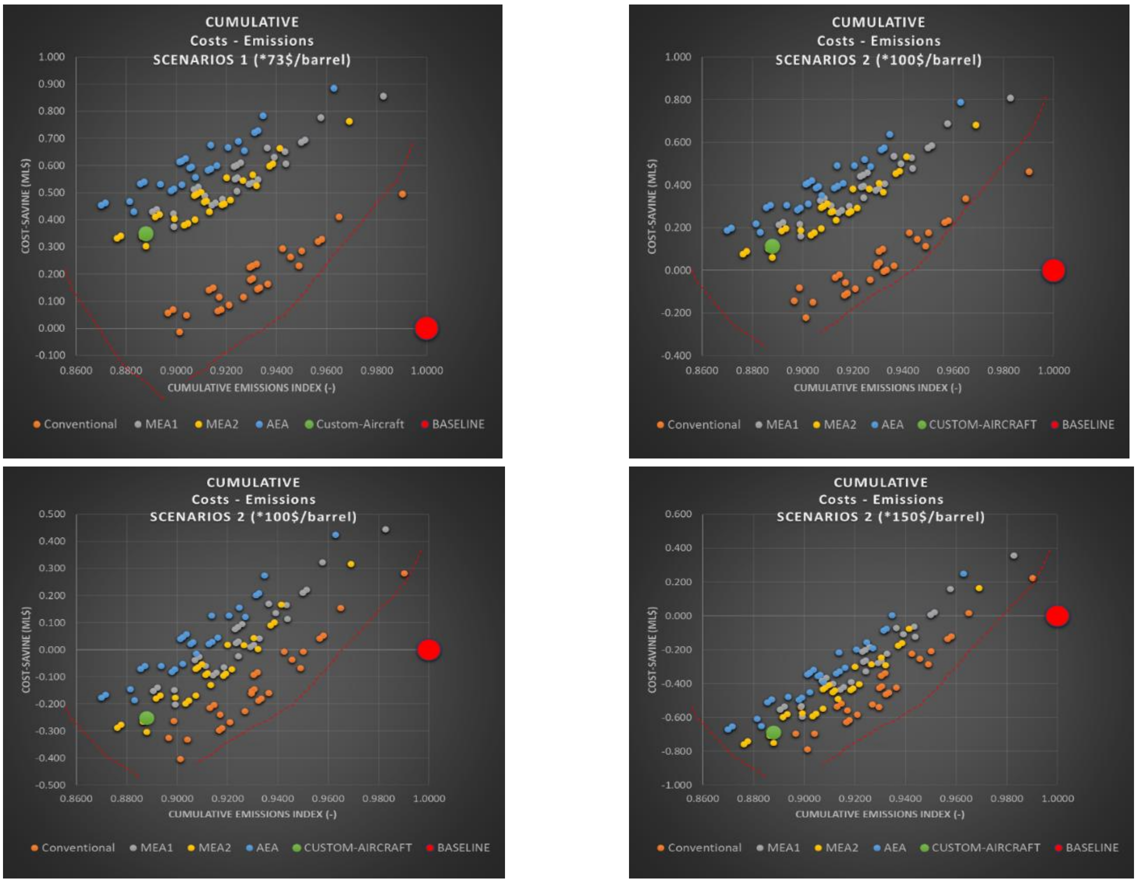


Fig. 25: Trade-off results represented for the scenarios indicated in Tab. 10. Results are indicated for each OBS architecture, for the baseline aircraft (red) and the customized aircraft(green)

2.5.5 Verification and Validation

The last step of AGILE 4.0 approach concerns the verification of the requirements shown in Tab. 4. This examination can be performed thanks to the results obtained through the execution of the workflows/optimization presented in the previous sections. The requirement verification framework implemented in the OCE has been used to accomplish this task. The CPACS files obtained after the workflow execution must be uploaded in the OCE, which automatically provides a table of requirement verification. In Fig. 26 an excerpt of the requirement verification framework obtained for the Enabling System results achieved is presented. For requirements concerning mission range, payload and cruise Mach number, the fulfillment is made possible by considering these items as tool input parameters. By consequence, the performance tool verifies if the mission defined through these items is feasible for the designed aircraft. If yes, the value assumed be the items will exactly be equal to the required one. By consequence, the compliance margin will be equal to zero. Other requirements such as the take-off and landing field length, the fuel consumption, the maximum take-off weight and the maintenance costs are output of the workflow execution. In this case the framework will compute a compliance margin by comparing it with the corresponding threshold value.

Requirement

Requirement	ID	Text	Type	Validation	Compliance value	Compliance margin (%)
Takeoff Field Lenght	R-0025	The Aircraft shall take-off at TOFL is maximal or equal to 4921 ft for condition: take-off ISA sea level	Performance	Valid	1061.457091	29.24
Landing Field Lenght	R-0011	The Aircraft shall land at LFL is maximal or equal to 4593 ft for condition: landing	Performance	Valid	1211.286153	13.48
Maintanance cost reduction	R-0035	The Aircraft shall reduce at AMC is minimal or equal to -10 % for condition: entire operative life maintenance costs	Performance	Valid	744.828	11.12
Engine maintenance	R-0041	The Engine shall reduce at EMC is minimal or equal to -10 % for condition: entire life eng. maint.	Performance	Valid	744.828	11.12
Fuel burnt reduction	R-0004	The Aircraft shall reduce fuel at FRed is minimal or equal to -10 % for condition: typical mission	Performance	Valid	4733.553047	8.65
Maximum Takeoff Weight (MWTO	R-0021	The Aircraft shall exhibit maximum take-off weight for condition: design mission	Design constraint	Valid	38164.674296	2.29
Design range	R-0028	The Aircraft shall fly at DR is equal to 1890 nm for condition: design range	Performance	Valid	1890	0
Design payload	R-0010	The Aircraft shall exhibit design payload in accordance with DP is equal to 9180 kg for condition: design mission	Design constraint	Valid	9180	0
Cruise Mach	R-0029	The Aircraft shall fly at MLR is equal to 0.78 Mach for condition: cruise condition 35000 ft	Performance	Valid	0.78	0

Fig. 26: Excerpt of Enabling System requirement verification framework.

3 APPLICATION CASE 7

AC7 deals with the design of a family of 8-pax business jets (as shown in Fig. 28), with TLARs provided by Bombardier. The main trade-off will be between the degree of commonality (for reducing OEM costs) and aircraft performance (for reducing operator costs).

3.1 System Identification

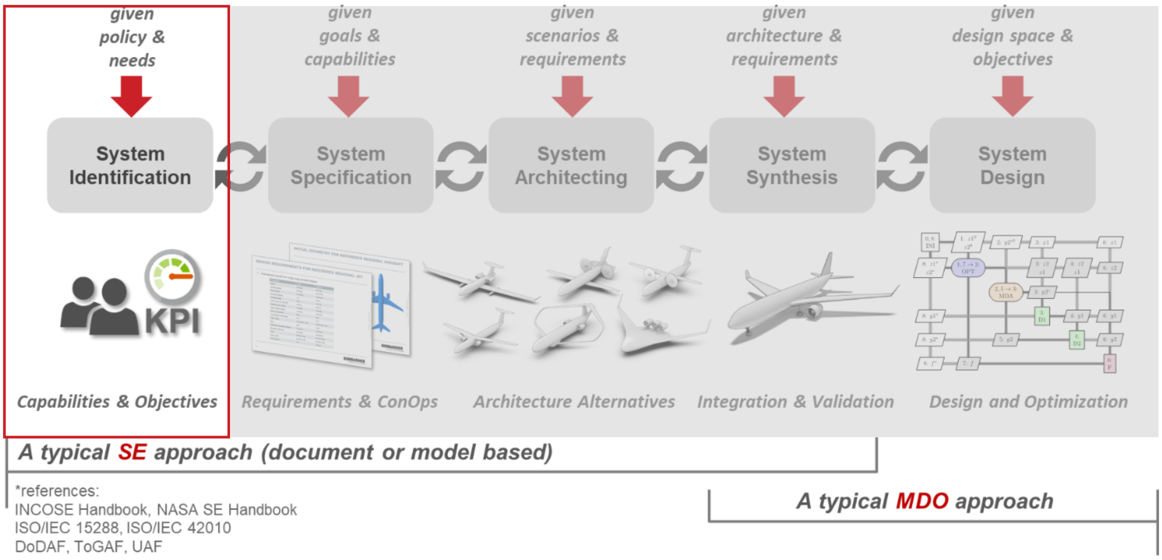


Fig. 27: AGILE 4.0 Step I: System Identification.

Fig. 28: Application Case 7

3.2 System Specifications

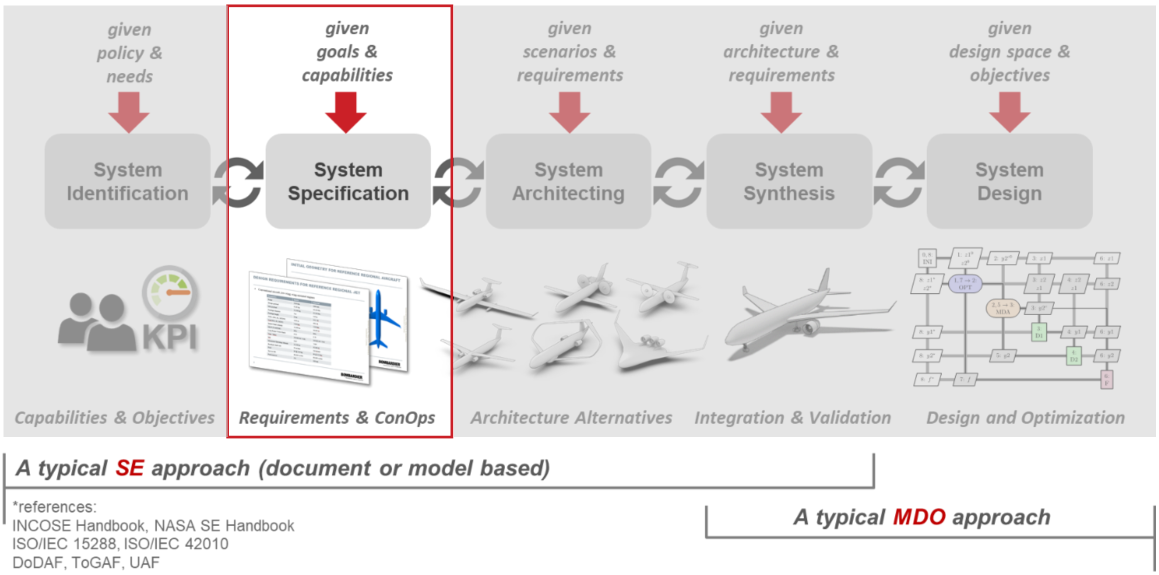


Fig. 29: AGILE 4.0 Step II: System Specification.

AC 7 has six stakeholders: OEM, Operator, Engine OEM, Passengers, Pilots, and Regulatory Authorities. Fig. 30 shows the stakeholders and needs as entered into the OCE.

The stakeholder hierarchy view is shown in Fig. 31. This use case does not have any hierarchy between the stakeholders, and therefore they are all displayed on the same level, below the main “Stakeholder” element. Fig. 32 shows the needs of the “Passengers” stakeholder. This stakeholder has three needs, as displayed below the “Passengers Needs” package. Each “Need” element shows its owning stakeholder, its ID and the text describing the need.

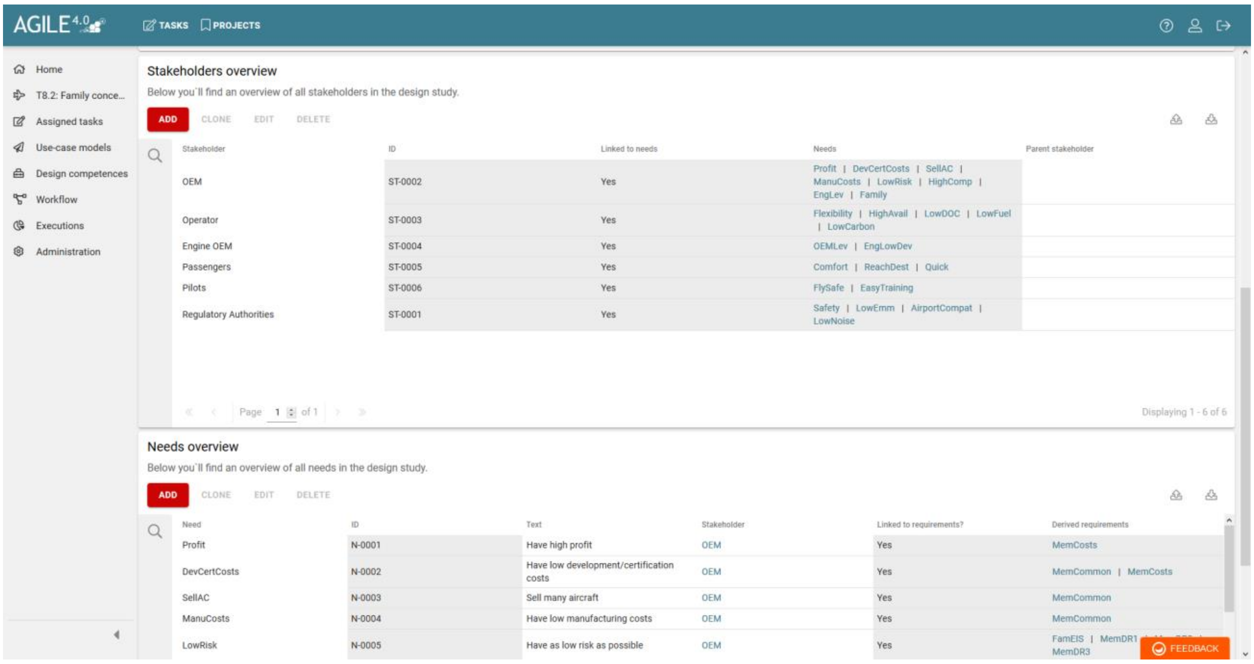


Fig. 30: Screenshot showing the stakeholders and needs of AC 7 in the OCE.

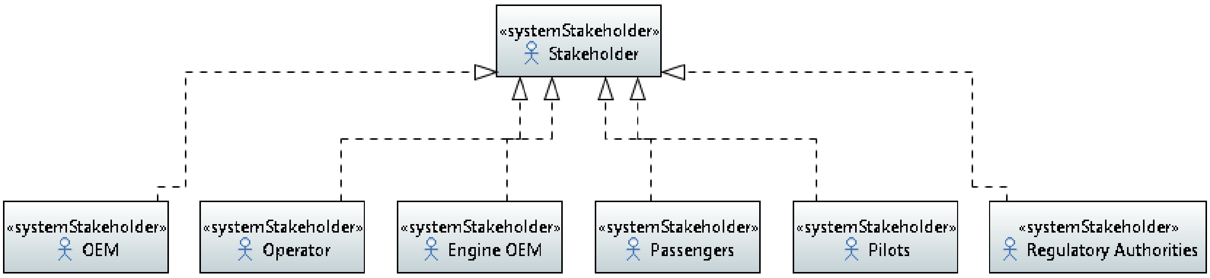


Fig. 31: Stakeholder Hierarchy view of AC 7. Al six stakeholders are at the same level.

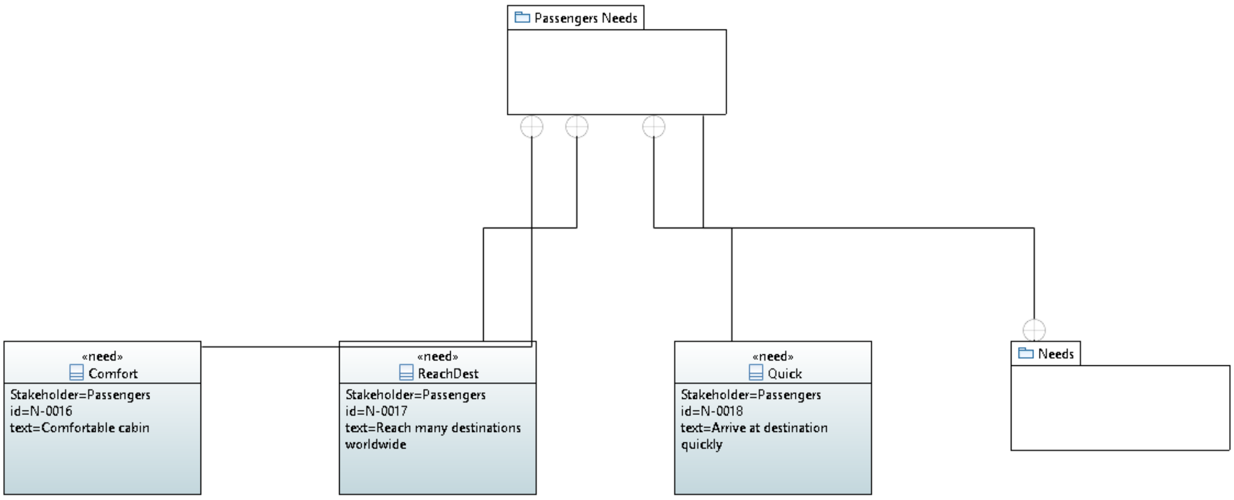


Fig. 32: Needs view of AC 7 for the needs of the Passengers stakeholder.

Two scenarios have been modelled for AC 7: "Requested Aircraft Not Available" (scenario 1) and "Aircraft Part Cannibalization" (scenario 2).
Fig. 33 shows the sequence diagram for scenario 1. In this scenario, the system of interest is the operator fleet, consisting of multiple members of a aircraft family. It shows the sequence of steps involved in booking a flight. The scenario then involves the booked aircraft becoming unavailable for the flight before the booking flight is executed, but after the booking has been confirmed. Due to aircraft commonality, the operator can simply switch out the originally booked aircraft with a similar one from the same aircraft family, without incurring additional difficulties due to pilot type ratings. Additionally, the passengers may notice a different cabin size, and the operator pays the same maintenance costs for each family member.

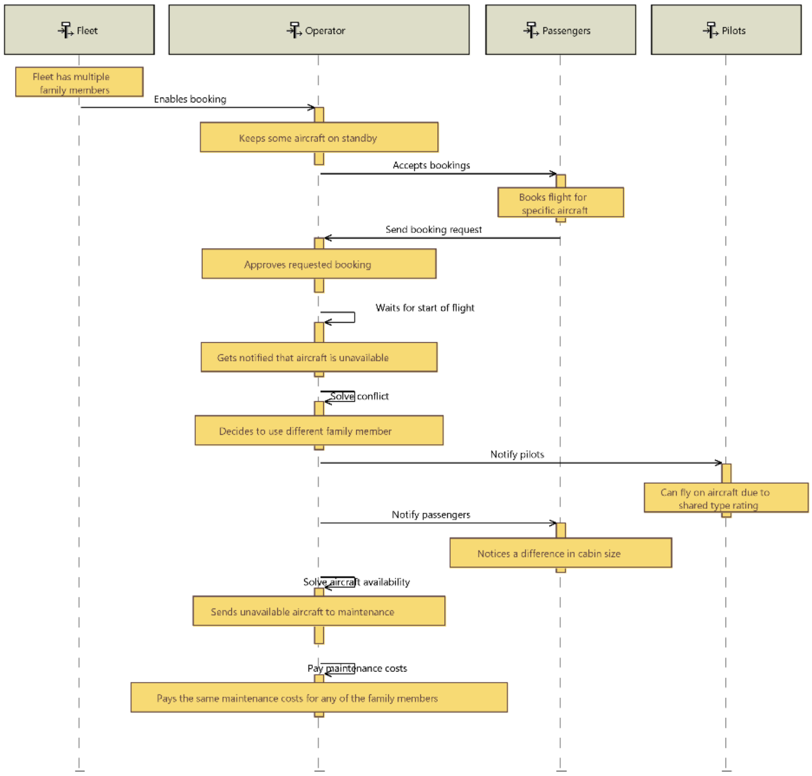


Fig. 33: Sequence Diagram of AC 7 scenario 1: “Requested Aircraft Not Available”.

Fig. 34 shows a screenshot of the OCE with the requirements of AC 7 entered. Fig. 35 shows the requirements belonging to the general set. It specifies which components are (optionally) shared and that the family contains three members. It also specifies the entry into service and derived from this the minimum TRL of all technologies.

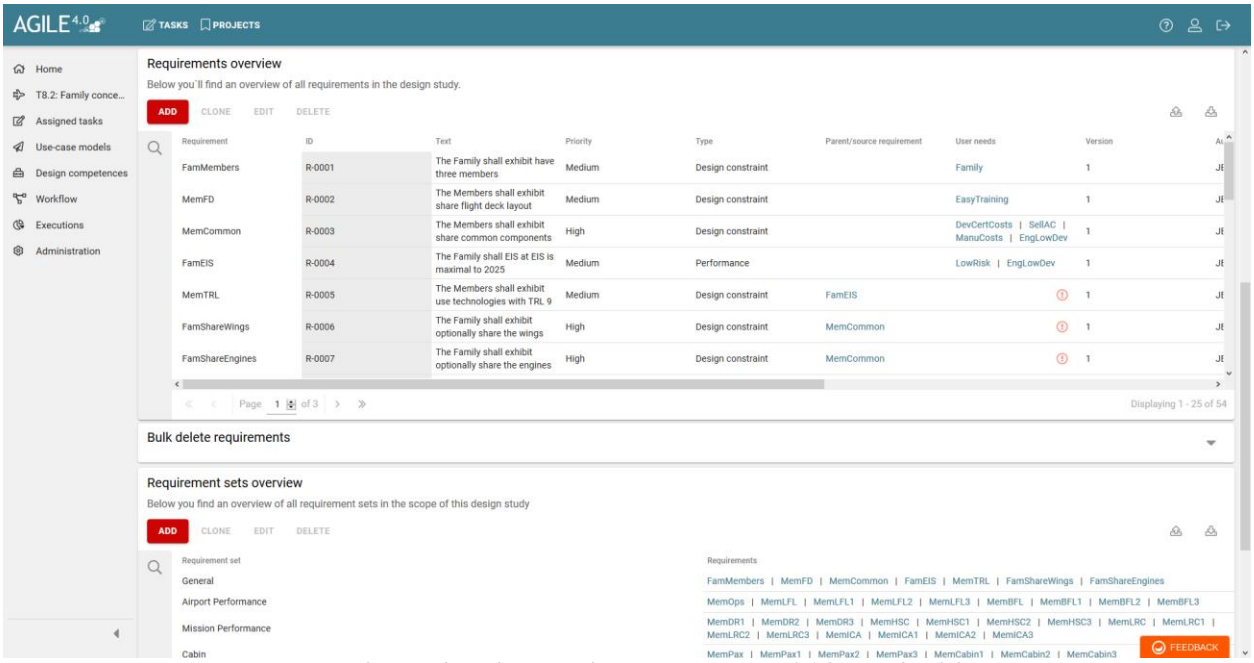


Fig. 34: Screenshot showing the requirements of AC 7 in the OCE.

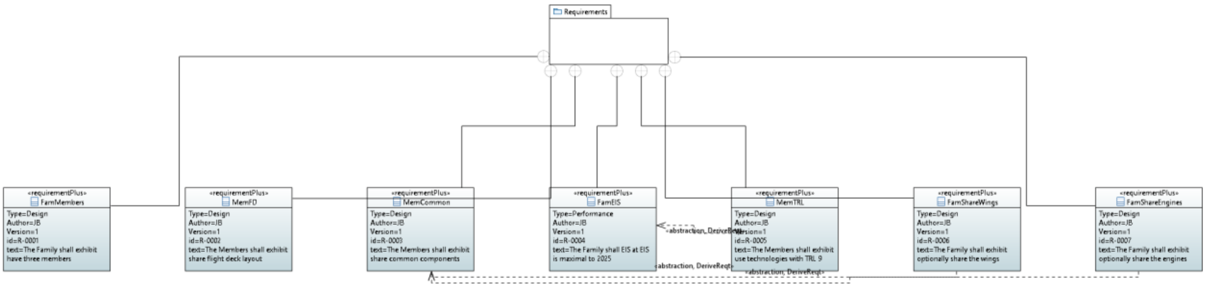


Fig. 35: The requirements set view of the "General" set of AC 7.

Fig. 36 shows the requirement pattern of AC 7 R-0036. This design requirement specifies that the cabin length of the first family member should be 25 ft.

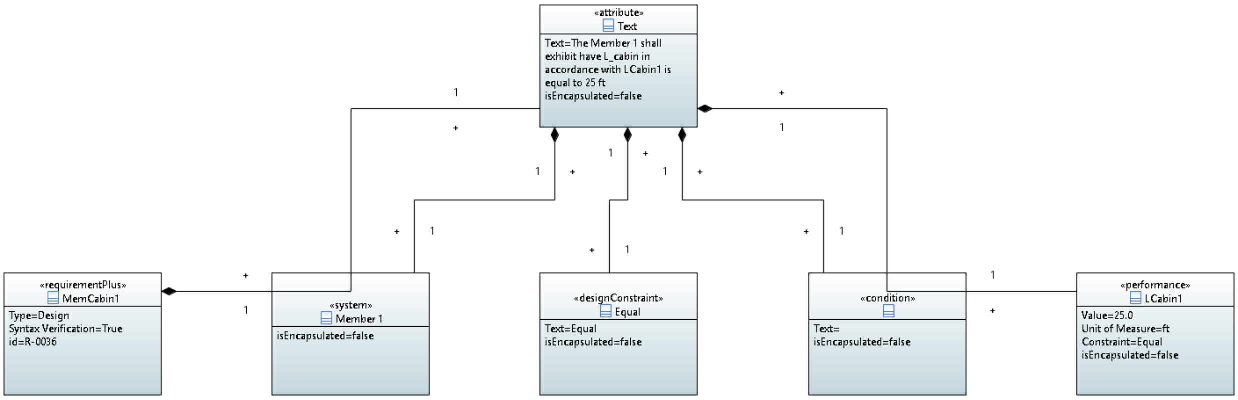


Fig. 36: Requirements pattern of AC 7 R-0036: a design requirement specifying the cabin length of the first member to be 25 ft.

Fig. 37 shows the traceability view of the requirements of the Cabin set of AC 7. From left to right it shows lower levels of derivation, starting with the needs on the highest level (most left). It shows that these requirements derive from two needs. These two needs lead to a requirement on the passenger capacity (R-0032), which is further broken down in one requirement for each family member (R-0033 to R-0035).

The need for a comfortable cabin derives three requirements specifying the cabin lengths of all members (R-0036 to R-0038). The right column of the traceability view shows the consequences assigned to the requirements. The consequences specify the impacts not meeting the associated requirements have.

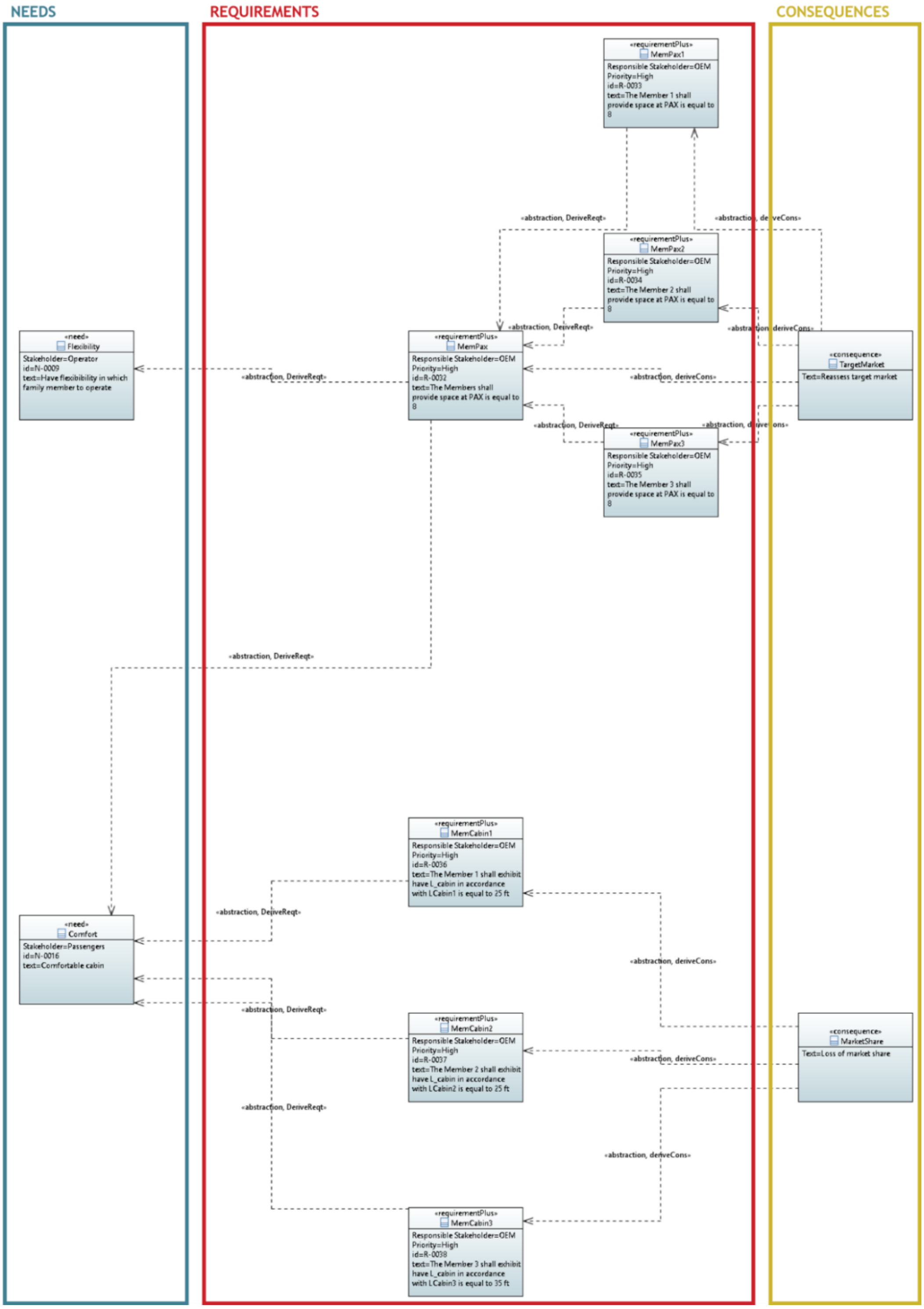


Fig. 37: Traceability view of the "Cabin" requirements set of AC 7.

3.3 System Architecting

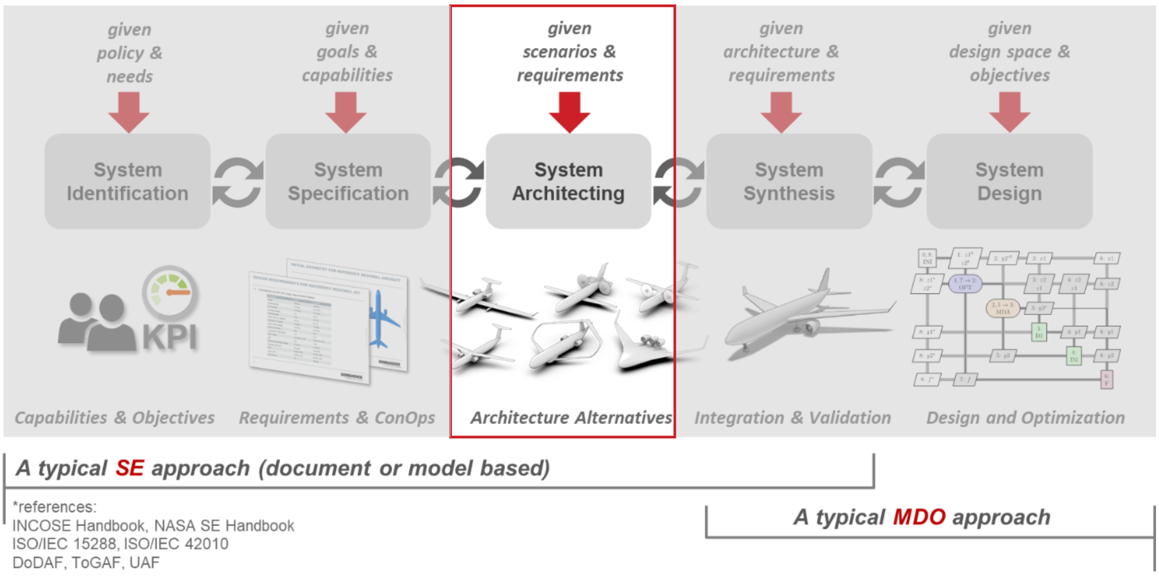
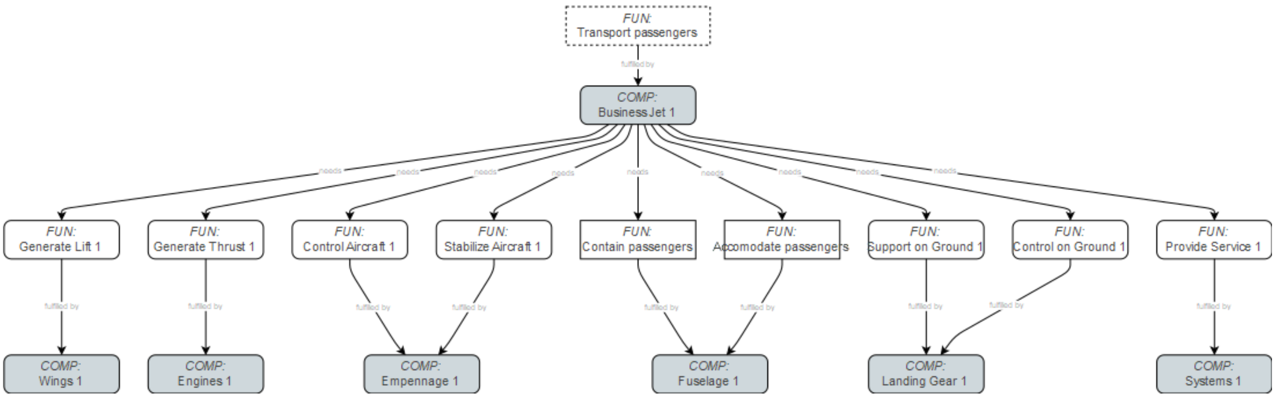


Fig. 38: AGILE 4.0 Step III: System Architecting.

The architecture of the System of Interest includes one component that represents a business jet, several induced functions for decomposing into its components, and finally components for fulfilling these induced functions (as shown in Fig. 39). Quantities of Interest are assigned to the main business jet component for recording aircraft-level inputs, design variables, and output metrics.



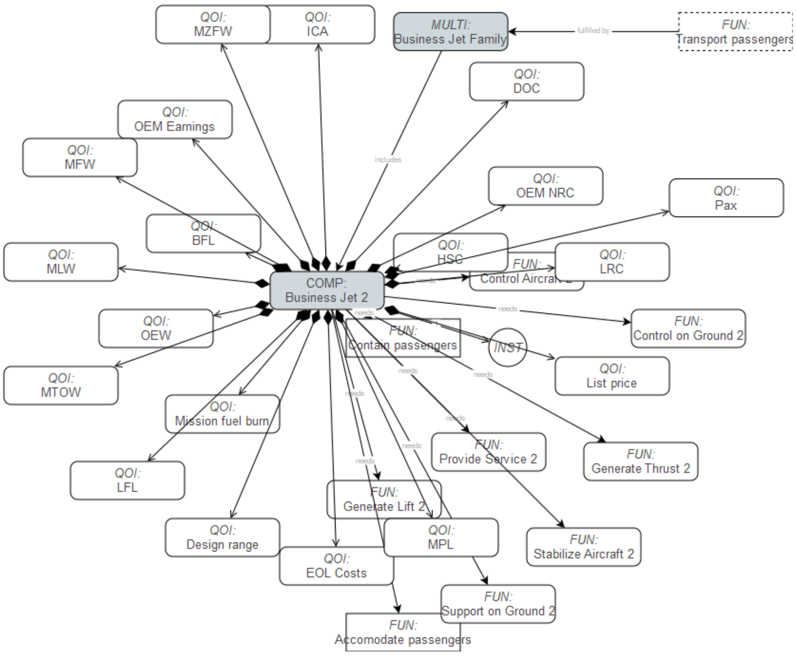


Fig. 39: AC7SoI Architecture model showing a component breakdown of one business jet on the top, and component details view on the bottom. Wings, engines, empennage, fuselage, landing gear, and on-board systems are shown.

The architecture model of the enabling system is shown in Fig. 40. It extends the SOI architecture model by including all three business jets and connecting them to the boundary function “transport passengers” through a multi-fulfillment element representing the business jet family. Component sharing choices are modeled by choosing between a component or a “shared version” of the component for certain functions. For example, the “generate lift” function can be fulfilled (for aircraft 1 and 2) by either a “wing” or a “shared wing”.

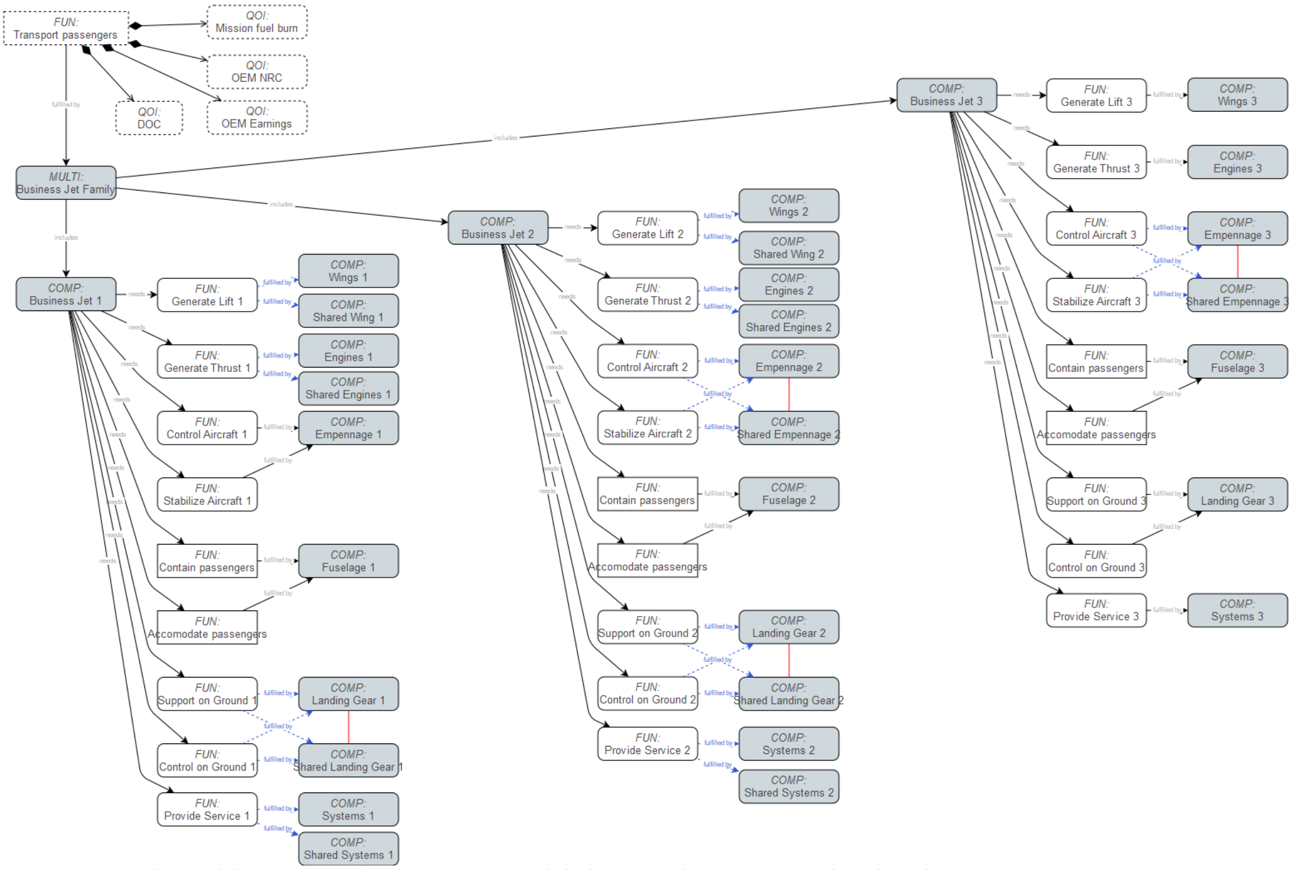


Fig. 40: AC7 Enabling system Architecture model showing three aircraft-level architectures with component sharing decisions.

3.4 System Synthesis

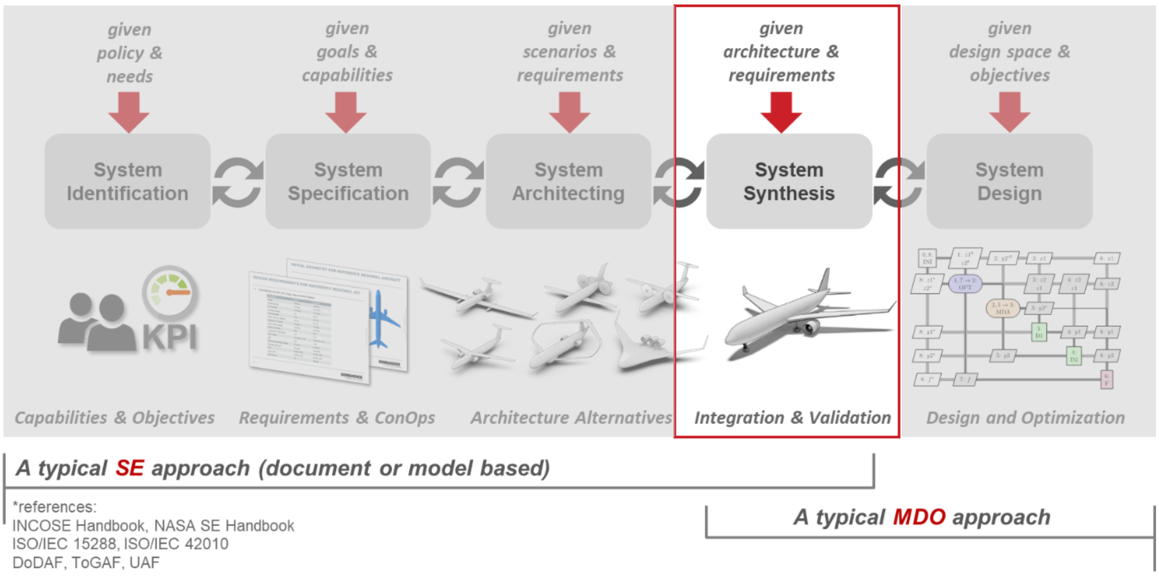


Fig. 41: AGILE 4.0 Step IV: System Synthesis.

Fig. 42 shows the architectural decisions list of the family architecture model. It shows 19 decisions, of which 10 are categorical and represent the component sharing decisions, and 9 are continuous representing wing design parameters.

Architecture Decisions

Search

#	Operation	Subject	Component Instance	Options	Linked Decisions
1	Fulfill function	Control Aircraft 2		Shared Empennage 2, Empennage 2	(1)
2	Fulfill function	Control Aircraft 3		Empennage 3, Shared Empennage 3	(1)
3	Fulfill function	Control on Ground 1		Shared Landing Gear 1, Landing Gear 1	(1)
4	Fulfill function	Control on Ground 2		Landing Gear 2, Shared Landing Gear 2	(1)
5	Fulfill function	Generate Lift 1		Wings 1, Shared Wing 1	
6	Fulfill function	Generate Lift 2		Shared Wing 2, Wings 2	
7	Fulfill function	Generate Thrust 1		Engines 1, Shared Engines 1	
8	Fulfill function	Generate Thrust 2		Engines 2, Shared Engines 2	
9	Fulfill function	Provide Service 1		Systems 1, Shared Systems 1	
10	Fulfill function	Provide Service 2		Systems 2, Shared Systems 2	
11	Continuous design variable	COMP: Wings 1 -> LE Sweep		Between 30 and 42	
12	Continuous design variable	COMP: Wings 2 -> LE Sweep		Between 30 and 42	
13	Continuous design variable	COMP: Wings 3 -> LE Sweep		Between 30 and 42	
14	Continuous design variable	COMP: Wings 2 -> Rear spar pos		Between 0.72 and 0.82	
15	Continuous design variable	COMP: Wings 3 -> Rear spar pos		Between 0.72 and 0.82	
16	Continuous design variable	COMP: Wings 2 -> t/c		Between 0.06 and 0.11	
17	Continuous design variable	COMP: Wings 3 -> t/c		Between 0.06 and 0.11	
18	Continuous design variable	COMP: Wings 1 -> Rear spar pos		Between 0.72 and 0.82	
19	Continuous design variable	COMP: Wings 1 -> t/c		Between 0.06 and 0.11	

Fig. 42: AC7 ADORE Architectural decisions list

To enable architecture optimization, architectures generated by ADORE must be linked to the MDO workflow using MultiLinQ. By combining information from the architecture model and tool input and output definitions, MultiLinQ is then able to show which tools are used to calculate which metrics. Fig. 43 shows a part of the mapping matrix, showing how aircraft-level TLARs are mapped to the aircraft-level analysis workflows.

		Tools							
Components	QOIs	FamilyCalc	OAD_1	OAD_2	OAD_3	OAD_Post_1	OAD_Post_2	OAD_Post_3	OAD_Pre
Business Jet 1			✓			✓			✓
Business Jet 1	Design range		✓						✓
Business Jet 1	ICA		✓						✓
Business Jet 1	LRC		✓						✓
Business Jet 1	Pax		✓						✓
Business Jet 2				✓			✓		✓
Business Jet 2	Design range			✓					✓
Business Jet 2	ICA			✓					✓
Business Jet 2	LRC			✓					✓
Business Jet 2	Pax			✓					✓
Business Jet 3					✓			✓	✓
Business Jet 3	Design range				✓				✓
Business Jet 3	ICA				✓				✓
Business Jet 3	LRC				✓				✓
Business Jet 3	Pax				✓				✓
Fuselage 1			✓						✓
Fuselage 1	Cabin length		✓						✓

Fig. 43: AC7 MultiLinQ Mapping matrix view

3.5 System Design

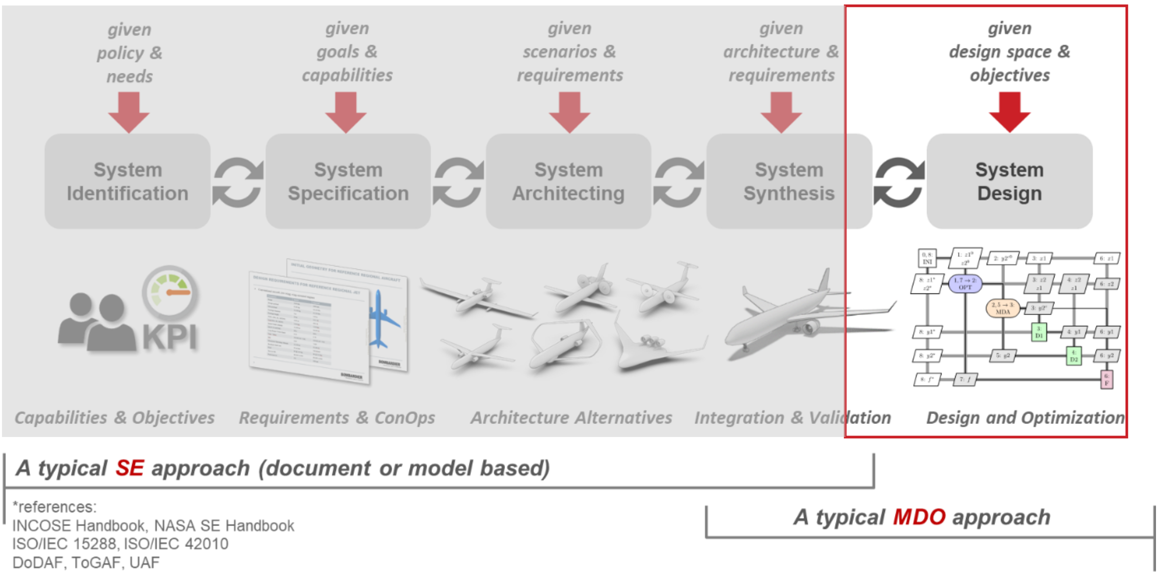


Fig. 44: AGILE 4.0 Step IV: System Synthesis.

3.5.1 Workflow implementation

The MDO workflow implementing the connection between overall aircraft design and higher-fidelity analyses are shown in Fig. 45. Family-level integration of aircraft-level results is shown in Fig. 46. Workflows are modeled using MDAx.

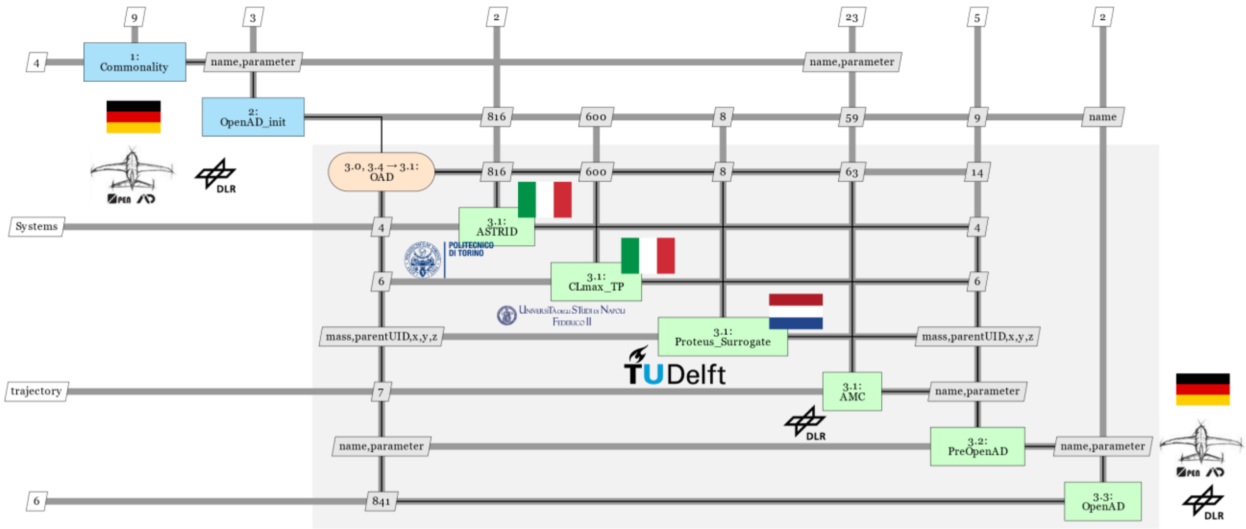


Fig. 45: AC7 MDAO XDSM of the aircraft-level analysis, also showing involved partners

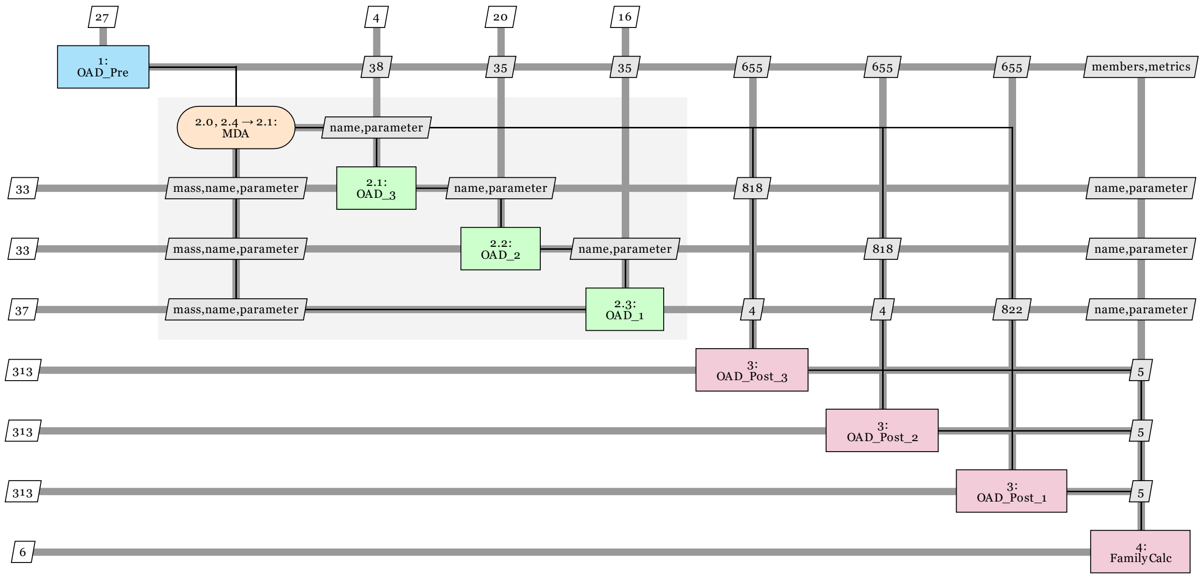


Fig. 46: AC7 MDAO XDSM of the family-level analysis

3.5.2 Workflow execution

The workflow was implemented in RCE, as exported from the MDAx model. All disciplines not executed by the DLR were implemented as surrogate models to speed up execution, except ASTRID (Polito) which was called through a Brics connection.

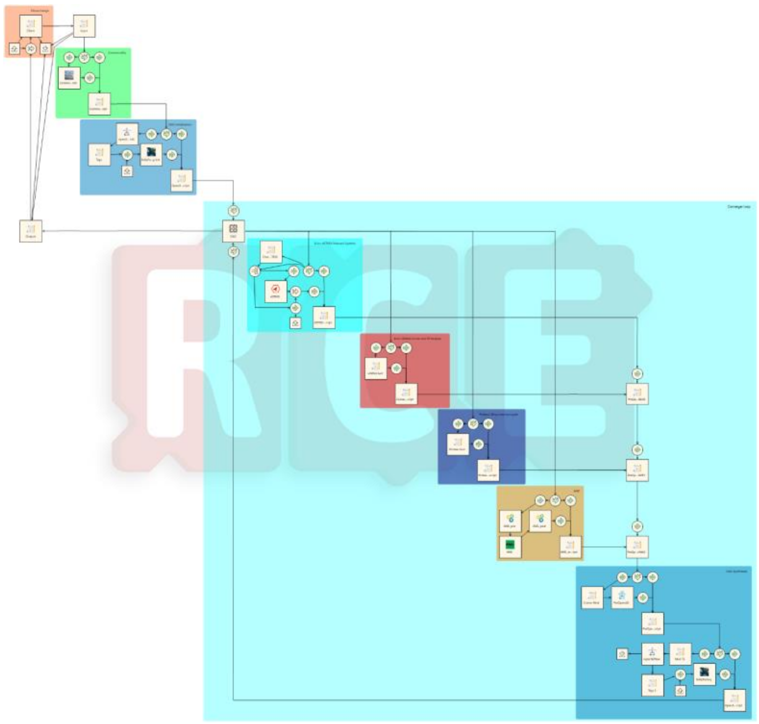


Fig. 47: AC7 aircraft-level workflow implemented in RCE

3.5.3 Optimization

Optimization was performed using the SEGOMOOMOE surrogate-based optimizer developed by ONERA. The ADORE design space was used to drive the evaluation, SEGOMOOMOE was called through a remote ask-tell interface for suggesting new design points to evaluate.

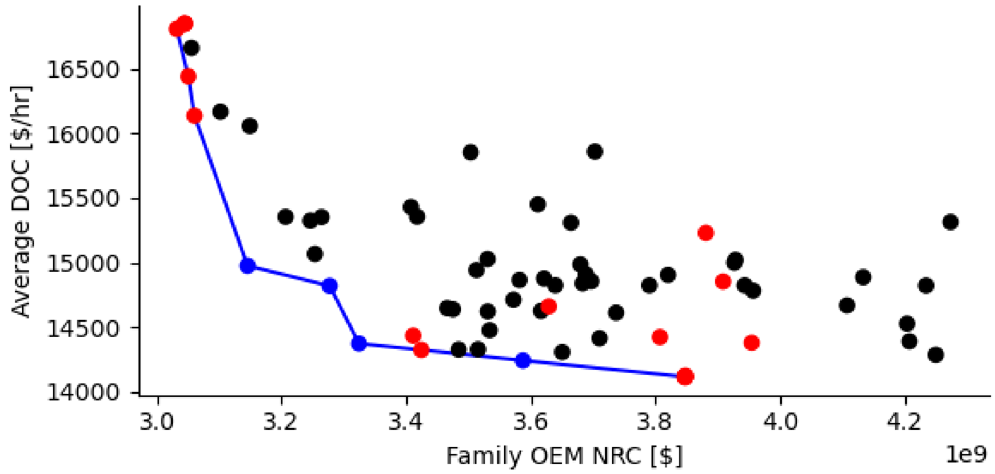


Fig. 48: AC7 results showing the main trade-off between family-level Direct Operating Costs (DOC) and manufacturer Non-Recurring Costs (OEM NRC). Pareto front is shown in blue; red dots are infill points suggested by ONERA's SEGOMOOMOE algorithm; black/blue dots were part of the initial LHS DOE.

3.5.4 Trade-off

The main trade-off is performed along the Pareto front between family-level OEM non-recurring costs and family-level average direct operating costs. It would be possible to also involve other parameters in the trade-off, such as manufacturing costs, maintenance costs, pilot-training costs, however due to project time constraints these trade-offs have not been performed.

Other than the trade-off of family-level performance metrics, it might also be interesting to perform scenario studies wherein one or more assumptions are varied to study the impact on the main NRC-DOC trade-off. For example, the number of yearly produced aircraft and/or yearly flight hours can be varied.

3.5.5 Verification and Validation

Fig. 49 shows how MDO constraints are defined from requirements. For AC7 these represent the landing field length and balanced field length requirements.

Constraint variables

Constraint variables will be used in solution strategies that implement optimizers, such as MDF and IDF. For each constraint please specify the type of constraint and the reference value.

ADD CLONE EDIT DELETE

Constraint variable	Constraint type	Reference value	Parameter	Parameter (manual input)	Requirement	Linked to requirement
Constraint: LFL	<	762		/cpacs/toolspecific/openAD /components /component[name="aircraft"] //parameters /parameter[name="desRange"]/value	MemLFL1	Yes
Constraint: LFL	<	762		/cpacs/toolspecific/openAD /components /component[name="aircraft"] //parameters /parameter[name="desRange"]/value	MemLFL2	Yes
Constraint: LFL	<	762		/cpacs/toolspecific/openAD /components /component[name="aircraft"] //parameters /parameter[name="desRange"]/value	MemLFL3	Yes
Constraint: BFL	<	1524		/cpacs/toolspecific/openAD /components /component[name="aircraft"] //parameters /parameter[name="desRange"]/value	MemBFL1	Yes
Constraint: BFL	<	1524		/cpacs/toolspecific/openAD /components /component[name="aircraft"] //parameters /parameter[name="desRange"]/value	MemBFL2	Yes
Constraint: BFL	<	1524		/cpacs/toolspecific/openAD /components /component[name="aircraft"] //parameters /parameter[name="desRange"]/value	MemBFL3	Yes

Fig. 49: AC7 Requirements verification framework; linked constraints

4 CONCLUSION AND OUTLOOK

The AGILE 4.0 Framework has been successfully used to perform the MBSE – MDO of two different application cases enabling considering parallelly:

1) two Systems: the System of Interest and the Enabling system
2) at least two domains: the aircraft design, the manufacturing, the certification

The whole process, the A4F steps allows the complete automatic reconfigurability of systems under investigation, reducing the set-up time, the human errors, improving the accuracy (also increasing the level of fidelity).

The applications demonstrate the powerful of the A4F and the success of the distributed team of experts approach.

What developed could be exploited for the generic design of complex systems.

APPENDIX A

In this section, a description of the activities and their relative costs considered to obtain results shown in Tab. 6 is presented. Tab. 11 shows a list of the development activities required to perform an engine retrofit and an OBS electrification, divided by categories. For each operation, an estimation of the number of people and the time necessary to accomplish the task are also indicated. As can be seen, the main expenditures are related to testing (32%), OBS design (29%), traveling, documentation and data management (26%). Around 13% of the development costs are related to flight technologies and structures. Tab. 12 shows the conversion costs. These data are used to compute the total cost of the removal, modification and installation of the upgraded components. For each one of these activities, minor time, manpower and related expenses are considered in the case of partial electrification with and without an engine replacement. results show that more than 40% of the total conversion cost is due to OBS replacement and installation. This is due to the heavy impact of this modification at the aircraft level. Around 30% of the conversion costs are due to the engine replacement. Finally, another 30% are due to materials supply, data management and traveling.

Tab. 11: List of the development activities and their related efforts (in terms of the number of people, time and costs) required to perform the aircraft retrofit.

Development Activity		Effort		
Field	**Type**	**People**	**Years**	**Costs [Million EUR]**
Structure	New engine attachment points	8	1	1.1
	Wing stress analysis	19	1.25	3.4
	Wing reinforcements design	9	0.75	0.95
	Flutter analysis	3	2	0.84
	Panels removal and installation	20	1	2.8
Flight Technology	Aerodynamics	10	3	4.2
	Performance	15	3	6.3
	Flight quality	5	3	2.1
	Weight and barycenter analysis	15	3	6.3
	Structural loads	20	3	8.5
OBS Design	Load and failure analysis, new installation drawings	10	3	4.2
	Electrical generation/distribution	18	3	7.5
	ECS electrical pack	9	3	3.8
	Thermal IPS design	9	3	3.8
	Air conditioning distribution	12	2	3.8
	FCS electrical actuation	18	3	7.6
	OBS design, engine installation	20	5	14.1
	Engine FADEC, autopilot	55	5	38.7
Testing	Wind-tunnel test support	16	1.25	2.8
	Flight test support	20	5	14.1
	System tests on the complete A/C	34	1	4.8
	Ground vibration-resonance test	4	0.2	0.11
	Wing static test and support	38	0.75	7.5
	Flight test	-	200 h	1.4
	Wind tunnel test	-	500 h	2.5
	RIG test (4×)	-	-	60
Documentation		15	3	6.3
Data Management		20	10	28.8
Staffing		38	5	26.8

Travels—Information technology	-	-	12.5
TOTAL			287.6

- Structures. Before the installation of the new technology on an existing aircraft, the operations must be supported by engineering efforts focused on the modification of the airframe structure. All the components that are set to remain unaltered do not need any structural modifications (i.e., reinforcements/redesign). The studies deal with the following aspects:
- New engine attachment points. New engines may be installed on different wing attachment points compared to the previous ones. A higher bypass ratio means that the fan size is increased; as a result, mounting these engines under a wing could be a challenging task that requires great engineering effort.
- Wing stress analysis. Due to the different geometries and characteristics of the new engines, the inertia, force and thrust generated will certainly change. The static aeroelastic deformation of the wing structure and load distributions, bending moment and torque need to be studied. For this purpose, a new structural finite-element model of the wing/engine system must be established.
- Wing reinforcement design. A possible conclusion of the wing stress analysis may be the realization that a wing reinforcement is needed, due to the issues described in the previous points.
- Flutter analysis. The engine module position modification along the wing in both spanwise and chordwise directions can influence the flutter characteristics. The natural vibration modes of the structure may also change with the adoption of new actuators. The structure should be capable of supporting this at the critical loads present on the maneuvering diagram.
- Panel removal and installation. The hydraulic and pneumatic circuits run across the wings and the fuselage, to connect the energy sources to the various users. If the onboard systems are modified, it is necessary to remove the fuselage panels and reinstall them after the replacement. The engineering effort will be focused on planning the operations of the fuselage panel disassembly and assembly.

Flight Technology.

- Aerodynamics. A computational fluid dynamics (CFD) analysis must be carried out to predict the drag, lift, noise, performance, structural and thermal loads for the updated aircraft systems.
- Performance. The aircraft mass distribution is an important parameter to be considered during the design process, due to its significant influence on performance and inertia. If the new engines are located at a greater distance from the fuselage, they will make a greater contribution to the rolling moment of inertia of the aircraft. In addition, their weight and efficiency changes will all influence the aircraft’s mass distribution.
- Flight quality. A certain amount of engineering effort is involved in the study and in the evaluation of the longitudinal and lateral-directional stability and control characteristics of the retrofitted aircraft.
- Weight and center-of-gravity analysis. The proper distribution of weight plays a large and important role in an aircraft’s overall performance. Both performance and stability depend on the location of the center of gravity. Therefore, all flight tests must be conducted with an accurate knowledge of the location of the center of gravity at any one point in time.
- Structural loads. An analysis that is performed on all the aircraft in terms of the new structural loads is required for certification purposes and to understand if reinforcing element installation is required.
- OBS Design. The partial or total electrification of the onboard systems requires intensive engineering work, aimed at designing the new architecture.
- Electrical generation/distribution. Power must be provided by an additional electrical generator and distribution system. These components must be sized appropriately and relocated along the aircraft.
- ECS, IPS, air conditioning, FCS. All the components that connect to the new electrified system must be redesigned.
- Load and failure analysis and new installation drawings. For the overall OBS architecture installation, failure analysis must be performed, and new component drawings must be provided.
- OBS design, engine installation, engine FADEC, and autopilot. The simultaneous engine and OBS upgrades imply the installation of a new FADEC (full-authority digital engine control) system and new autopilot software.
- Testing. Certification of the new system is essential after the execution of the retrofitting modifications. All the activities required to set up, assist and analyze the tests and test results must be accounted for. Of course, in the case of reduced retrofitting activities, certain test operations that were considered become unnecessary.
- Wind tunnel tests. Once the new engine has been chosen, the combination airframe and new engine must be tested. A wind-tunnel test campaign must be organized and carried out to predict the aerodynamic performance of individual aircraft components, as well as the new overall configuration. The engineering effort required to process the test data and to obtain the new drag polar curves is also considered.

- Flight tests. After the retrofit updates, a flight test campaign is carried out to determine the new aircraft characteristics (previously estimated via wind tunnel tests), to assist the engineering design and developmental process and to verify the attainment of technical performance specifications and objectives, to establish the system's operational effectiveness and operational suitability.
- System tests on a complete A/C and RIG test. Several test systems must be assessed to analyze the behavior of the new onboard systems, starting from the standalone component up to its integration into the aircraft. Four different RIG tests must be performed: tests of the electrical, propulsion, avionic and flight control systems. In addition, an avionics software development process is required by law. This cost item must be considered since the engine's FADEC and the autopilot are changed.
- Ground vibration-resonance test. The modifications to the structure and mass distribution could bring the necessity of new ground vibration tests, performed to meet certification requirements.
- Technical documentation. After such an innovation, it is essential to make an engineering effort to update the various aircraft manuals: the repair manual, the aircraft flight manual (AFM), the flight crew operating manual (FCOM), and the weight and balance manual (WBM).
- Data management. This cost item includes the engineering effort required to control the configuration and manage the data by people who handle information such as onboard equipment serial numbers and the way that these systems interface with the structure. Typically, this activity lasts almost all the life of the upgraded aircraft, which is the reason why this cost can be elevated.
- Staffing. In this value are included all the people who have not yet been considered: airworthiness, reliability, maintainability and testability engineers, safety and chief engineers, and the people who deal with design quality assurance, costs and planning.
- Traveling and information technology. In this cost item are allocated the materials to support engineering research and the costs to sustain every kind of travel (e.g., the movements of goods and supplies). Travel costs are calculated. The cost associated with information technology is linked to the number of licenses required. A realistic value may be EUR 20,000 per license.

Tab. 12: List of the conversion activities and their related effort (in terms of the number of people, time and costs) required to perform the aircraft retrofit.

Conversion Activity		Effort	
Field	**Type**	**Months**	**Costs (Million EUR)**
Engine Removal	Pylon, engine, nacelle	1	0.64
	Wing skin panel	1	0.64
Engine Modification	New engine attachments points	2	1.28
	Spar, ribs, skin reinforcement	0.5	0.32
Engine Installation	Pylon, engine, nacelle	1	0.64
	Wing skin panel	0.5	0.32
OBS Removal	Fuselage skin panel	1	0.77
	Hydraulic distribution	0.5	0.38
	Bleed distribution	0.5	0.38
	Seats, interiors, floors	2	1.54
OBS Installation	Electrical distribution and generation	2.5	1.92
	ECS, IPS, APU, TPs	1	0.77
	Fuselage skin panels	0.5	0.38
Others	Materials	-	3.0
	Travels	-	1.0
	Reception, painting and delivery	-	0.5
TOTAL			14.48

In the following, a brief description of the conversion activities presented in Tab. 12 ,divided into categories, is presented.

- Removal. The entire propulsion system must be removed, including the components attached to the wing. According to the retrofit typology, the hydraulic or the bleed distribution systems must be dismounted. To allow these activities, a preliminary operation that consists of panel disassembly is required. These must be removed from the wing and all along the fuselage, including the floor, beneath which some of the cables and systems components are located. As a consequence, the fuselage interiors must also be removed.

- Modification. After the engineering studies are complete, there is a very high chance that the wing must be reinforced. Indeed, the presence of a new engine that can be moved to a different position may lead to new torsional and gyroscopic loads. Furthermore, new engine attachment points must be created since the new engine will have different dimensions from the previous one.
- Installation. The new engine and the new electric system must be inserted into the aircraft, including new power generators. The components to which the new system is linked must also be modified, in order to ensure OBS compatibility. Finally, the panels that were previously removed from the wing and the fuselage must be reinstalled.
- Material, travel and management. The different and complementary activities required to support the removal, modification and installation phases must be considered. To compute this cost, a formula has been utilized by modifying its characteristic factor. A value of EUR 24/h per worker has been considered for the computation of material costs. The value that is assumed to compute travel costs is EUR 8.0/h per worker. Finally, the parameter used for other activities, such as the reception, painting and delivery of the new aircraft is EUR 4.0/h.

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