Regional jet retrofitting through multidisciplinary aircraft design

Massimo Mandorino[1], **Pierluigi Della Vecchia**[2], **Fabrizio Nicolosi**[3] **and Giovanni Cerino**[4]**.**

[1,2,3]University of Naples Federico II, Via Claudio, 21, 80125, Naples
[4]Leonardo Aircraft Division, Viale dell'Aeronautica, Pomigliano D'Arco (NA)

[1]massimo.mandorino@unina.it

Abstract. Multidisciplinary collaborative aircraft design is applied to a 90 passengers regional jet aircraft highlighting the impact on costs and performance. Two retrofitting packages have been 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 a reference existing aircraft, the impacts of retrofitting process have been carefully evaluated on capital costs and revenues at industrial level through a developed methodology. At aircraft level, masses, performance, noise, and emissions have been computed with dedicated competences increasing the estimation reliability. Overall process is implemented in the framework of the AGILE 4.0 research project in a collaborative remote multidisciplinary approach. Results show that such retrofitting activities are expensive and must be evaluated since the design stage with a bottom-up approach requiring competences coming from designer experience to correctly define the process work-breakdown-structure and its implications.

1. Introduction

During the last decade aircraft manufacturers (OEM) were focused on the re-design of existing platform to increase the competitiveness, reducing operative costs, and decreasing the environment footprint. Except for the Airbus A350, no one "new design" was carried out and maybe no one will be available for the next 20 years. It is the case of the Boeing 737 Max, the A320 neo family and the Embraer E2-jet family. Suffice it to say that the average time-to-market declared from these OEM to develop a "new design" from abstraction up to the market is around 20 years [2], while the re-design of some components of existing platform is around 5-7 years [1]. Considering the regional jet aircraft in the 151-210 seats group, the last aircraft model release took place in 2016 (A321neo) and an aircraft renovation in this seat category is expected in 15 or 20 years. The same happens for the other categories, meaning that existing aircraft fleet will operate for many years with a technological gap not in-line with noise and emission limits or operational costs competitiveness [1][3].

In this time frame a retrofitting activity on existing fleet becomes more and more appealing depending on the scenarios and costs.

In the RETROFIT European research project [4], a list of technologies inventory is proposed, ranging from power-plant, aerodynamics, structure and materials, avionics, equipment and so on. Winglet installation, engine replacement or the application of advanced materials could lead to benefits in fuel consumption without employing the amount of time required to introduce a new aircraft generation. For large transport aircraft, this process is generally conducted, airframe OEM, by an engine OEM or both, considering activities such as the design of the modification, the design of other hardware of the aircraft influenced by the retrofitting, establishing and certifying the new performance of the aircraft, retuning flight characteristics and much more. Especially the certification of the modification would entail a very large effort as well and be impossible without active cooperation of aircraft OEM Industries.

Moreover, depending on the Technology Readiness Level (TRL) and expected cost-benefits results some "Performance Improvements Packages" could become more feasible and attractive than others[4][5]. Just as example, typically, cabin interior is characterized by a maintenance cycle which has different timing with respect to the aircraft overhaul and maintenance one. Consequently, for an airline is possible to retrofit their cabin products every 5-7 years [6], which is a very brief range of time compared to the one referred to typical aircraft update activities.

By using the guidelines of the European commission, the main interesting areas identified as being important are the Environmental performance, Cost-effectiveness of the aircraft Operational improvements Passenger and Crew wellbeing (safety, comfort). A cost benefit analyses is essential to establish since the preliminary design stage the feasibility and the scope of a such complex activity. For this reason, a multidisciplinary design, analysis, and optimization (MDAO) could be a viable process to consider whole aspects related to a retrofitting process: design problem variables, constraints and objectives, considered at the same time allowing to reduce inefficiencies, risks and "the sometimes-spectacular cost and schedule overruns"[3]. In this paper the AGILE 4.0 (2019-2022) collaborative MDO is employed as "means of compliance" to demonstrate the impact of a complex retrofitting process on a regional jet platform[7]. The previous AGILE project (2016-2018) has developed an approach, the so-called AGILE Paradigm, focusing on the acceleration of the deployment and operation of collaborative Multidisciplinary Design Analysis Optimization systems, which in turns can be exploited to accelerate the development of complex products, such as novel aerospace systems [8]. The AGILE 4.0 European research project makes a bridge between the MDAO and MBSE (model-based systems engineering), leveraging MBSE principles to streamline the development of agile MDAO design systems. The paper presents a formulation of a retrofitting process involving not-only the aircraft design domain (typically considered during the conceptual aircraft design), but also industrial domains, such as production, certification, and maintenance. In particular industrial domains are carefully evaluated in the cost's estimation: a bottom-up approach has been used to formalize the costs estimation process. This approach makes an extensively use of both industrial experts' knowledge and AGILE 4.0 architectural framework, leading to a well-structured and defined problem formulation. In the sec. 2 the MDAO formulation is presented, starting from the reference aircraft, the disciplinary competences involved and the technical formalization using the AGILE 4.0 developed technologies. In the sec. 3 results are discussed considering the possibility to retrofit the aircraft power-plant and OBS architecture. Results are presented at aircraft level and industrial level. Finally, conclusions are addressed.

2. *Multidisciplinary workflow*

The retrofitting tasks is accomplished through the approach developed in the AGILE and AGILE 4.0 research projects developing a collaborative remote MDO and MBSE problem formalization. In this paper the AGILE 4.0 application case 6 (AC 6) will be described, as implemented through the developed technologies. Care will be posed to the results, while for the technologies the reader is postponed furthering articles [9][10].

The reference aircraft considered in AC 6, is a regional-jet 90 passenger aircraft with a design range of 1890 nm, whose main characteristics are summarized in Table 1 and in Figure 1. The aircraft is like the Embraer E-175, with two turbofan engines like the CF34-8E[1] and conventional OBS.

The retrofitting application is here focused on advanced powerplant and OBS electrification. In order solve this task, a workflow architecture has been defined. The workflow represents the collection of analysis competences used in the analysis and optimization. Thanks to the AGILE and AGILE 4.0 technologies[7][8] it is easy reconfigurable, extensible, and improved in terms of level of fidelity and number of tools.

---

[1] https://www.geaviation.com/sites/default/files/datasheet-CF34-8E.pdf, General Electric CF34-8E, accessed 16/06/2021

Table 1. Aircraft main characteristics

Aircraft	**Characteristics**
Wing Area	81.40 m^2
Wingspan	27.19 m
Design Mission	1890nm + 100nm + 5% reserve
Typical Mission	720 nm
MTOW	39485.00 kg
MOEW	23871.15 kg
Mpayload	9180.00 kg
Mfuel*	6433.80 kg
Engine BPR	5.4
T0	78200 N
OBS	Conventional

*Design Mission

Figure 1 – AGILE 4.0 AC 6 Aircraft, Engines and OBS highlighted

2.1 Modelling

Different scenarios can be easily modelled into the OCE. For sake of simplicity a scenario called “Environmental Restriction” is here explained accordingly to the MBSE approach. In this scenario, it is expected an aggressive emissions restriction by Governments, pushing the Airliners to “retrofit” existing heritage fleets. The complexity of scenario involves multiple stakeholders, and three systems (the aircraft as whole, the engine and the winglet). The Airliners will refer to the aircraft OEM to reduce emissions, improving fuel consumption without DOC penalty. The investment in retrofitting must be carefully evaluated, considering acquisition costs for equipment (engines, OBS, winglet) but also engineering costs, certification, and maintenance. The schema clearly identifies not only the Actors (stakeholders: Government, Airliner, OEM, Engine OEM, Winglet supplier, Certification authorities and Passengers), but also the Entities (systems: Aircraft as whole, engine, and winglet for this example). The retrofitting operations are mainly carried out by OEM: Aircraft OEM, Engine OEM and T2 Winglet supplier. The retrofitted aircraft, subject to in force rules, can be reinterred in flight after certification process, aiming for fuel, emissions, and noise reductions. The benefits are appreciated from operators (Airliners) and passengers.

The scenario is translated into a disciplinary analysis workflow, as a multidisciplinary collaborative multi-fidelity workflow based on the AGILE 4.0 Operational Collaborative Environment (OCE); an example of a XDSM converged DOE automatically created into the AGILE4.0 OCE is shown in Figure 2. An example of MBSE scenarios, generated in the OCE and reproduce with Capella[2] is shown in Figure 3.

---

[2] https://www.eclipse.org/capella/, Model Based Systems Engineering, accessed 16/06/2021

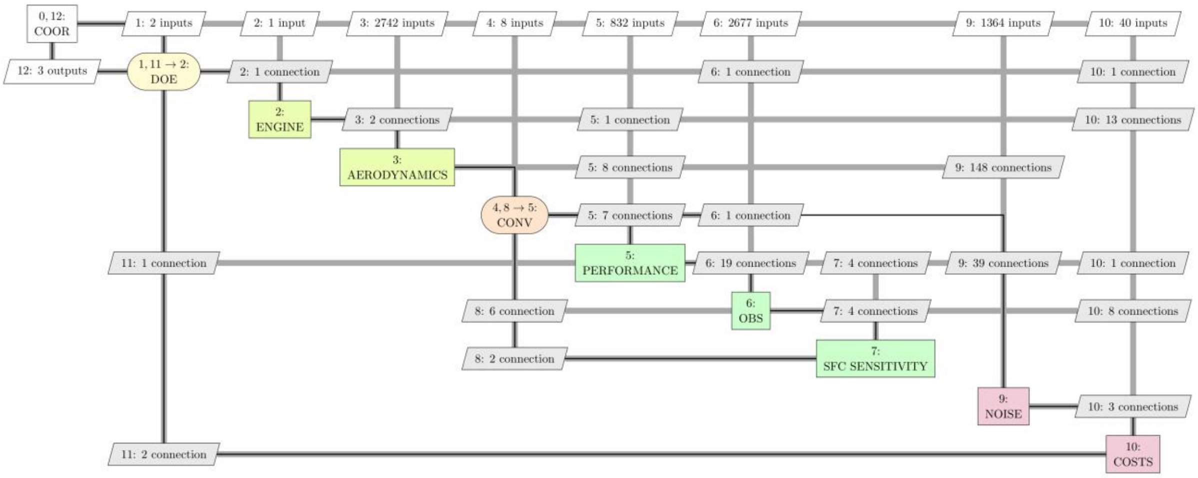

Figure 2 - XDSM view of AC 6 in AGILE 4.0 research project; Example of converged DOE

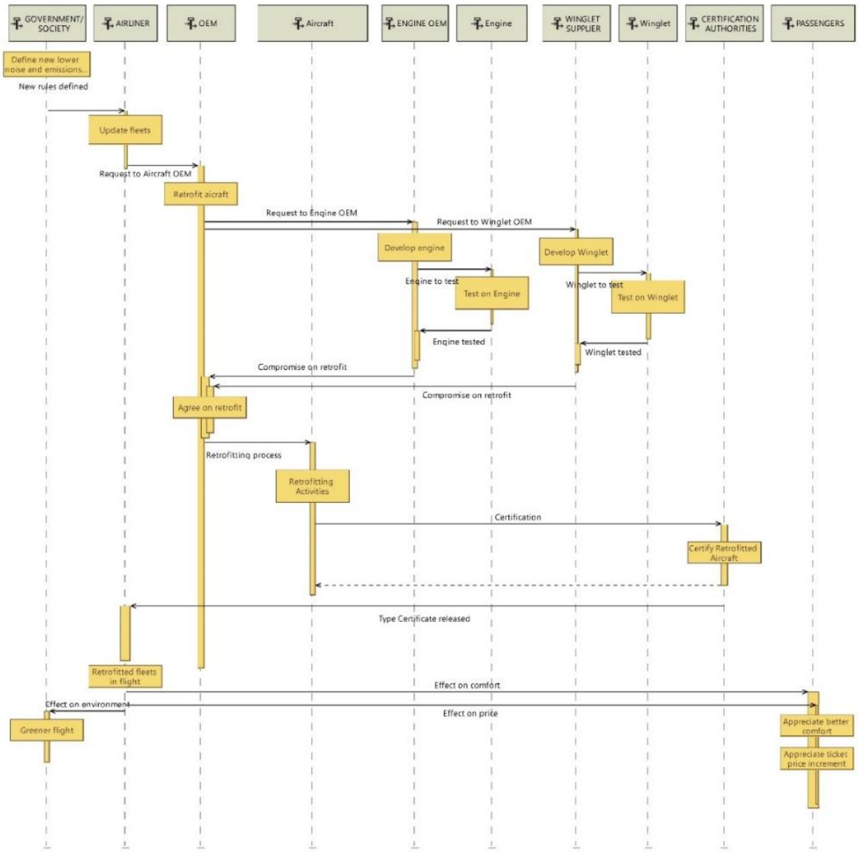

Figure 3 - Sequence Diagram of UC 6 scenario 1: "Environment Restriction"

2.2 Tooling

The disciplinary competences used in the AC 6 analysis are shown in Figure 2 and here described.

2.2.1 Engine. The engine competence is a surrogate-based tool capable to define the main engine characteristics such as: *i)* Thrust and Fuel Flow as function of Mach number, Altitude and ratings; *ii)* powerplant mass and pylon mass; *iii)* nacelle geometry *iv)* Engine list price*; v) Engine noise deck, expressed as 1/3 octave band in a polar arc. The engine performance maps are based on GASTurb 11 engine modeler built on 4 different engine BPR (5.4, 9, 12, 15) with the same top level engine* *requirements; the engine price, masses and engine noise deck are based on semiempirical and statistical correlations.*

2.2.2 Aerodynamics. The aerodynamic branch allows to compute both low-speed and high-speed aerodynamics. It is based on semiempirical approaches and main output are the drag polar for all flight conditions (take-off, climb, cruise, landing), the lift coefficient up to the stall and the moment coefficients. Aerodynamics receives engine geometry as input, computed the different BPR and engine location aerodynamic impact.

2.2.3 On-board-system. The OBS discipline allows the overall on-board-system sizing. Here different OBS architecture can be modelled, named: i) C(conventional) ii) MEA1(more electric aircraft iii)MEA2 (more electric aircraft) and iv) AEA(all electric aircraft). The discipline also allows the secondary power computation (power-off-takes) and their impact on engine fuel flow.

2.2.4 Performance & Mission. This discipline computes the overall ground and flight performance as accordingly to a simulation-based approach. The overall mission profile, fuel consumption, flight time and gaseous emissions are computed. Finally, the convergence on maximum take-off weight (MTOW) is performed within the converger loop.

2.2.5 Noise. The noise competence provides the values at the certification points accordingly to the FAR36 and ICAO Annex 16 [11][12] references. Moreover, the noise footprint is also provided on a georeferenced map accordingly to a selected airport. The method is based on a semiempirical approaches coming from ESDU (see also [13]).

2.2.6 Costs. In the cost's competence are evaluated the recurring and not recurring costs, the aircraft price and the direct operative costs based on semiempirical approaches proposed by Kimoto et al.[14] and AEA method[15]. Moreover, to estimates the costs associated to a retrofitting process, a methodology has been developed. This method is a typical quantitative bottom-up method needing of high-level of knowledge coming from industrial experience. Selecting a retrofitting package, all the activities and associated costs are computed.

2.3 Executing

Thanks to the AGILE 4.0 OCE, the assembled disciplinary workflow previously described can be automatically translated into an "executable" workflow. The execution is performed into RCE [9][10] in a collaborative remote manner using the Brics [9][10] technology to remotely run a disciplinary competence. Each disciplinary specialist runs by own side the analysis automatically updating the results following available to further disciplines. The executable workflow into RCE environment is shown in Figure 4.

In the execution different engine (depicting and different BPR) and different OBS architecture are considered with the aims to trade-off between costs and performance.

3. Results discussions

Four different engine BPR and four different OBS architecture are here considered to describe the achieved results. Results are divided into aircraft performance and retrofitting costs. Finally capital costs vs revenues are discussed. Two different missions are analysed: the design mission and the typical mission both at design payload.

3.1 Aircraft performance

Considering the aircraft design domain, the impact of varying the engine bypass ratio (moving from a conventional EIS 2000 to advanced EIS 2025+) and OBS architecture (from conventional to more electric or all electric aircraft) has been evaluated focusing on, MTOW, block fuel, emissions, and noise. Moreover, all flight and ground performance are verified and considered as constraints in the *converger* loop.

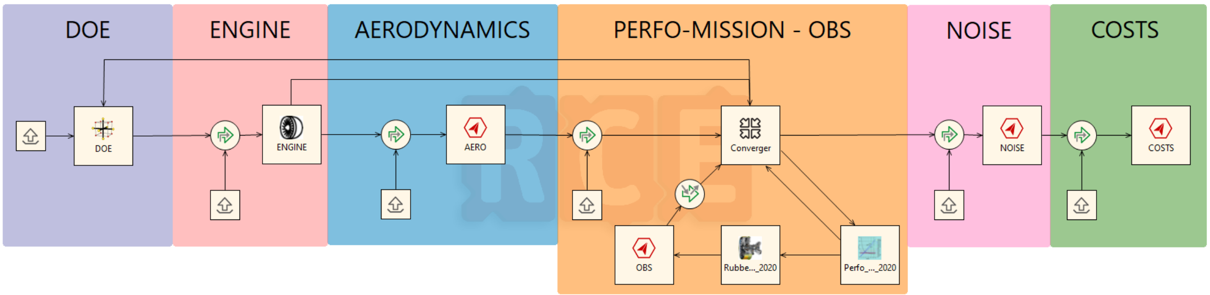

Figure 4 – Executable workflow of AC 6 in AGILE 4.0 research project; Example of converged DOE

Results are summarized from Figure 5 to Figure 10. Figure 5 shows a possible MTOW reduction due to both engine and OBS retrofitting. The best solution should be a BPR = 9 and MEA1 OBS architecture (MTOW reduction of 4% respect to the baseline). The impact on fuel weight is shown in Figure 6 and Figure 7 for design and typical mission respectively; adopting an advanced engine (with higher BPR) leads to a fuel reduction ranging from (12% to 14%), while the OBS electrification could lead to further fuel reduction ranging from 2% for the MEA1 architecture to 4% for the AEA architecture. The best fuel reduction can be achieved for a higher BPR (> 12) and an AEA OBS architecture. Similarly CO_2 emissions can be reduced for higher BPR and AEA on-board-system architecture (see Figure 8). Finally, Figure 9 and Figure 10 show the effects of advanced engine on cumulative noise and footprint. Results shows a potential cumulative certification noise reduction of about 15 EPNL dB, coming from mainly from take-off phase due to the improvement on engine side.

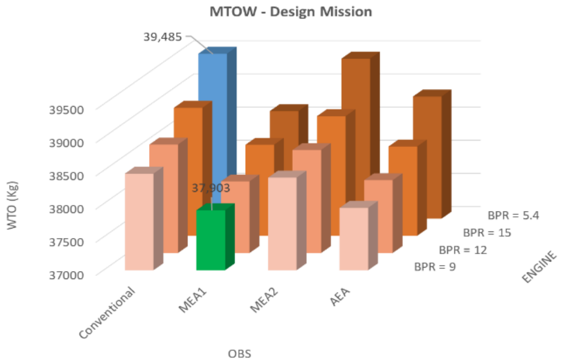

Figure 5 – MTOW vs Engines BPR and OBS architecture, Design mission

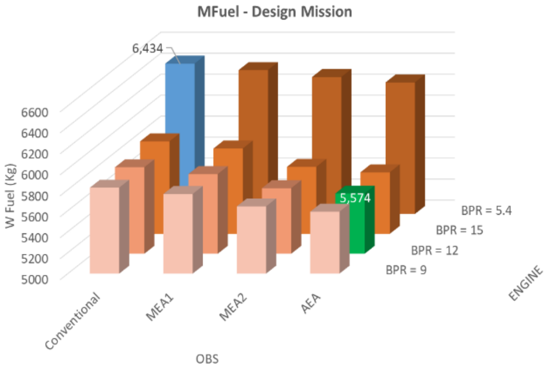

Figure 6 – Fuel mass vs Engines BPR and OBS architecture, Design mission

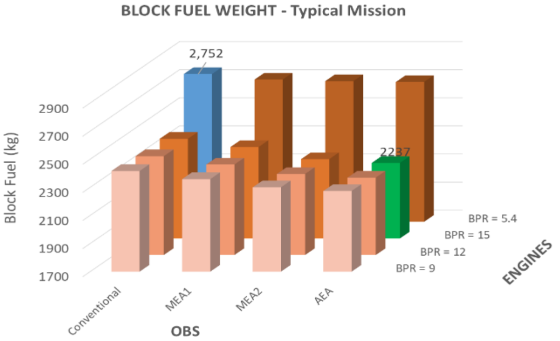

Figure 7 – Block fuel vs Engines BPR and OBS architecture, Typical mission

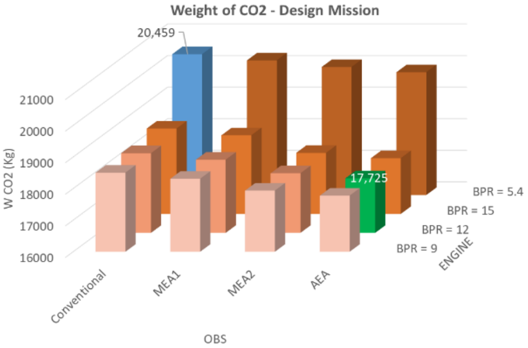

Figure 8 – CO_2 Emissions vs Engines BPR and OBS architecture, Typical mission

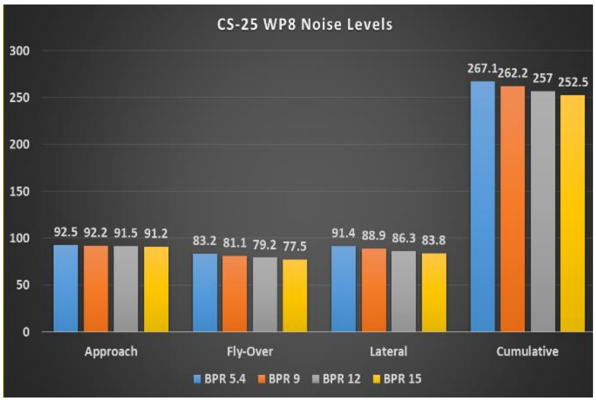

Figure 9 – Certification Noise vs Engines BPR; (OBS effects is negligible at this stage)

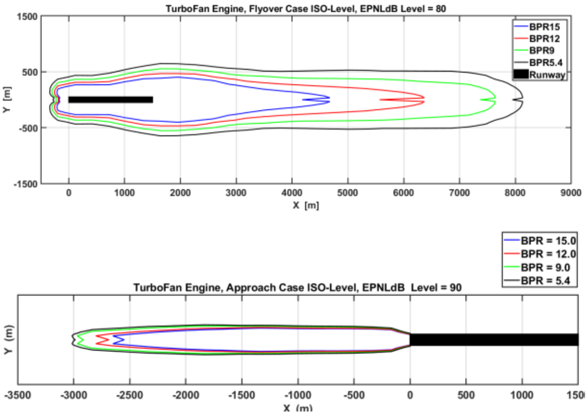

Figure 10 – Noise footprint vs Engines BPR; (OBS effects is negligible at this stage)

3.2 Retrofitting costs

Costs due to retrofitting coming from 3 items:

1. Development costs
    a. Engineering
    b. Testing
    c. Others
2. Conversion costs
3. Equipment costs

Depending on the *retrofitting packages*, these aliquots must be detailed and are computed using a bottom-up approach based on the industrial experience. This is necessary to account costs otherwise neglected. The total retrofitting costs will be the sum of the three parts, actualized for learning curves and equipment discounts, mainly depending on the number of aircraft to be retrofitted.

3.2.1 Development Costs. These costs are intrinsically *non-recurring* costs and they come from three main items: engineering, testing and other costs. In the engine, OBS and engine + OBS the following percentage have been computed: 288Mln. € for complete engine+OBS retrofitting, about 128Mln. € for engine retrofitting and about 194Mln. € for OBS retrofitting, as shown in Figure 11, Figure 12 and Figure 13. Results show that the impact of OBS retrofitting acts on whole aircraft, requiring more time and more costs respect the only engine retrofitting. These costs must be distributed on the number of aircraft (fleet) to be retrofitted: higher is the number of aircraft and lower will be the impact.

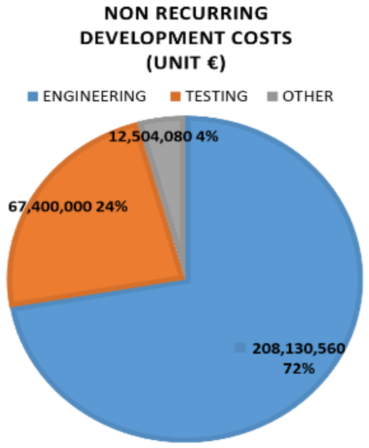

Figure 11 – Development costs to retrofit engine+OBS; Total Costs = 288 Mln €

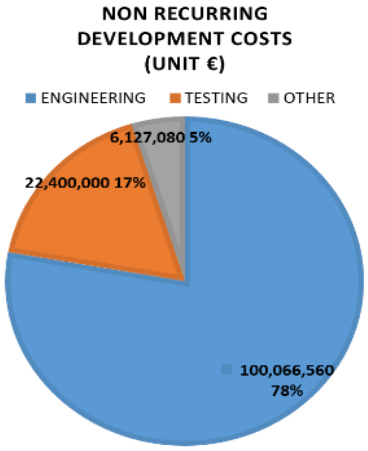

Figure 12 – Development costs to retrofit engine; Total Costs = 128 Mln €

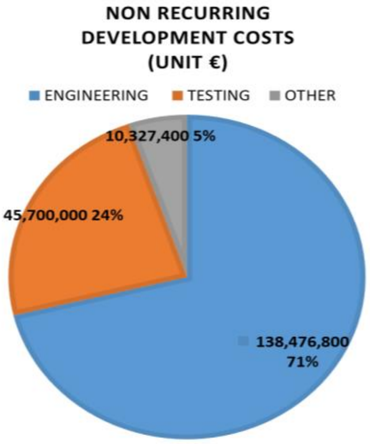

Figure 13 – Development costs to retrofit OBS; Total Costs = 194 Mln €

3.2.2 *Conversion Costs.* Conversion costs represent costs associated to overall activities, materials, and others to perform the retrofitting. They are mainly due to employers' man/hours due to remove, modify and install the new equipment's. In the conversion costs are considered also costs (non-recurring) such as all the needed equipment, instruments, and others to really perform in an assembly line the process (assembly stairs, instruments, etc).

Table 2. Overall Conversion costs

Conversion costs	**(Mln €)**
Engine	6.55 €
OBS	7.93 €
Engine + OBS	14.48€

3.2.3 *Equipment Costs.* Equipment costs are on the most challenging costs' items to be estimated. For the purposes of this paper two different approaches have been used: engine unit price has been estimated accordingly to a statistics regression based on public available data; OBS price has been assumed used the method suggested by [14] mainly based on on-board-system weight. Depending on the number of aircraft to be retrofitted a discount can be applied to the equipment manufacturer to the OEM which retrofits the aircraft. For the same level of engine static thrust, the effect of advanced engine price is accounted.

Table 3. Aircraft main characteristics

Equipment	**Unit price (Mln €)**
BPR = 5.4	2.5€
BPR = 9.0	6.7€
BPR = 12.0	7.1€
BPR = 15.0	7.6€
MEA1	7.5€
MEA2	8.4€
AEA	8.3€
OTHERS	1.7€

3.3 Capital costs and revenue. Once all the retrofitting cost have been calculated, it is possible to make an estimation of the year expenses due to the activity for a single aircraft. This value is dependent on the dimension of the retrofitted fleet. Development cost are distributed over the number of aircraft. Conversion cost are affected by a learning curve considered to estimate a reduction in operation time during the advance in activities. Equipment cost are multiplied by an agreement factor that take into account for possible discount on the final equipment selling price. In order to make a comparison between incurred cost and related benefits, an estimation on annual revenue is also computed. New engine and OBS architecture ensure to the aircraft a higher efficiency, by consequence, after their installation, fuel and emission reduction brings to a decrease in cost and taxes. Also, a reduction in maintenance cost is considered. In Table *4* an example of capital cost and revenue breakdown is presented. 10 years of aircraft utilization are considered. Results are referred to the installation of a geared turbofan with BPR = 12 and AEA system architecture.

4. *Conclusions.*

The impact of an engine and on-board-system replacement and modernization process on a regional jet platform has been presented. AGILE 4.0 architectural framework gave the possibility to set-up an automatic workflow able to compute effects on performance and costs of such a retrofit process. From the performance point of view, all the retrofit activities considered are greatly convenient. A significant reduction in fuel consumption, emission and noise generated during the flight are obtained. By contrast, the expenses saved thanks to this upgrade does not overcome the investment required to carry on all retrofitting activity. Government incentives such as lower landing fees, lower flying restriction (for example limitation in night flights) and increased slots could be some possible bonus that would economically encourage the aircraft and engine manufacturer to undertake a retrofitting activity. Final remark is on the Fuel price: it has been today actualized at 1.46 $/gal (around 0.48 €/kg); to reach a breakeven point fuel price must be three times the actual value.

Table 4. Capital Cost and Revenue

NUMBER AIRCRAFT	**300**			**500**			**700**		
RETROFIT type	**ENGINE***	**OBS§**	**ENGINE*+ OBS§**	**ENGINE***	**OBS§**	**ENGINE*+ OBS§**	**ENGINE***	**OBS§**	**ENGINE*+ OBS§**
CAPITAL COSTS (Ml€) Per Aircraft	14.952	12.008	26.846	13.230	10.760	23.922	13.026	10.491	23.468
CAPITAL COSTS per Year (Ml€) per Aircraft	1.495	1.201	2.685	1.323	1.076	2.392	1.303	1.049	2.347
Development	0.427	0.647	0.960	0.256	0.388	0.576	0.183	0.277	0.411
Conversion	4.585	5.551	10.136	4.454	5.392	9.846	4.323	5.234	9.557
Equipment	9.940	5.810	15.750	8.520	4.980	13.500	8.520	4.980	13.500
REVENUE(Ml€) Per Aircraft	0.554	0.256	0.863	0.554	0.256	0.863	0.554	0.256	0.863
Fuelς	0.422	0.069	0.605	0.422	0.069	0.605	0.422	0.069	0.605
Emissions	0.00052	0.00039	0.00096	0.00052	0.00039	0.00096	0.00052	0.00039	0.00096
Noise	0.00775	0.00016	0.00783	0.00775	0.00016	0.00783	0.00775	0.00016	0.00783
Maintanance#	0.125	0.187	0.249	0.125	0.187	0.249	0.125	0.187	0.249
CAPITAL - REVENUE	0.941	0.945	1.821	0.769	0.820	1.529	0.748	0.793	1.484

**ENGINE BPR=12; § AEA OBS Architecture; #-5%, -7.5%, -10%; ςFuel price = 1.46 $/gallons*

5. References

[1] AirInsight 2016 Embraer E-Jets E2 Building on Success, **ISBN: 1539631583**

[2] IATA Aircraft Technology Roadmap to 2050 2019

[3] Pickar C F 2021 It’s about time: Toward realistic acquisition schedule estimates Tech. Rep. Acquisition Research Program **NPS-PM-21-037**

[4] Baalbergen E, D2.5 – Report on Technology Inventory *Reduced Emissions of Transport aircraft Operations by Fleetwise Implementation of new Technology RETROFIT* **GA: 265867**

[5] Jesse E, Van Aart P, Kos, J D4.2 – Cost-benefit studies of possible future retrofit programmes Reduced Emissions of Transport aircraft Operations by Fleetwise Implementation of new Technology RETROFIT **GA: 265867**

[6] IATA Cabin interior retrofits and entry into service program. Best practices guide February 2019

[7] Ciampa P, Nagel B, La Rocca G, A mbse approach to mdao systems for the development of complex products. vol. 2020-3150. Virtual: **AIAA Aviation**, 2020, URL:https://zenodo.org/record/4046434. doi:10.2514/6.2020-3150.21

[8] Ciampa P. and Nagel B. Streamlining Cross-Organizational Aircraft Development Processes: an Overview of the AGILE Project, ICAS 2018, Belo Horizonte, Brazil

[9] Ciampa, P D; Moerland, E; Seider, D; Baalbergen, E; Lombardi, R; D'Ippolito, R, “A collaborative Architecture supporting AGILE Design of Complex Aeronautics Products.” AIAA Aviation 2017, AIAA Paper 2017-4138, Denver, USA, 2017.

[10] Baalbergen, E., Moerland, E., Lammen, W., Ciampa, P. D., “Methods Supporting the efficient Collaborative Design of Future Aircraft”. Paper 844, 6th CEAS Air & Space Conference Aerospace Europe, Bucharest, Romania, 2017.

[11] ICAO Annex 16, “Environmental Protection, Volume I – Aircraft Noise”, International Standards and Recommended Practices, Fifth edition, July 2008.

[12] FAR-36, “Noise standards: Aircraft type and airworthiness certification”, Code of Federal Regulations, January 2003.

[13] Casale, C., Polito, T., Trifari, V., Di Stasio, M., Della Vecchia, P., Nicolosi, F., Marulo, F., Implementation of a Noise Prediction Software for Civil Aircraft Application, AIDAA XXV International Congress, 9-12 September 2019, Rome, Italy

[14] B. W. Kimoto D. P. Marsh M. N. Beltramo, D. L. Trapp. Parametric study of transport aircraft systems cost and weight. Tech. Rep. NASA CR 151970, Science Application, Inc., Los Angeles, California, April 1977.

[15] Association of European Airlines. Short-Medium range aircraft – AEA requirements. December 1989.

Acknowledgments

The research presented in this paper has been performed in the framework of the AGILE 4.0 project (Towards Cyber-physical Collaborative Aircraft Development) and has received funding from the European Union Horizon 2020 Programme under grant agreement n◦ 815122.