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Regional jet retrofitting design: from stakeholders' needs and system's requirements to MDAO workflow formulation

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Abstract

In this paper, a process useful for the verification of economic, environmental and performance requirements related to the retrofit of 90 passengers regional jet aircraft is described. The requirements are defined according to the stakeholders' needs involved in the process. Multiple scenarios are put in place, ranging from environmental restrictions to volatility of fuel price, aircraft fleet to be retrofitted to passengers' comfort level. Two retrofitting packages are considered: the re-engining of conventional power-plant platform with advanced geared turbofan and the on-board-system modernization, considering different level of electrification. Starting from the definition of the architectures, which represent the starting and the target points of the design, a multidisciplinary collaborative aircraft design workflow is generated and executed to analyze the retrofit solutions. Results coming from the disciplinary competences introduced for the analysis are exploited to verify the fulfilment of profits, costs, performance, and emission requirements. The overall process is implemented in the framework of the AGILE 4.0 research project, moving towards a thorough Model Based System Engineering problem definition.

Keywords: Requirement's verification, Aircraft retrofit design, Collaborative design, MDO, MBSE

1. Introduction

During the last decade different aircraft manufacturers (OEM) were focused on the re-design of existing platform with the aim of increase their competitiveness, reduce the operative costs, and decrease the environmental footprint. Innovative solutions are continuously investigated to deal with new government regulations, competitors, constraints, and customer needs. Government-funded programs have been established with the aim of reducing the air transport environmental impact also accounting for passengers' satisfaction, safety, and security. [1], [2]. The fulfilment of these target can be challenging considering the tight deadlines required by these programs. By consequence, the choice of re-design a part of the components of an existing platform instead of developing a completely new design is mainly related to a matter of time. Indeed, the upgrade of existing platform employs around 5-7 years to accomplish design, manufacturing, and certification phases before starting the deliveries [3], [4], [5]; while the average time required to accomplish the same activities on a completely new platform is around 20 years [6]. In addition, in the time range, the only chance for an airline to adopt innovative technology is to pursue a retrofitting activity. Significant examples of this attitude are the upgrade solution opted by most significant OEM: the Boeing 737 family, the A320 family and the Embraer E2-jet family, the ATR family. RETROFIT project [7] and IATA Aircraft Technology Roadmap [6] illustrates which are the most attractive retrofitting activities employable nowadays and in the following years, such as engine replacement, avionics and on-board-system modernization and aerodynamic improvements (wing-tip devices, etc.).

The analysis and results presented in this paper are obtained in the framework of the AGILE4.0

research project [8], [9], where collaborative Multidisciplinary Aircraft Design Analysis and Optimization (MDAO) are performed involving the aircraft design domain (typically considered during the preliminary aircraft design) and industrial domains, including manufacturers, suppliers, maintainers, and certifiers perspective. This kind of approach makes an extensively use of AGILE 4.0 architectural framework (A4F) [10], which provides several tools in the context of Operational Collaborative Environment (OCE). This environment allows to design complex product considering Stakeholder's' needs, Top Level Aircraft Requirements (TLARS), the scenario in which the system is generated, and the system architecture definition. The process is led by the Model Based Systems Engineering (MBSE) tools which streamline the development of a Multi-disciplinary Design Analysis and Optimization (MDAO) workflow able to design the enabling systems and enable the verification of the TLARS previously defined.

The paper is structured as follow. Sec. 2 describes the steps required to design the retrofitting activity of a 90 passenger regional jet aircraft considering both System Engineering and traditional design and optimization approaches. Sec. 3 illustrates the MBSE phases that must be followed. Here, the scenario in which retrofitting activity is performed, the involved stakeholders, their needs and requirements are indicated. In addition, the system architectures model necessary to satisfy the introduced requirements, is described. In Sec. 4 the MDAO phases are described. In particular, the System of Interest (SoI) and the Enabling System (ES) to be analyzed are defined. The generation of two workflows which include all the disciplines needed to solve the MDAO problem is illustrated. These workflows enable the computations of both SoI and ES economic, environmental and performance characteristics. Achieved analysis and optimization results are presented. The final phase, which concerns the verification of the requirements' fulfillment, is described in Sec. 5. Finally, conclusions are addressed.

2. Systems Engineering Product Development process

The aircraft retrofit design is performed through different phases which aim to include in the development cycle a System Engineering approach, in addition to the typical design and optimization activities. Figure 1 represents these phases. 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 fulfillment verification. The third phase concerns the system architecture modelling. A model of the systems under analysis is generated, describing how each systems' components fulfill the requirements. Here, different solutions can be modeled, each one is generated through a decision-making process.

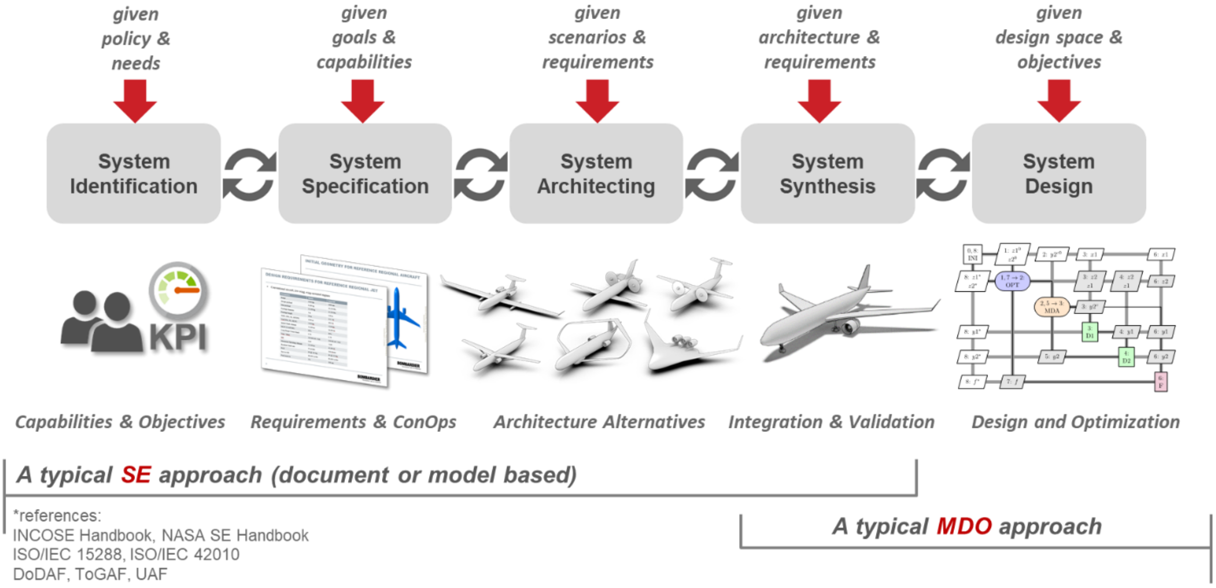


Figure 1: Systems Engineering Product Development process followed in this paper.

The last two phases concern the MDAO process. The first one is mainly focused on the definition of the system to be analyzed. 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 analyzed 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 in order 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.

3. Model Based System Engineering Design

3.1 Scenario modelling

The first step of the MBSE approach concerns the scenario modelling. This task is performed using Capella [11], a model-based engineering public domain tool which allows to model different scenarios into the OCE framework. One of them concerns an "*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 Figure 2 an extract of "*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.

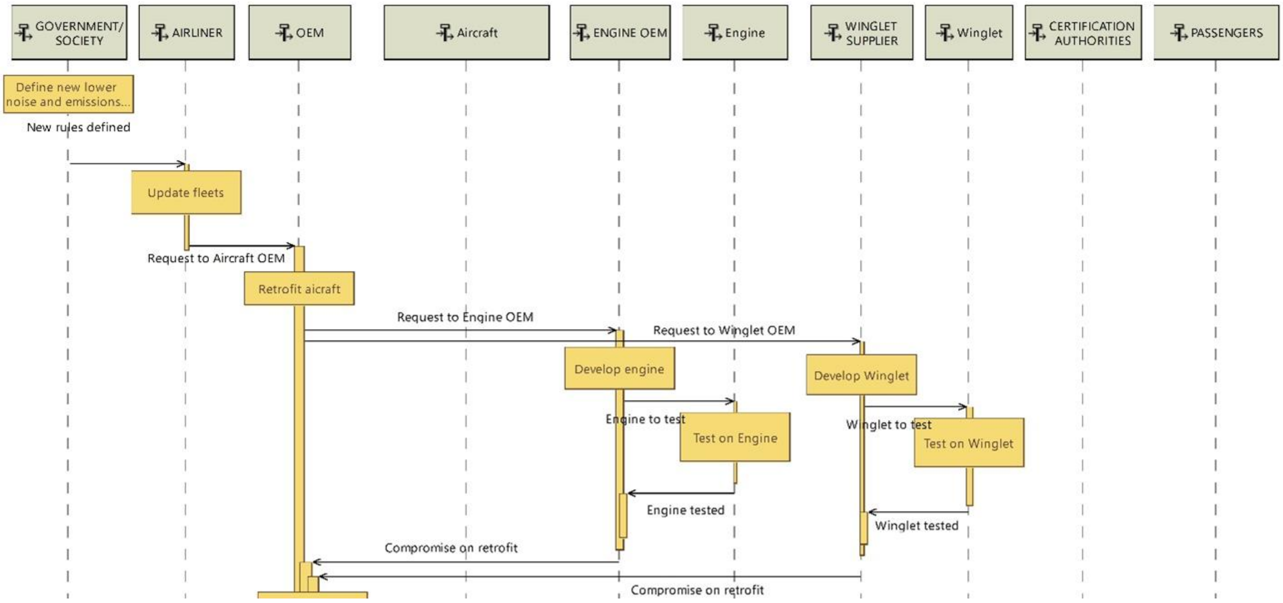


Figure 2: Extract of "Environmental Restriction" scenario modelled through Capella, an MBSE tool.

3.2 Stakeholders, Needs and System's Requirements

Considering the scenario described in Sec. 2, 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 KE-Chain [12], a web-based portal which provides centralized and integrated access to the OCE. Table 1 and Table 2 represent a part of the needs defined for each stakeholder and requirements necessary to meet the stakeholder's need represented according to the MBSE approach.

Table 1: 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)
	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	Operate in any available airport
	Need the exclusivity
CERTIFICATION AUTHORITY	Guarantee for a safe aircraft
	Environmentally friendly aircraft
MRO	Easy inspection activities
	Keep the same facilities to accomplish maintenance activities
PASSENGERS	Comfortable flight also in terms of noise in cabin
	Affordable ticket price
	Would like to pay for a "green" flight
MARKET	Establish economic trends (fuel price)

Table 2: 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 Aircraft shall reduce its maximum take-off weight with respect to reference system 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

3.3 Architecture modelling

Within the OCE, it has been possible to easily model a system architecture representing both the SoI and ES under analysis. Starting from the functional requirement indicated in Table 2, 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 Figure 3 and Figure 4 two extracts of the complete architecture model are represented. The model is obtained through ADORE [13], a tool connected with the OCE implemented in KE-chain which allow to generate architectures model though graphical user interface. Figure 3 represents the model concerning the engine components, including nacelles, attachment points, starter, generator and fuel systems. Instead, Figure 4 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.

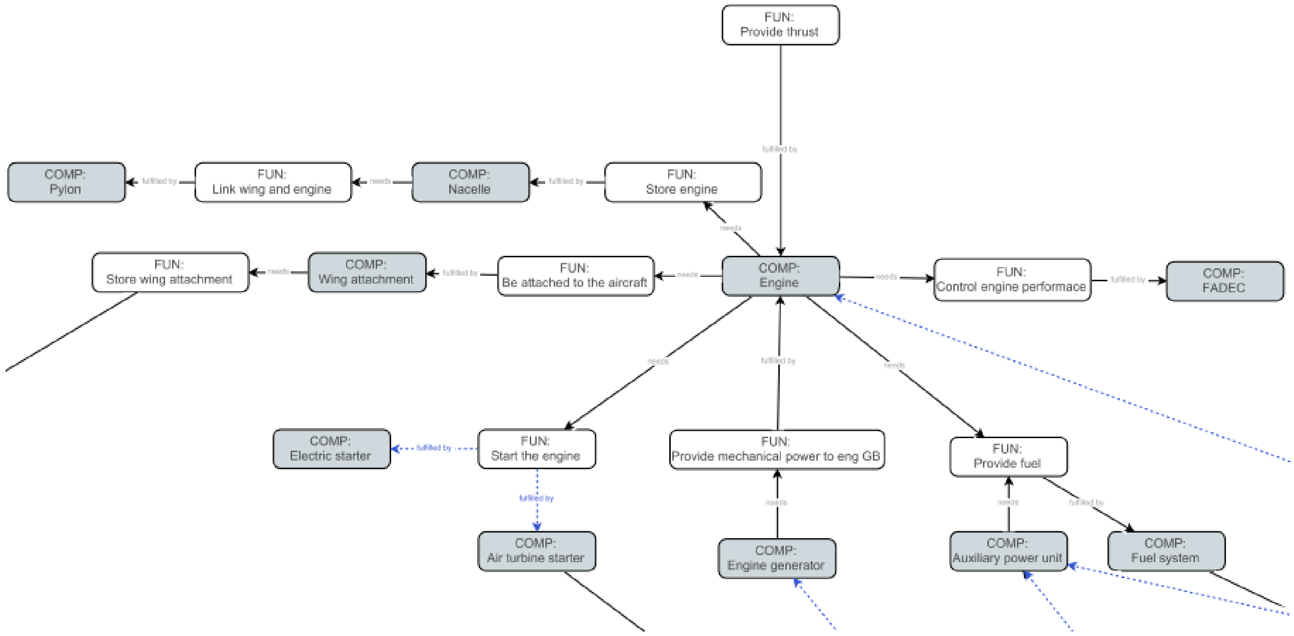


Figure 3: Architecture Model extract related to the Engine.

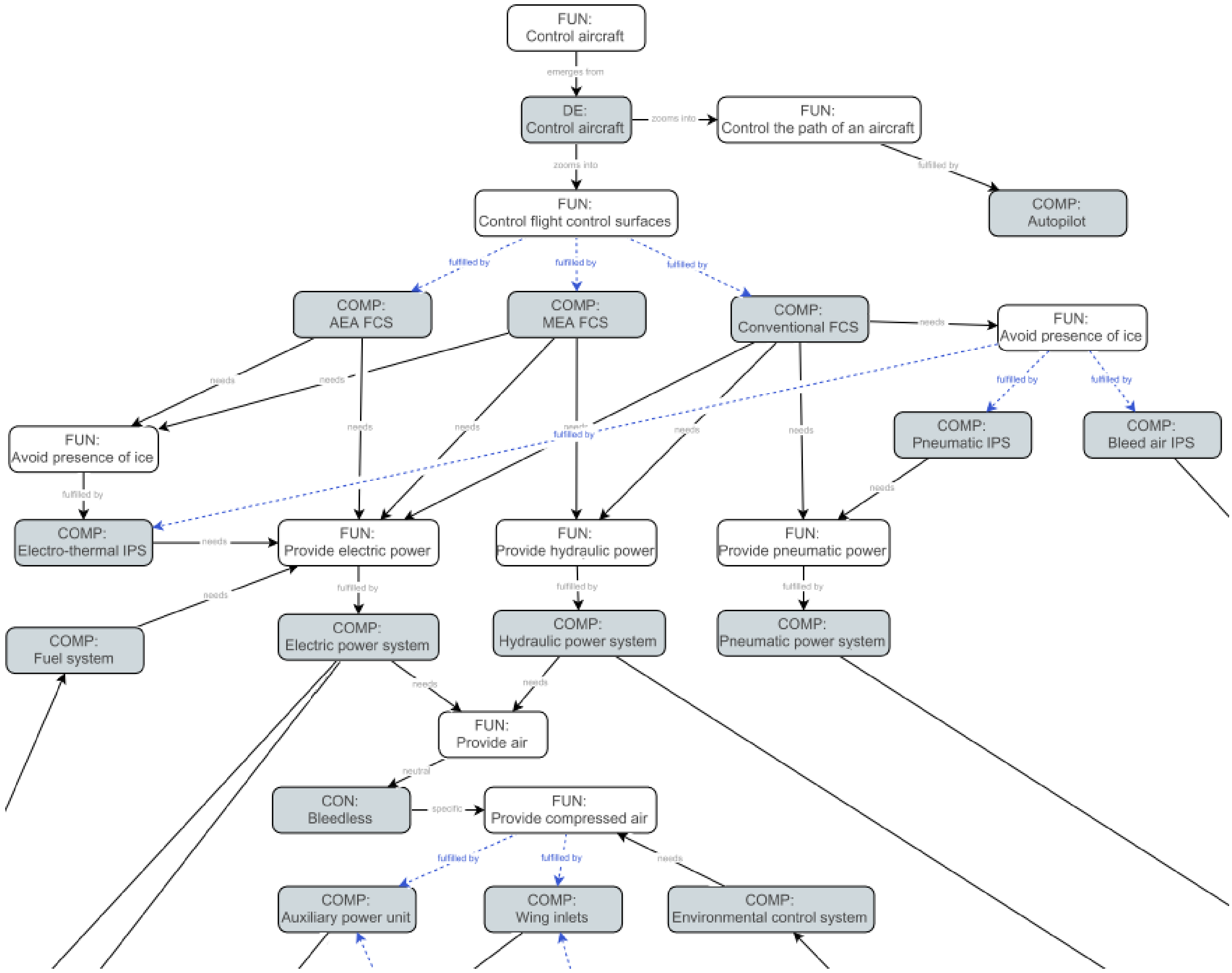


Figure 4: Architecture Model extract related to the OBS.

4. Multi-Disciplinary Design and Optimization

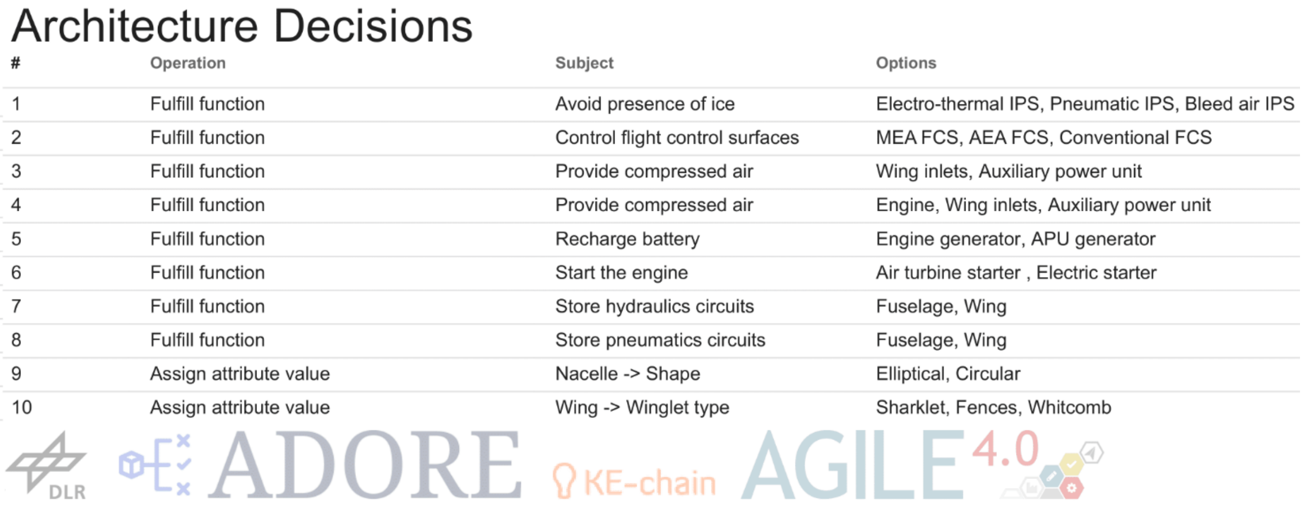
4.1 System definition

Once defined the systems architecture model, a decision panel like the one represented in Figure 5 is automatically generated. Indeed, when a model's function can be satisfied by more than one component, the designer must choose which elements will fulfill it. The main choices concern the 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 control system will necessary be provided by electric power. Otherwise, if a conventional OBS configuration choice is made, the ice control system can be powered by electricity, pneumatic energy or bleed air. Two main architectures have been generated through the decision panel illustrated in Figure 5. They represent the systems which will be designed and analyzed in the final part of the MDAO process. Below, a description of both systems is provided.

System of Interest. This system represents the baseline aircraft, a conventional regional jet 90 passenger aircraft with conventional OBS architecture and 2010 reference engine architecture. OBS are powered by all three possible considered power systems: batteries, hydraulic and pneumatic systems. Batteries are charged by engine generator. The fuselage will store the pneumatics and hydraulics circuits. Compressed air is provided through both engine and auxiliary power unit (APU). Nacelles shape is circular and fence-type winglets are installed on the wing.

Enabling System. This system represents the retrofitted aircraft, generated starting from the baseline one. Different Enabling Systems can be generated, depending on the chosen retrofitting packages. Advanced High BPR geared turbofan engine installation like Pratt & Whitney PW1000G-series and OBS architecture electrification can be considered. In addition, two level of electrification can be selected. An example of enabling system is represented by an engine with BPR equal to 15 and AEA OBS architecture, more details can be found in [14]. No hydraulic and pneumatic system are installed on the aircraft. Since the innovative engines are bleed-less, other sources, such as APU, are exploited to provide pressurized air to the systems and allow the batteries to be recharged. Nacelle's shape is elliptical; Whitcomb-type winglets are installed on the wing.

Figure 6 illustrates the System of Interest under analysis, highlighting components which can be retrofitted, leading to the above described Enabling System.



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

Figure 5: ADORE Decision panel. It indicates the possible choice which can be made to generate a new architecture.

Figure 6: Reference regional jet aircraft. Engines and OBS highlighted.

4.2 MDAO Workflow formulation

Different MDAO problems must be addressed to design and analyze the system described in Sec. 4.1. The first step to define an appropriate workflow consists in the definition of the available tools. The design of a retrofitting activity is not a straightforward activity; indeed, it involves different phenomena. For instance, it is essential to analyze 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: surrogate-based tool capable to define the main engine's geometrical, economical and performance characteristics with reference to the engine BPR considered.
- 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 [15]: 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.
- PERFORMANCE & MISSION [16], [17]: 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 [18]: 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 [19] and ICAO Annex 16 [20]. It also provides the noise margin from the certification limit. The method is based on semiempirical approaches based on ESDU methodology [21].
- 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. [22] and Association of European Airlines [23]. 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.

All the information concerning the above-described disciplines can be insert in the OCE, through KE-Chain platforms. Input and output of each tool must be indicated in a common parametric language. In this case, CPACS [24] 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. Figure 7 and Figure 8 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 (Figure 7) 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, air emissions of the reference platform are computed. In conclusion, costs and price of the platform under analysis are estimated.

The Enabling System MDO workflow (Figure 8) 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, air 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.

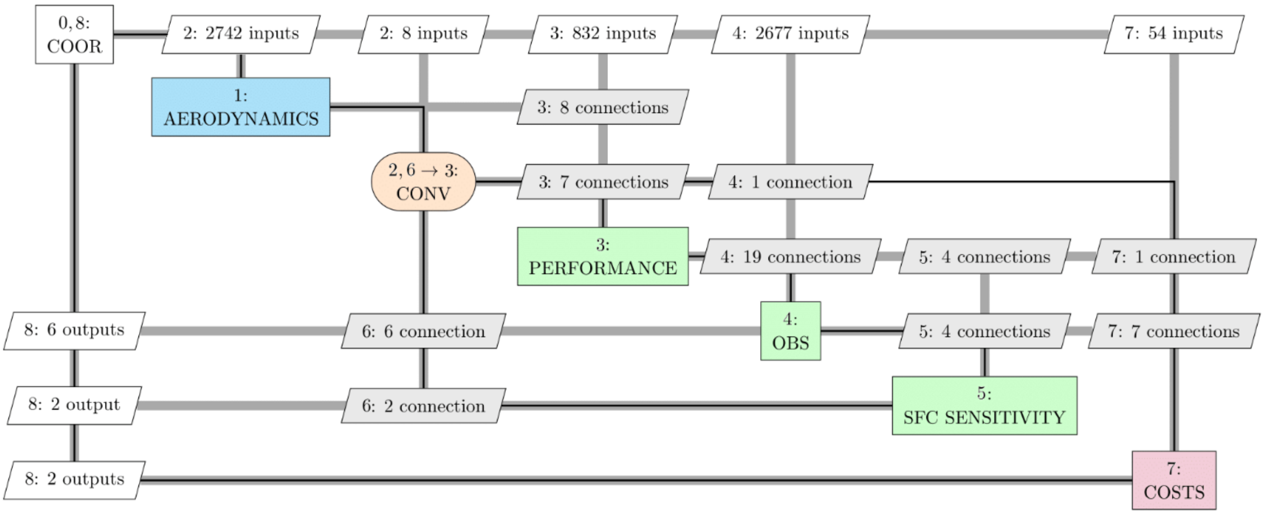


Figure 7: MDAO XDSM of the System of Interest.

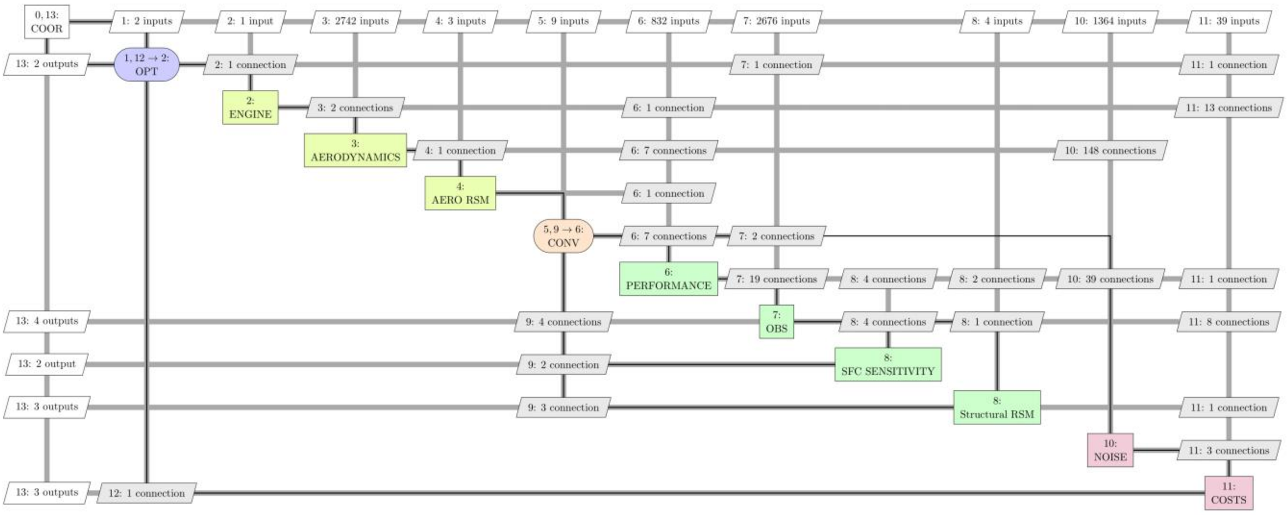


Figure 8: MDAO XDSM of the Enabling System.

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.

4.3 MDAO Workflow results

In this section, some examples of results achieved through the execution of the workflow described in Sec. 4.2 are presented. In Table 3 are summarized the main assumption related to the following computations. 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 [25]. The noise emissions costs are computed considering the current taxes required by Frankfurt airport [26]. These assumptions are directly linked to the scenario presented in Sec. 3.1, 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.

Table 3: Hypothesis assumed to compute the retrofitting costs and savings.

Costs Savings Analysis Hypothesis	
Retrofitted fleet	700 units
Typical mission range	720 nm
Cruise Mach	0.78
Cruise altitude	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	[5-10] %
Manufacturer profit margin	7%
Learning curve rate	0.95
Agreement saving	50 %
Fuel price	€0.65/kg of kerosene / €88 per barrel
Noise taxes	Frankfurt airport taxes

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. Figure 9 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 Figure 9 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.

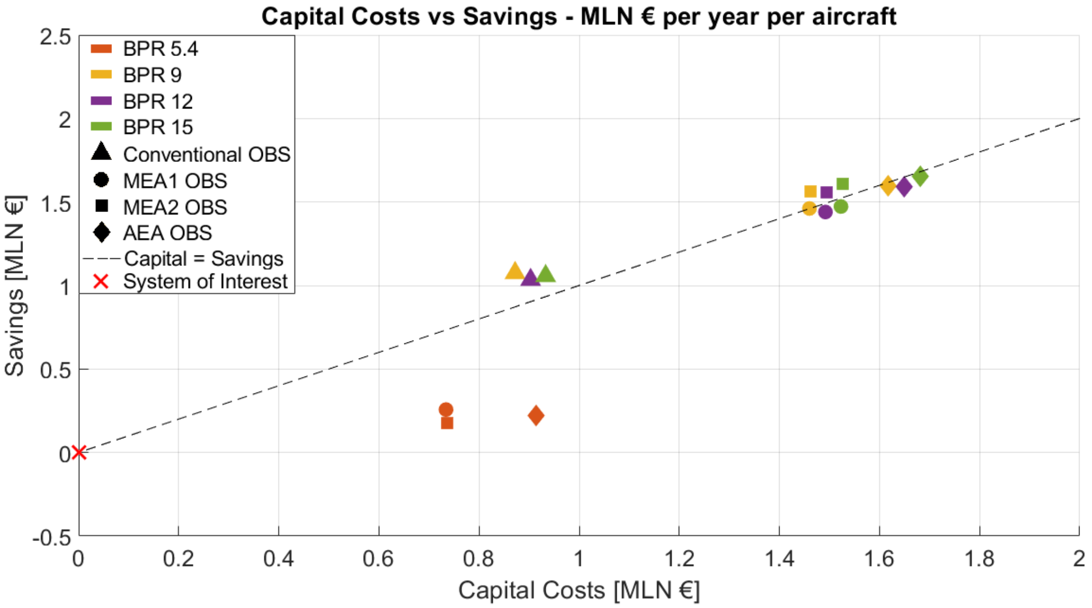


Figure 9: Capital Costs and Savings represented for the System of Interest and different Enabling System solutions. The color of each point represents the engine BPR, the shape (triangle, circle, square or diamond) represent the OBS level of electrification. The assumptions of the analyses are indicated in Table 3.

The MDAO workflow presented in Sec. 4.2 have been also exploited to perform optimization analysis and decision-making activities. In the following, the results of a multi-objective optimization are illustrated. Four different optimization variables are considered: i) OBS level of electrification, ii) engine BPR, iii) engine position along fuselage direction, iv) engine position along vertical direction. The first variable is categorical, since four different OBS architecture are considered, the others are continuous variable. In addition, four constraints are considered for the optimization: i) The ES maximum take-off weight must be lower the System on interest one, ii) ES take-off distance must be minor than SoI one, iii) ES landing distance must be minor 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 conclusion, four objective functions are considered: i) difference between capital costs and saving required to perform the retrofitting activity, to be minimized, ii) maximum 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.

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

In this equation, *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 [20]. 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). Figure 10 represents the results for objective number i) and iii) of the optimization. The blue cloud of points represents all the Enabling Systems evaluated to perform the optimization. These points differ in OBS level of electrification, Engine BPR and position. The orange set of points represent a Pareto front of the optimization. Indeed, they represent the optimum achievable ES. As it is possible to notice, there is not a single point which minimize both cost-savings and CEI. For this reason, the Airliner will choose among the orange set of points as final solution according to its needs. The minimum achievable difference between costs and savings is around € -0.2 Mln per aircraft per year. This result is obtained considering a conventional OBS architecture with an engine BPR equal to 9. The CEI obtained in this case corresponds to 0.90. On the opposite side, the minimum achievable value of CEI is around 0.87. In this case a fully electric OBS architecture is selected, with an engine BPR equal to 15. Indeed, this solution led to the maximum performance and emission improvements with a difference between costs and savings slightly higher than zero. As said before, the System of Interest is characterized by a cost-savings difference equal to zero and a CEI corresponding to 1. It means that all the ES considered generate emission lower with reference to the SoI but not all of them are more economically convenient.

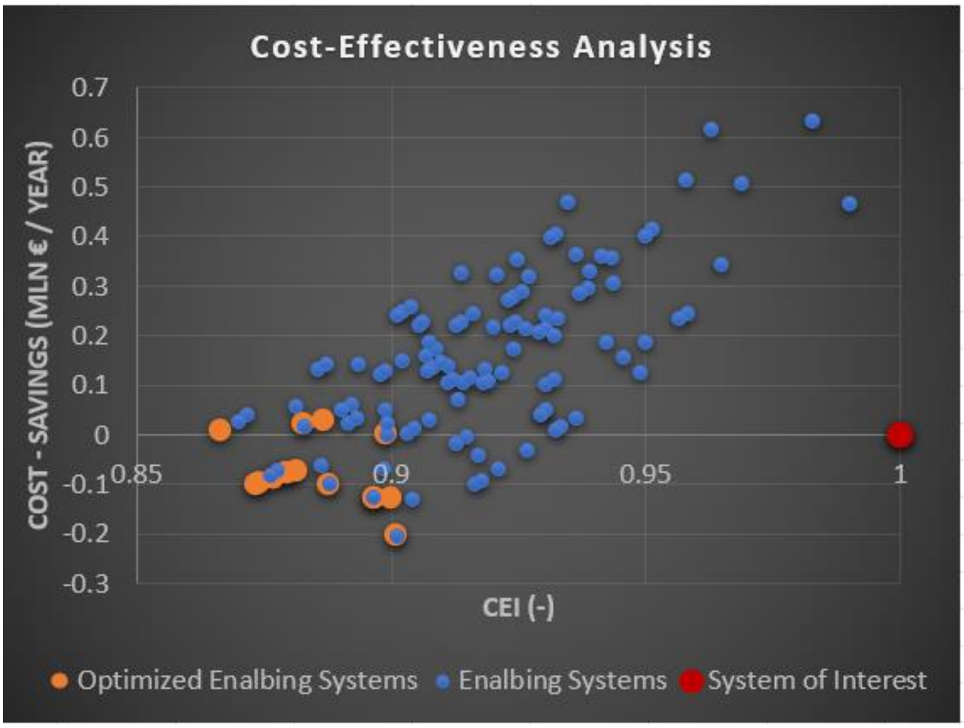
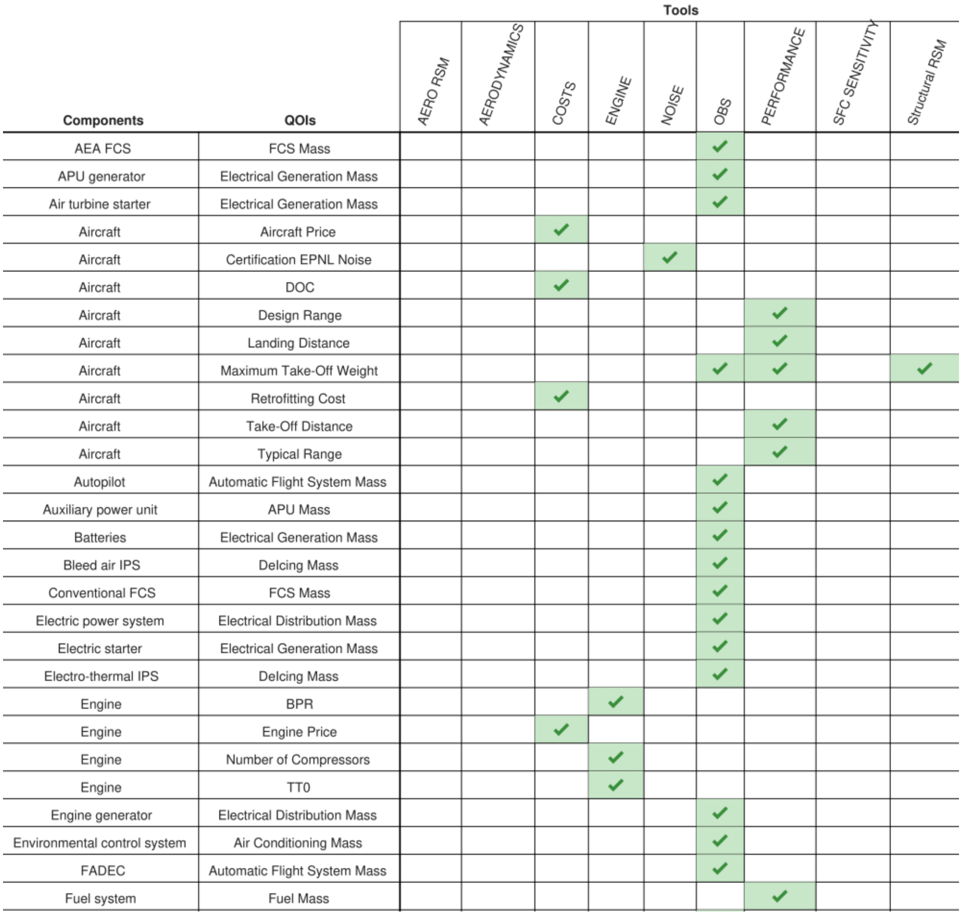


Figure 10: MDAO results. Cost – Savings vs Cumulative Emission Index. Data are represented for SOI, ES and optimum ES. The assumptions of the analyses are indicated in Table 3.

5. System Verification and Validation

The final step of the design process consists in verify the effectiveness of the workflow and its related results. Two phases are required to achieve this task. The first one concerns the verification of the connection between the MBSE architecture and the MDAO workflow. The second one consists in verify if the final system, designed and optimized through the workflow, fulfills the requirement considered during the whole process.

In KE-Chain, MultiLinQ [13] tool has been provided to accomplish the first step. 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, QOIs for the engine can be the fuel consumption and 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 described in Sec. 4.1. After importing the CPACS file obtained through the workflow execution, MultiLinQ allows 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. Figure 11 represents an excerpt of the mapping matrix obtained for the ES presented in Sec. 4.1. 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 Figure 11 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.



		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							✓		

Figure 11: Excerpt of Enabling System mapping matrix generated through MultiLinQ.

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

Figure 12: Excerpt of Enabling System requirement verification framework.

The second step concerns the verification of the requirements shown in Sec. 3.2. This examination can be performed thanks to the results obtained through the execution of the workflows presented in

Sec. 4.2. A requirement verification framework is implemented in KE-Chain. The CPACS file obtained after the workflow execution must be provided to this platform. Then, the framework automatically provides a table in which for each requirement the value of the related QOI and the margin for its limit is indicated. In this way it can be verified if each requirement is satisfied or not. In Figure 12 an excerpt of the requirement verification framework obtained for the Enabling System results achieved is presented. All the requirements presented in Sec. 3.2 have been fulfilled. 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.

6. Conclusions

The retrofitting activity design of a regional 90 passengers' jet has been performed thanks to the AGILE 4.0 methodology and framework. A MDAO collaborative remote workflow has been generated starting from the needs of stakeholders involved in the activities' scenario. The whole process has been performed in an online collaborative MBSE environment, through which it has been possible to verify the coherence of the model and the fulfillment of the requirements. In this way, a bridge between the MBSE and MDAO approaches has been generated. First, the scenario in which the retrofitting activity is performed is illustrated, representing a situation in which the upgrade operations become a need for the Airliners. From the scenario, the stakeholders involved in the process are defined, describing all their needs. These needs are converted in requirements for the system design, introducing several logic prepositions useful to verify if the requirement is fulfilled or not. After that, the system architectures are modelled through ADORE. In this way both Systems of Interest and Enabling System are defined. Each system architecture is characterized by several Quantities of Interest, which represent input or output of the analysis framework. In this way, the disciplines involved in the process are linked to the system under analysis. Starting from these disciplines, an MDAO workflow is defined to analyze, design and optimize the Enabling System. Optimized solutions have been presented and compared to the baseline aircraft. The whole process is performed within the AGILE 4.0 OCE framework. Finally, this environment allowed to verify and validate economic, environmental and performance requirements fulfillment and the coherence of the system architecture models. The optimized solutions meet all the introduced requirements. In addition, they allow to generate an economic profit up to € 0.2 Mln per year per aircraft or a cumulative noise and air emission reduction up to 13% with respect to the baseline aircraft.

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