UNIVERSITÀ DEGLI STUDI DI NAPOLI
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Cost Modelling in Collaborative Aircraft Design: A Retrofitting Cost Estimation Methodology

Relatore:
Prof. Pierluigi Della Vecchia

Correlatori:
Ing. Massimo Mandorino
Ing. Giovanni Cerino

Candidato:
Ilaria Sorrentino
M53001026

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To my Father

Abstract

Analysis of scenario

Collaborative aircraft design is a process where the product is designed through close collaboration of designers from several disciplines usually co-dependent. A substantial part of the cost of a new product is committed in the early design phase, therefore, cost modelling should be integrated into the multidisciplinary design process to attain longer-timescale and cost-effective projects. The aviation industry needs innovative solutions, disruptive technologies to make economic growth compatible with sustainability and environmental constraints in terms of new noise rules, emission trading and increasing fuel prices. The main thesis motivation is to assess a cost estimation methodology for aircraft retrofitting at industrial level. The thesis is the result of a collaboration between University of Naples Federico II and the Leonardo Company - Aerostructure Division in the framework of the AGILE 4.0 research project.

Statement of the problem

This work focuses on the preliminary aircraft design estimation of non-recurring, recurring and operating costs through an automated Python-based workflow. Therefore, the implementation of the process aims to investigate the cost effectiveness and benefits of implementing new technologies into the existing fleet of commercial aircraft. The agreed retrofit technologies can be categorised in more fuel-efficient engines with high bypass ratio and more electric on-board systems architectures.

Adopted methodology

Acquisition and operating costs estimations are computed through tools provided by Leonardo Company while the retrofit activity is simulated with a dedicated tool. The modules are integrated in the DLR's engineering framework RCE using CPACS XML-based data format. A methodology to estimate the effects on the performances of a partial or total electrification of the on-board systems (OBS) architecture coupled with the installation of high bypass ratio engines on an existing fleet is developed.

Main results

More Electric Aircraft (MEA) and All Electric Aircraft (AEA) concepts are contemplated. Three advanced OBS architectures (MEA1, MEA2, AEA) and three bypass ratios engines (9, 12, 15) are the candidate retrofit technologies. Considering the typical mission, the installation of engines with BPR = 15 brings to an 8% reduction of Direct Operating Costs (DOC) per flight with 12% less fuel consumed and a 12% reduction of CO2 mass emitted. The Model Based System Engineering (MBSE) technology allows to visualize the stakeholders, activities and entities involved in the retrofit program. The cost analysis process is applied starting from the conventional aircraft configuration (baseline), a regional turbofan designed during AGILE 4.0 project, and moving towards more innovative architectures.

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Acronyms

DLR	German Aerospace Center
LCC	Life Cycle Cost
RDTE	Research, Development, Test, Evaluation
RC	Recurring Costs
NRC	Non-Recurring Costs
DOC	Direct Operating Costs
IOC	Indirect Operating Costs
CER	Cost Estimating Relationship
WER	Weight Estimating Relationship
DAPCA	Development and Procurement Costs of Aircraft
NASA	National Aeronautics and Space Administration
ATA	Air Transportation Association of America
AEA	Association of European Airlines
ICAO	International Civil Aviation Organization
ADP	Aircraft Delivery Price
TI	Total Investment
TNAC	Transport Aircraft Noise Classification
ECAC	European Civil Aviation Conference
LAQ	Local Air Quality
LTO	Landing and Take-off
ERLIG	Emission Related Landing Charges Investigation
IATA	International Air Transportation Association
UHBR	Ultra High Bypass Ratio
MBSE	Model-Based System Engineering
GE	General Electric Company
SNECMA	Société Nationale d'Étude et de Construction de Moteurs d'Aviation
NEO	New Engine Option
CEO	Current Engine Option
MEA	More Electric Aircraft
AEA	All Electric Aircraft
APU	Auxiliary Power Unit
MRO	Maintenance Repair and Overhaul
BPR	Bypass Ratio
OBS	On-Board System
FAA	Federal Aviation Authority
SFC	Specific Fuel Consumption
OEM	Original Equipment Manufacturer
FCS	Flight Control System
ECS	Environmental Control System
WIPS	Wing Ice Protection System
AC	Alternating Current

Acronyms

$FADEC$	Full Authority Digital Engine Control
AFM	Aircraft Flight Manual
$FCOM$	Flight Crew Operating Manual
WBM	Weight and Balance Manual
CFD	Computational Fluid Dynamics
$PACK$	Pressurization Air Conditioning Kit
DOE	Design Of Experiments
MDO	Multidisciplinary Design Optimization
$MDAO$	Multidisciplinary Design Analysis and Optimization
$CPACS$	Common Parametric Aircraft Configuration Schema
XML	Extensible Markup Language
RCE	Remote Component Environment
$PIDO$	Process Integration and Design Optimization
GUI	Graphical User Interface

Glossary

NO_x	Nitrogen Oxides	-
CO	Carbon Oxide	-
S	Wing Surface	m^2
b	Wing Span	m
AR	Aspect Ratio	-
MAC	Mean Aerodynamic Chord	m
l_f	Fuselage Lenght	m
$MTOM$	Maximum Take Off Mass	kg
OEM	Operative Empty Mass	kg
PL	Payload Mass	kg
m_{fuel}	Fuel mass	kg
m_{oper}	Operational Items mass	kg

1
Introduction

Contents

1.1 Motivation

This Master's thesis is the result of a collaboration between the University of Naples Federico II and the Leonardo Company - Aerostructure Division in the framework of Horizon 2020 AGILE 4.0 research project. The aim is to assess a cost estimation methodology for aircraft retrofitting at industrial level. This work focuses on the cost analysis during preliminary aircraft design carried out through the development of a methodology to be integrated into a collaborative remote workflow. Therefore, the implementation of the automated process aims to investigate the cost effectiveness of retrofitting new technical solutions into the fleet of commercial aircraft.

A substantial part of the cost of a new product is committed in the early design phase, therefore, cost modeling should be integrated into the multidisciplinary design process together with other analyses to attain longer-timescale projects and programs. Through a multidisciplinary design optimization, the key factor is the product definition (the aircraft system) to trade-off on cost and performance.

The aviation industry needs highly innovative solutions, disruptive technologies and other step-changing approaches to face challenges such as new noise rules, new safety and security demands, emission trading, increasing fuel prices. The development of innovative technologies can be achieved through integration and optimization on system-level of simulations with the appropriate level of fidelity. Research into the application of collaborative MDAO (Multidisciplinary Design Analysis and Optimization), have been a point of focus in projects such as AGILE, a European program which targets significant reductions in aircraft development costs and time to market, leading to more cost-effective and greener aircraft solutions. After that, AGILE 4.0 project is born in order to significantly extends the first project scope adding manufacturing, maintenance, and certification aspects and extending the aircraft product optimization to the entire life cycle and addressing the extensive aeronautical supply chain.

1.2 AGILE 4.0 Project

AGILE 4.0 project [1] is the successor to the Horizon 2020 project AGILE (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts), coordinated by the German Aerospace Center (DLR). The objective is to significantly reduce the cost of aircraft development and the time required for this process.

One major challenge is to make the aircraft industry able to comply with economic growth with sustainability and environmental impact, while remaining competitive and innovative. The high level objective of the project is to connect all the people, skills and technologies involved in in the collaborative, multi-national and cross organizational aeronautics processes, by means of an integrated cyber-physical aeronautical supply chain, during the entire life-cycle of the product. The composition of the AGILE 4.0 consortium and capabilities available enables to address realistic development scenarios integrating multiple stakeholders and covering all the aspects of the development of complex aeronautical systems.

1.3 Thesis Framework

The thesis is made up of four main chapters:

Chapter 1 focuses on the description of the thesis motivation and the context in which the work has been developed. Therefore an overview of European AGILE 4.0 project is exposed.

Chapter 2 provides an idea of the importance of cost estimation at the early aircraft design stage. Starting from an overview of the Life Cycle Cost, the state of the art of methodologies for LCC components calculation is provided. The last part of this chapter deals with the principal application of this work: the retrofit activity. Therefore, the rational behind the choice to perform changes in aircraft technology to benefit from both environmental impact and better flight operation is illustrated.

Chapter 3 presents the development of a methodology for the generation of a cost estimation approach for preliminary aircraft design in a multidisciplinary environment. A description and validation of already existing tools for the estimation of production and operating costs is provided. The focus is then shifted on the method developed to estimate the costs associated to a retrofit program with a detailed description of the activities and processes involved in it.

Chapter 4 presents the application of the automated cost process in the distributed design environment. The process is applied starting from the conventional aircraft configuration, a regional turbofan designed during AGILE 4.0 project, and moving towards more innovative architectures. The objective is to estimate the effects of a partial or total electrification of the on-board systems architecture coupled with the installation of high bypass ratio engines on an existing fleet.

2
Aircraft Costs

Contents

2.1 Cost Estimation during Aircraft Design

Aircraft design strategy is constantly changing. The industry now is costumer-driven with the objective to reduce manufacturing costs. Cost-consciousness starts in the conceptual design phase to ensure competitive success. For the designers, it is important to have the right cost evaluation just from the initial phase of the project because this is the point in which crucial decisions, with the highest effect on the total committed costs, are taken. In order to prove that a design is cost efficient the Life Cycle Cost (LCC) needs to be analyzed and should be done as early in the design phase as possible. Life Cycle Cost is the total cost associated with an aircraft from inception through leaving service at the end of its life.

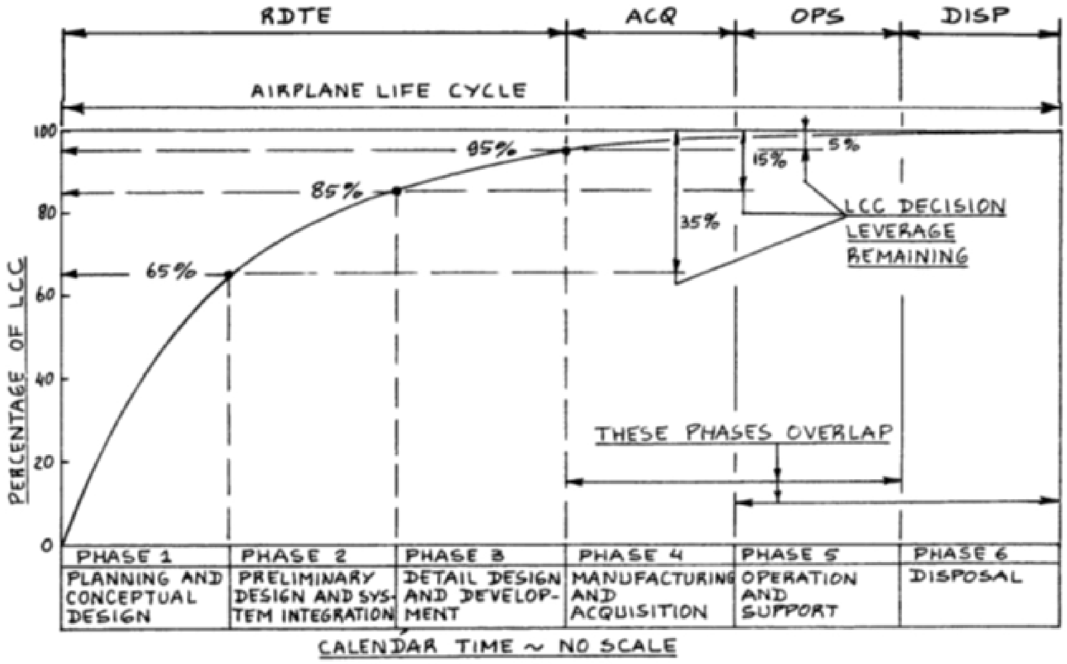


Figure 2.1: Impact of Airplane Program Phases on Life-Cycle Cost [2].

Fig. 2.1 shows the relationship between the LCC components and the aircraft design phases. The importance of LCC assessment during the conceptual design phase results from the fact that around 65% of the total LCC of an aircraft is determined by the end of the conceptual design phase (see Fig.2.1). Thus, the inclusion of LCC assessment in the conceptual design process is essential to capture the cost impact of design changes. Therefore, after the preliminary design phase, already 85% of the total LCC is locked in. For preliminary cost estimating purposes, the LCC of airplane program is divided into four categories:

1. Research, Development, Test and Evaluation (RDTE) costs; (Phase 1,2,3)
2. Production costs (Phase 4)
3. Operation costs (Phase 5)
4. Disposal costs (Phase 6)

Two primary components of the system life cycle can be identified: acquisition and operating costs. Acquisition cost is composed of research, development, testing, evaluation and production costs, it is primarily associated with the manufacturer.

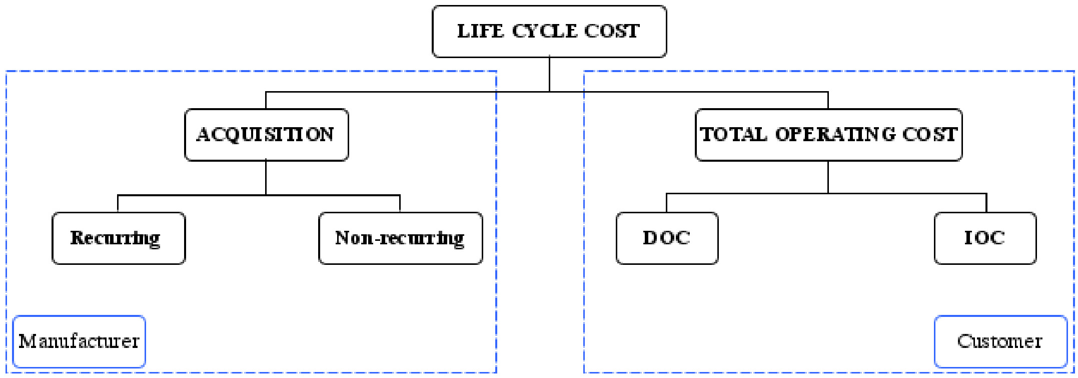


Figure 2.2: Life Cycle Cost categorization.

Another useful way to look at the acquisition costs is to classify them into recurring and non-recurring costs, as done in this thesis. Operating cost includes Direct Operating Cost (DOC) and Indirect Operating Cost (IOC), it is associated with the costumer or airline. In Fig. 2.2 it is shown the LCC cost categorization adopted in this work.

The motivation to estimate costs is to assist decision making and cost management, enabling the designers to find the best cost-function trade-offs during the conceptual design phase. However, cost modeling tools are required to guide cross-functional and multi-disciplinary teams in decision making, although it is widely acknowledged that it is extremely difficult to obtain fast and accurate estimates [3]. A cost estimation is more precise as the project moves forward since during the design process, the full specifications of a product are not known, and hence, it is challenging to produce a precise estimate. However, manufacturer experiences on costs estimation can be modelled and applied in the early stages of the design, leveraging to the best cost-design solution.

Chapter 4 explains these cost modelling tools from industrial perspective, highlighting how they are useful to examine the effects of retrofitting an existing aircraft product aiming to better fuel efficiency, reliability always paying the attention on costs.

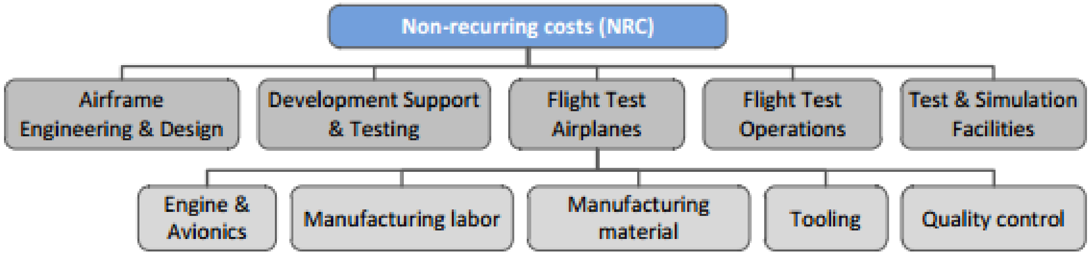


Figure 2.3: Cost components of non-recurring costs [5].

2.2 From the Perspective of the Aircraft Manufacturer

2.2.1 Recurring and Non-recurring

The main aircraft manufacturer costs classification is into recurring non-recurring costs (see 2.1).

Non-Recurring costs. They include any costs of Research, Development, Testing and Evaluation (RDTE) efforts. A non-recurring cost is generally a capital expenditure, it is sustained prior to the first unit of production and only once in the life cycle of a work activity. Examples of non-recurring costs can include pre-production activities, tool development, engineering models built for test purposes [4], Lammering et. al. [5] propose the non-recurring cost breakdown shown in Fig. 2.3.

Recurring costs. These costs occur throughout a programme's life and arise due to the repetitive nature of production costs. Examples of recurring costs include cost of raw material, tool maintenance, labor costs. It must be pointed out that the recurring costs per product unit should reduce with the production quantity increasing.

In the context of re-engine programs, or in general in a retrofitting, non-recurring costs are associated to systems engineering while recurring costs would include the unit cost of new engines (or in general a components to be retrofitted).

2.2.2 Overview of Different Modelling Approaches

The cost estimating methodology of a project is usually a combination of methods used in particular stage of life cycle and any estimates obtained from one approach need to be crosschecked by others.

Several cost modeling approaches are used in aerospace industry, most of the existing models can be directly associated with one of these three different methods: è corretto? analogical, bottom-up (analytical) and parametric techniques [6].

- **Analogy based cost estimation techniques**. Analogy based cost estimation techniques employ similarity criteria based on historical cost data for products with known costs [7]. Costs of the actual project are estimated looking at the similarities and differences with similar cases with the assumption that similar products have comparable costs. In conceptual design stage, there is no sufficient historical data to develop a statistically valid parametric estimating model; or no enough available information, time, or resources to conduct an engineering estimate. The technique depends in the user's judgment to identify the analogousness and differences between the two cases.
- **Bottom-up cost estimation techniques**. Bottom-up cost estimation techniques, as the name suggests, require the decomposition of the production cycle into work steps and the determination of the final cost as a summation of all these components. An important drawback of the engineering bottom-up approach is the great amount of required product details, it is needed an expert knowledge and effort to create an estimation. It is applied when detailed design data is available so that it is often used in production stage, after design is frozen and released. It does not allow the cost to be computed at very early stages of design [4].
- **Parametric cost estimation techniques**. Parametric cost estimation techniques consist of applying statistical methodologies expressing the cost as a function of different independent variables. The resultant relationships are often called "Cost Estimating Relationships" (CERs). The CERs illuminate how and how much a product's physical characteristics and properties affect its cost. This approach has several applications in different industries, the key is to identify the exact "Cost Drivers". Parametric cost estimating is based on historical data to develop the CERs. That is the reason why it is also called

Approach	Advantages	Disadvantages
Bottom-up	Cause and effect understood Very detailed estimate	Difficult to develop and implement Substantial, detailed expert data are required Requires expert knowledge
Analogy	Cause and effect understood More easily applied than the bottom-up method	Appropriate baseline must exist Substantial, detailed data are required Requires expert knowledge
Parametric	Easiest to implement Non-technical experts can apply method Uncertainty of the forecast is generated Allows scope for quantifying risk	Can be difficult to develop Factors might be associative but not causative (i.e. lack of direct cause-and-effect relationships) Extrapolation of existing data to forecast the future, which might include radical technological changes, might not be properly forecast

Table 2.1: Comparative assessment for cost estimating methods [8].

statistical estimating. The database of estimating will influence the accuracy and reliability of results. With limited information at early stages, parametric approach has its merit, and it is the preferred approach for developing cost estimates until actual cost data are available.

Table 2.1 summarises the advantages and disadvantages associated with each of the three approaches [8]. However, it is very difficult generally within aerospace to gain access to well documented costing data. Fig. 2.4 shows the relation between the cost model types and their uses today in the phases of the design timeline.

As the program progresses, the level of detail of the information about the product increases and so the cost estimates accuracy improves. According to Asiedu [10], the cost estimates at the Conceptual Design Phase have a - 30 to +50% accuracy while at the Detail Design Phase cost estimates should be within - 5 to +15%. Good estimations result in the most economical project cost, this can be understood by Fig. 2.5. Inaccurate estimates can increase the cost of a product

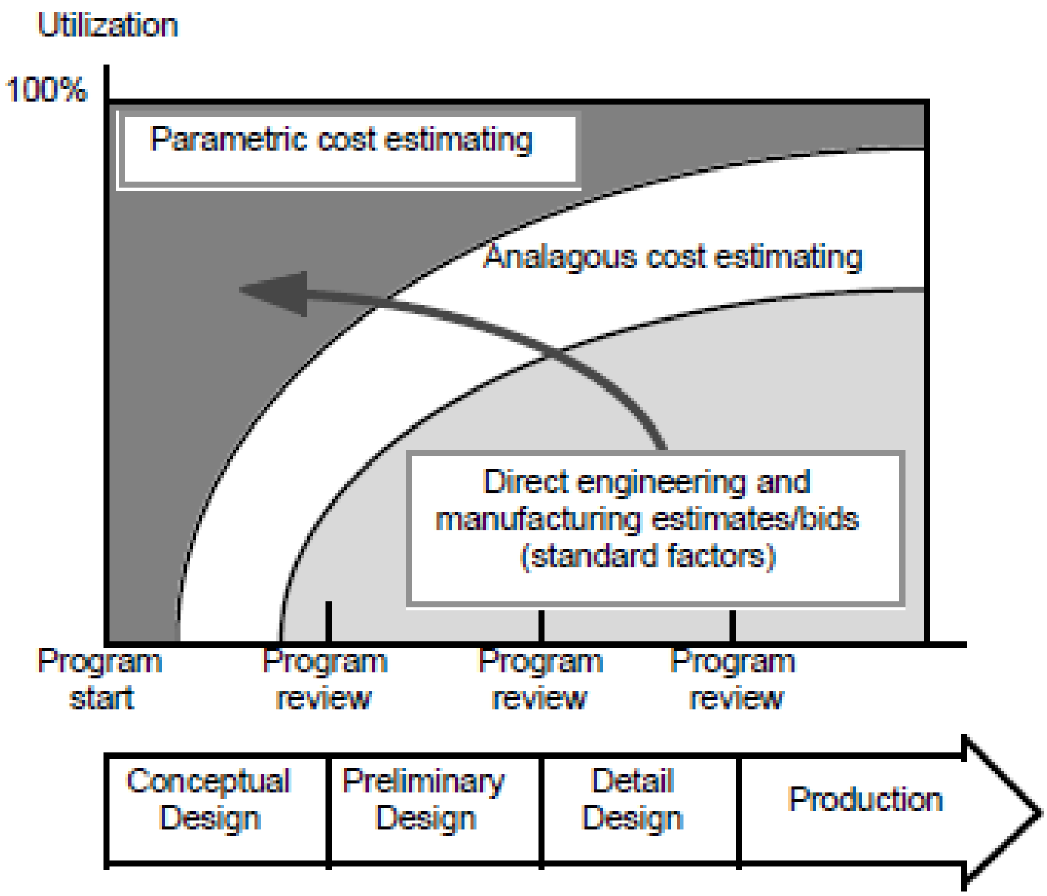


Figure 2.4: Cost Estimating Methods vs. Program Phase [9].

project because underestimates will cause reorganization, re-planning [11] while overestimates will led to a waste of monetary resources.

2.2.3 Parametric Equations for Estimating Aircraft Costs

A lot of the available development and production cost estimating methods in literature are CERs, and so, based on the third technique presented in section 2.2.2. RAND Corporation developed many aircraft parametric cost models mainly for acquisition of military aircraft. A set of CERs for conceptual aircraft design developed by RAND Corporation [13] is known as “DAPCA IV” (Development and Procurement Costs of Aircaft). The relationships are obtained using cost data gathered from airframe manufacturers and from other US Department of Defense references. Since the data is gathered from military programs, the models are more

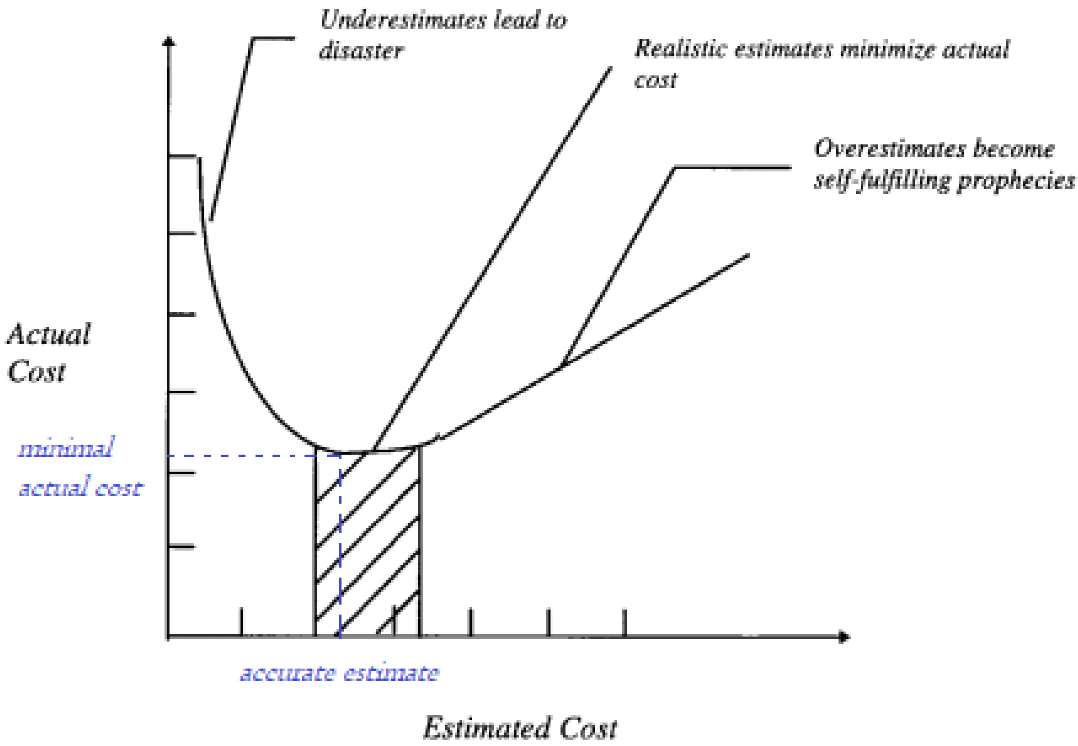


Figure 2.5: Achieving minimal cost with accurate estimating [12].

suitable to calculate the cost of military aircraft and not so much for commercial ones. Many cost models are based on RAND's achievements so that they are quite similar in form. The National Aeronautics and Space Administration (NASA) has sponsored a study done by Kimoto et al. [14] to determine parametric cost estimating relationships for commercial and military transport aircraft. The Cost Driver for this method is the weight while the model developed by RAND indicates the speed as a significant independent variable for estimating aircraft costs. Apart from the CERs, in this NASA report Weight Estimating Relationships (WERs) are also developed, which can be used when there is a lack of information on some systems' weight. These CERs and WERs were derived from a sample of 26 transport aircraft, 17 of which were commercial aircraft and the other 9 military ones, unlike DAPCA reports, which use only military aircraft and with various mission types. The flexibility of these models makes them applicable to be used for any year by applying a simple inflation factor. The tool presented in this work used to estimate design, development and production costs is based on the technique explained in

NASA CR151970 report [14]. The cost estimating relationships, on which *NR Cost* tool (explained in the details in section 3.2) is based, are for recurring production costs and do not include the engine cost. So engine unit price should be known or estimated in different way.

Recurring Costs for each unit include the following cost items:

- **Airframe Production Costs**. Airframe Production Costs are estimated by *NR Cost* tool through the CERs presented in NASA report. Such costs are listed in Tab. 2.2, the percentages are approximate and may vary significantly for specific designs.
- **Powerplant Cost**.
- **Avionics Cost**.
- **Armaments Cost**.
- **Operational Items Cost**.

Non-Recurring Costs for each unit include the following cost items:

- **Design, Engineering and Development Support Cost**.
- **Flight Tests Cost**.
- **Tooling Cost**. It is a measure of tooling cost reduction due to technology improvements since 1970, date of the cost formulation.
- **Test Articles Cost**.
- **Pre-Series Cost**.
- **Other Cost**.

An example of break down of the Unit Price of the Aircraft, one of the main outputs of *NRCost* tool, is shown in Fig. 2.6. Recurring costs occupy about 70 percent of the final aircraft price, this percentage is influenced a lot by the learning curve rate. Non-recurring costs allocated to each aircraft produced vary significantly with the number of production units.

The methods just showed are very old, NASA Parametric Study dates back to 1977, different technologies, materials and techniques have emerged and it is obvious that these CERs are not recommended to be used on novel configurations. On the

Cost Element	Percentage of Total Aircraft Cost (%)
Structure 31%	
Wing	10
Tail	2.8
Fuselage	14
Landing Gear	2.0
Pylons	2.2
Propulsion Installation 1.0%	
Engine Installation	0.3
Fuel System	0.7
Systems 15%	
Flight Controls	2.5
Hydraulics	0.8
Electrics	3.0
Air Conditioning	1.5
Anti Icing	0.2
Auxiliary Power Unit	0.4
Furnishings and Equipment	5.1
Instruments	1.6
Avionic Installation	0.2
Total 47%	

Table 2.2: Airframe Production Costs.

other hand, NASA method is still useful for comparison up to an acceptable degree of accuracy.

2.3 From the Perspective of the Operator

2.3.1 Operating Costs

Operating costs (OC) arise during operation after an aircraft is sold, they depend on aircraft cost, which is known when it is purchased and, for this reason, aircraft manufacturing costs are analyzed first, followed by OC analysis. Aircraft Operating Costs can be grouped into two main categories which are Direct Operating Costs (DOC) and Indirect Operating Costs (IOC).

- **DOC**. Direct Operating Costs are the operational costs directly involved with

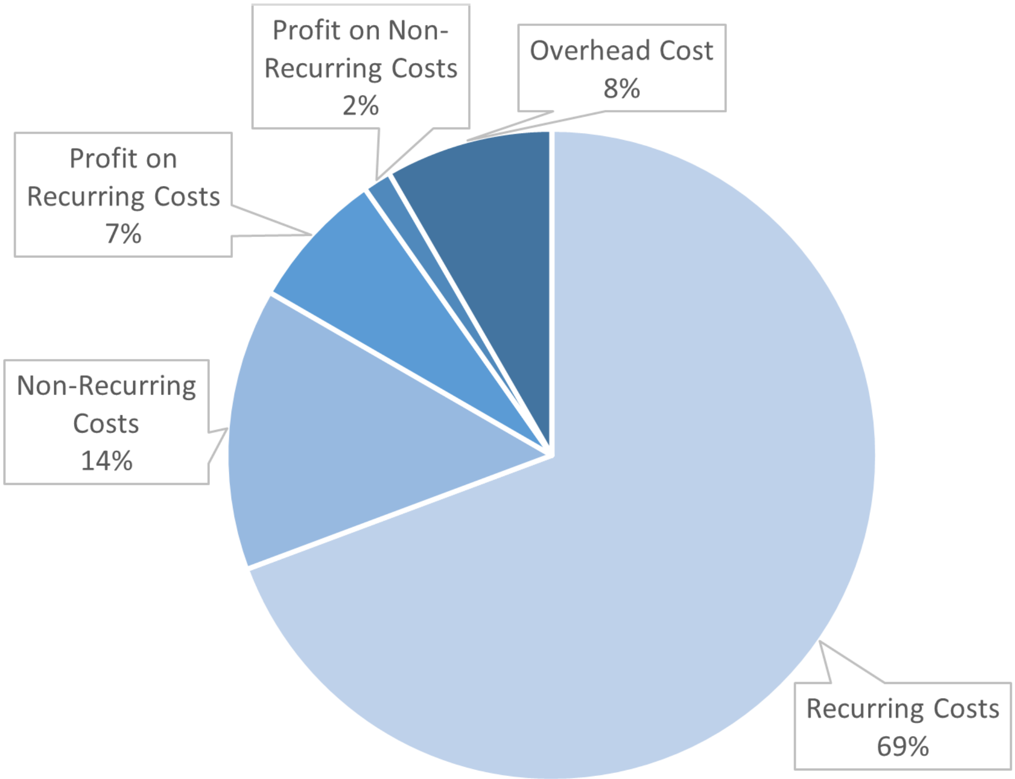


Figure 2.6: Break down of the Unit Price of a Regional Jet.

a mission flown. Such costs consist in capital, fuel, flight crew, cabin crew, maintenance. Furthermore, landing fees, emissions and noise taxes and other government charges (like navigation charges) are nowadays included.

- **IOC**. Indirect Operating Costs are operating expenses that are not directly connected with the aircraft and to its characteristics. IOC are the costs related to the management strategies and level of service of the airline and include items such as training costs, public relations cost expenses, the costs of handling and meals or the costs of maintenance and depreciation of the ground equipment and facilities [15].

IOC is difficult to estimate well, since it depends on the services that the airline (customer) offers, in the state-of-the art methods IOC are usually modelled as a percentage of DOC. Therefore, DOC is useful and widely-used parameter for comparative analysis. Estimation of the Direct Operating Costs (DOC) is an important part of the design process, since it provides a measure of how much it costs to fly an aircraft in a given mission and with a given utilization [16]. Operating Costs are important to be estimated since the manufacturers often cite data regarding DOC in their advertisement material in order to persuade potential customers to purchase their aircraft rather than someone else's. Typically, aircraft manufacturers use standard methodologies in their cost comparisons, while customers (airlines) always generate their own methodologies based on many things, such as fleet size, route structure, procedures [17].

2.3.2 Direct Operating Costs Estimation Methodologies

In 1944, the Air Transportation Association of America (ATA) developed the first method to estimate Direct Operating Costs [18]. Liebeck et al. [19], in a study for NASA, with data on the costs of McDonnell Douglas aircraft in commercial service up to 1993, later developed a method based on the ATA method, named DOC+I method, where the "+I" denotes the addition of the interest costs associated with the financing for the acquisition of the aircraft. In 1989, the Association of European Airlines (AEA) has also drawn a methodology for calculating the DOC [20], in particular there is one method for Short and Medium Range Aircraft and another one applicable to Long Range Aircraft. These methodologies depend initially on estimating aircraft price, as already stated in section 2.3.

From Fig. 2.7 it is possible to see the different DOC components (colored boxes) considered by the three methodologies just mentioned. In the figure it is highlighted that in ATA method cabin crew costs, landing fees and navigation fees were considered as part of IOC, Liebeck and AEA incorporated them in the DOC. The AEA method is similar in structure to that developed by Liebeck et al. but with the addition of the ground handling fees. Some DOC components are evaluated in the same way by the three methods but using different coefficients, for example the Insurance costs per year are calculated always as a percentage of the Aircraft Delivery Price (ADP), for the sake of simplicity see Eq. 2.1.

$$C_{ins} = k_{ins} ADP \tag{2.1}$$

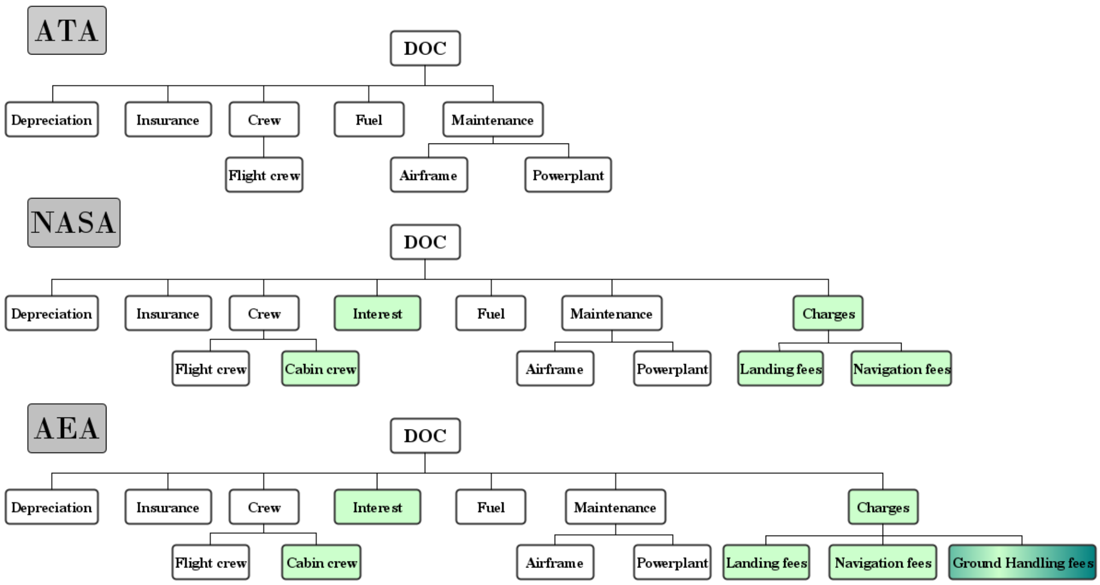


Figure 2.7: DOC components for ATA, NASA and AEA methodologies.

	ATA	NASA	AEA
k_{ins}	0.0023	0.0035	0.0050

Table 2.3: Insurance costs coefficients for ATA, NASA and AEA methodologies.

k_{ins} is listed in Tab. 2.3.

In the following sections, Operating Costs for different Aircraft configurations will be estimated through *AEADOC* tool. As the name suggests, this tool is based on AEA for Short-Medium Range Aircraft methodology, the DOC components considered can be see from Fig. 2.7 with the addition of Noise and Emission charges.

2.3.3 DOC Breakdown

Starting from the left side of the Fig. 2.8, there is a typical TOC breakdown of a commercial transport aircraft. DOC can be split into two macro-categories: Ownership cost (capital cost) and Cash Operating Cost. For commercial aircraft operation, the capital cost contribution to DOC can be around 30-40 percent of the total DOC. It is for this reason that industry is driven to reduce cost of manufacture to minimize as much as possible depreciation, interest and insurance costs. Each DOC cost item is explained in detail in this section. The objective of all commercial air operators is to make a profit, it means that the airlines revenue

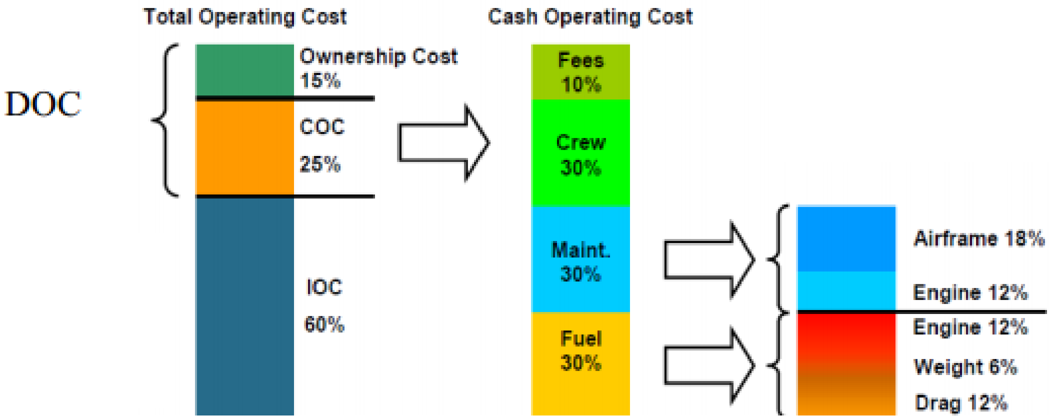


Figure 2.8: Total Operating Cost components [21].

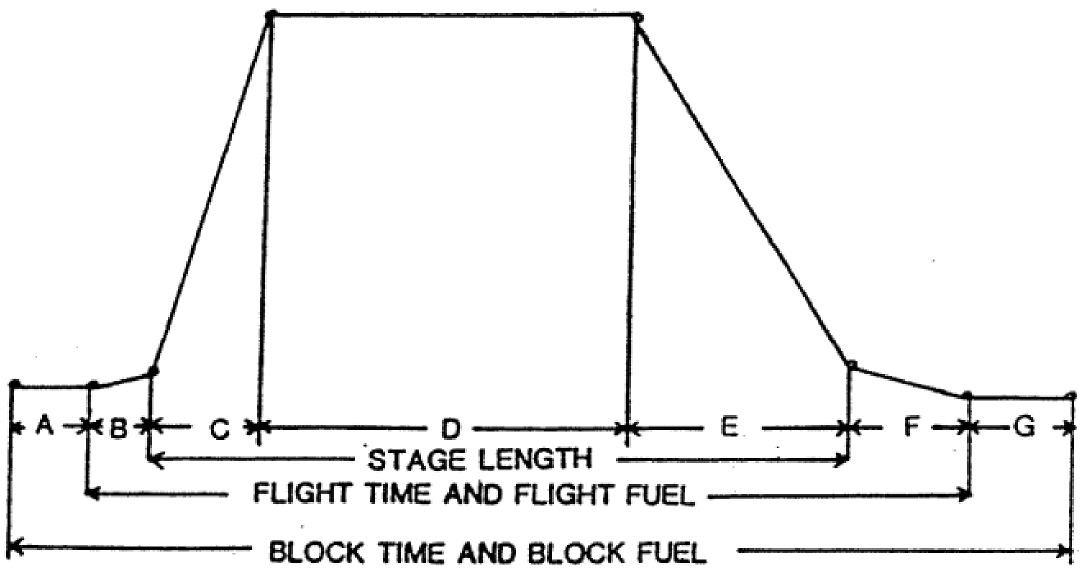


Figure 2.9: Flight profile for DOC estimation according to AEA method [20].

must be greater than the operating costs. Direct Operating Costs depend on the mission flown by the aircraft, a trip for calculating DOC according to AEA 1989 methodology is shown in Fig. 2.9. DOC can be expressed in terms of \$/hour, \$/mile, ¢/seat-mile, this methodology estimates each DOC component in \$/block hour, assuming $Block\ time = Flight\ time + 0.25\ hrs$. The DOC cost items, shown in Fig. 2.7, are briefly analysed.

- **Capital Costs**
  - **Depreciation**. The depreciation corresponds to the reduction in value

of the aircraft over the useful service life. It depends on the Total Investment (TI), obtained as the sum of aircraft delivery price (value known after the manufacturing costs estimation) and the the price of the spares purchased with the aircraft. After the end of use, the item can still be sold at a price equal to its residual value.

  - **Interest**. Most aircraft purchases are financed through the use of long-term debt and a down payment from company funds. Interest charges are difficult to quantify since the agencies apply different fees dependently on the world economic climate, the local exchange rates, the credit standing of the purchaser. This cost also depends on the total investment and it is calculated with the aid of an average interest rate, assumed in this work as a constant value for simplicity.
  - **Insurance**. The most common practice is to pay insurance to insurance companies. These companies evaluate the probability of the failures of the total aircraft system, even if the loss of the airplane could not happen for technical problems (as in the case of terrorism). In the Eq. 2.1 it is showed how this DOC item is estimated.

- **Cash Operating Costs**
  - **Crew Costs**. Crew cost includes the salaries for the cockpit and cabin staff. The approach here applied states that crew cost can be obtained simply by multiplying a proper labour rate Labour Rate by the number of crew members [22]. The methodology is based on the 1989 labour costs and the result must be updated to the current year.
  - **Fuel Costs**. This DOC component can be estimated knowing the fuel price for the year in which the DOC computation in performed. It is published in various statistical works and journals, also IATA website offers an up-to-date valuation.
  - **Maintenance Costs**. In DOC methods, the norm is to differentiate between airframe and engine maintenance costs which are further subdivided into labour and material components. The maintenance of an

aircraft can go from simple transit checks after every flight, which last around 15 minutes to half an hour, to major processes where the aircraft has to be completely taken apart for a thorough inspection of all of its parts [16]. The great variability of the maintenance needed by an aircraft leads to a difficulty in predicting the costs associated. Several aircraft and engine characteristics are necessary and to be taken directly from manufacturer's data (e.g. mass of the airframe, mass of the all the engines, bypass ratio).

- **Charges**. The following fees and charges are considerend in AEA methodology.
  * Landing fees. This DOC component is due to the use of the airfield with its runways and depends essentially on the aircraft weight.
  * Navigation charges. These costs are charged by air traffic authorities of each country to pay for the costs of providing air navigation services, including costs of maintenance, operation, management and administration of the service. The distance flown within a defined area and the aircraft weight are used as measures to quantify the navigation charges.
  * Ground handling charges. This item includes ground services connected, for example with passengers, luggage, parking and starting the aircraft. Other services involved are refuelling, de-icing and maintencance duties. The AEA method supplies a simple equation to take into account this DOC component involving essentially the payload weight.

None of the methods previously introduced considers the taxes associated with noise and emissions, mainly because this is a very recent concern and most of the methods already have a few decades. In this work these additional DOC components are estimated since airlines are interested in making economic growth compatible with sustainability and environmental constraints, while remaining competitive and innovative.

* Noise charges. Noise-related charges are one of several types of airport charge. Guidance on airport charges is provided by the International Civil Aviation Organization (ICAO). States have the flexibility to decide on the method of cost recovery and charging to be used. Any noise-related charges should be associated with the landing fee, possibly by means of surcharges or rebates, and should take into account the noise certification provisions of ICAO Annex 16 [23]. Aircraft's noise levels are measured at three certification points, as shown in Fig. 2.10: Approach, Sideline (Lateral) and Flyover. These noise levels must comply with the ICAO noise Standards. The methodology for noise charges calculation is the one recommended by the Transport Aircraft Noise Classification Group (TNAC) within the European Civil Aviation Conference (ECAC); here, noise charges depend on the aircraft certified noise levels, the noise threshold of the particular airport for departure (T_d) and arrival (T_a) and the unit noise rate at arrivals and departures expressed in $ per EPNdB (Effective Perceived Noise level expressed in decibels).
* Emission charges. Some States may opt to apply emission charges to address LAQ (Local Air Quality) problems at or around airports. It is recommended that the aircraft emissions charges scheme be based on data that most accurately reflect the actual operations of aircraft, as it happens in this document. The pollutants considered in this document are NO_x and CO. The term NO_x is referred to nitrogen oxides, CO stands for carbon oxide. The emission related charges are determined as a function of the mass of emitted polluting substance during Landing and Take-off cycle (LTO). ERLIG (Emissions Related Landing Charges Investigation Group) developed a standardized model to estimate these costs. From Fig. 2.11 it is possible to see airports that apply environmental charges, in order to incentivise the use of quieter or lower-emission aircraft by airlines.

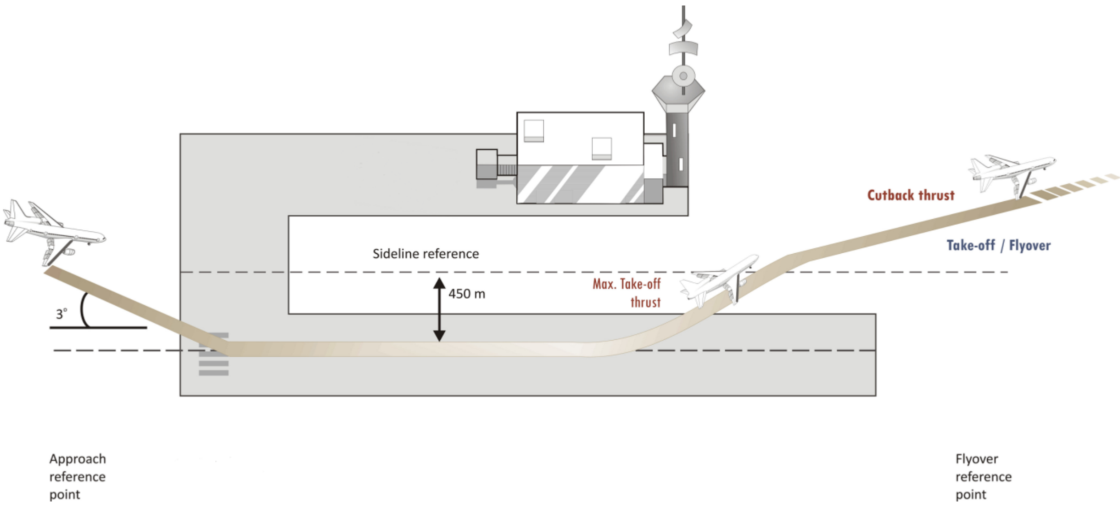


Figure 2.10: Aircraft noise certification reference measurement points [24].

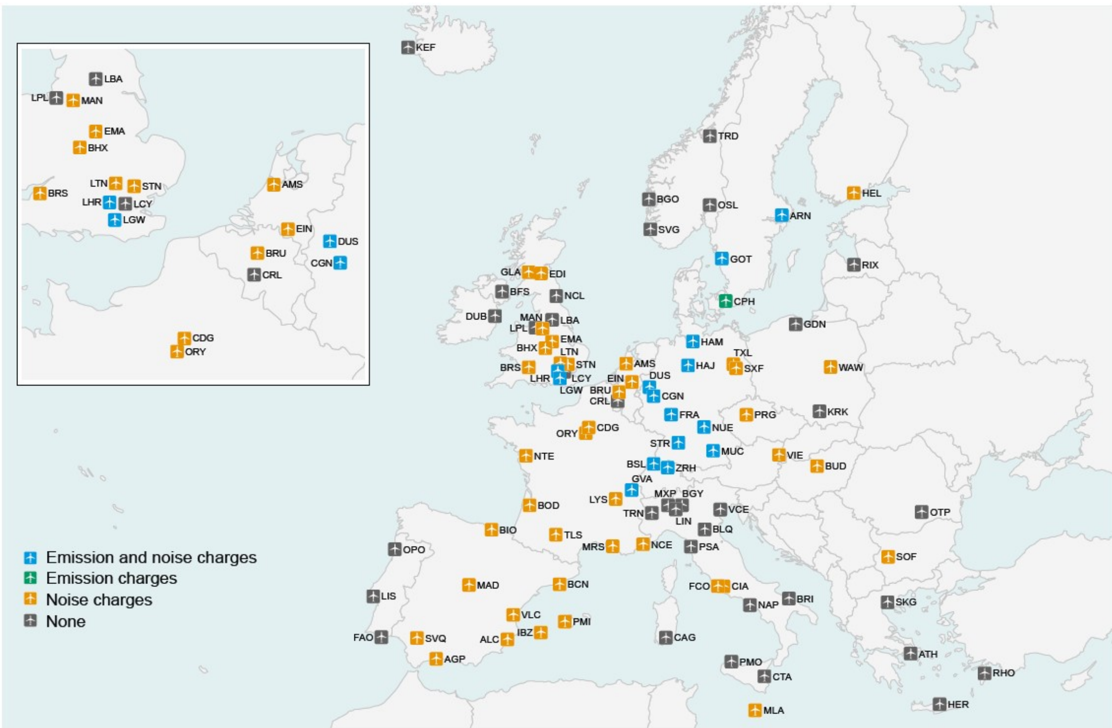


Figure 2.11: Environment related charging schemes at 100 busiest EU28+EFTA airports in terms of flight movements, updated to 2019 [25].

2.4 Retrofit in the Commercial Aircraft Industry

IATA (International Air Transport Association) recognizes the need to address the global challenge of climate change and adopted a set of ambitious targets to mitigate emissions from air transport. To achieve these targets a strong effort is required from all stakeholders of the aviation industry working together on a strategy based on: technology (more fuel-efficient aircraft), efficient aircraft operations, infrastructure improvements and positive economic measures [26].

Airlines are confronted with emission trading, new noise rules, increasing fuel prices, new safety demands, higher passengers' level of comfort [27]. Achieving these goals is a challenging task, several technologies may be retrofitted to existing aircraft with still a long life to serve to reduce emissions and fuel consumption. One engine related technology is the the use of Ultra-high by-pass ratio (UHBR) turbofan, this will lead to a change in conventional jet engine architecture to improve its efficiency to reduce fuel burn [28]. The aviation industry is also investing significant effort in advanced design of onboard equipment to obtain a more efficient use of onboard energy.

In this work the focus will be exclusively on changes in aircraft technology, but the environmental impact can be reduced also through airline's operational procedures, enhanced management of aircraft. In this work the possibilities and attractiveness of retrofitting new technological solutions into an existing fleet of commercial aircraft will be analysed.

2.4.1 Experience with previous Re-engine Programs

The decision of an airline to re-engine aircraft in its fleet implies technical and operational consequences that can be translated into economical consequences. Whatever the change of technology, this will be adopted if the benefits outweigh the cost associated with it. A re-engine program may starts with an engine OEM (Original Equipment Manufacturer) that offers a new engine to an airframe OEM for a current aircraft, or, as usual, an aircraft OEM request to an engine OEM for a more efficient engine. At this point, two options are possible: a retrofit for existing aircraft and new engines for new production aircraft. Retrofits are more common in military programs than in commercial applications, the notable exception is the DC-8 60 series.

In the 1970s, several airlines approached McDonnel Douglas for noise reduction modifications, in 1977 GE/SNECMA (GE Aviation and Safran Aircraft Engines) CFM56-2 high-by pass turbofans engines were selected to replace Pratt Whitney JT3D engines and to power the next generation DC-8's. Grumman Aerospace was contracted to supply engine nacelles and the redesigned pylons that were required for the new engine [29]. The Super Series 70 program was a profitable success for all parties involved: roughly 70% quieter that the 60 Series, with engines up to 23% more fuel-efficient than the old engines. The consequences were a reduction of operating costs and extended range [30]. Several of the largest airlines that owned the DC-8, including Delta, United and Flying Tiger have committed themselves to retrofitting. The reasons were: it was less expensive than buying a whole new fleet, and retrofitting improved the performance and quality of the airplane. The Series 70 was also able to meet later, more stringent noise regulation that were implemented it the 1980s [31].

In more recent times, in 2010, Airbus launched the A320neo (New Engine Option). The first A320neo rolled out of the Airbus factory in Toulouse on 1 July 2014 and it made the first flight on 25 September 2014. Moreover, the original A320 family has been renamed A320ceo (Current Engine Option). The evolution from CEO to NEO is a part of a larger industry enhancement with the aim to improve aircraft efficiency, decrease fuel consumption and lower environmental impact.

From A320ceo to A320neo, Airbus did not choose the retrofit solution but the production of a completely new aircraft with 95% commonality, which is a key factor for the company's customers and operators [32].

The baseline A320neo jetliner has a choice of two engines: the PurePower PW1100G-JM from Pratt Witney and the LEAP-1A from CFM International (General Electric/Snecma). A key contributor to the NEO's performance is the use of fuel-saving Sharklets wingtip devices. These 2.4-metre-tall wingtip devices are standard on NEO aircraft and allowed Airbus to significantly increase fuel efficiency. A320neo shows impressive figures in terms of noise reduction: the 85 decibel maximum noise-level contour at take-off is around 50 per cent lower than that of A320ceo. The aircraft has demonstrated also to be 15 percent more fuel efficient than comparable models [33]. The major visible, external differences between the two aircraft can be seen in Fig. 2.12. The cabin has seen several improvements,

Figure 2.12: A side-by-side comparison of the Airbus A320ceo and A320neo [34].

both technologically and ergonomically: better pressurization, greater luggage space, better passengers' comfort and noise reduction systems. An important aspect to be considered is that the airlines have the possibility to feature the majority of the A320neo' s technological enhancements without ordering a new aircraft. The one exception is the new engines, which are exclusively a component of the A320neo but the ability to retrofit certain features to A320ceo models is a useful solution for airlines with a tighter budget [35].

2.4.2 MEA - More Electric Aircraft

In the chapter 4 are shown costs associated with a retrofit program which consists into a gradual replacement of most of the on board hydraulic and pneumatic systems by electrical systems, passing through intermediate configurations.
This study has been done since the Aviation industry is embracing the concept of More Electric Aircraft (MEA) to eliminate many drawbacks that bleed air systems and hydraulic systems used to suffer from (low efficiency, lack of reliability and high maintenance cost) and reduce the carbon footprint that these systems have generated over years. In MEA not all the on board systems are electrically powered, but most of them. Generally speaking, some hydraulic, pneumatic and mechanical power could be still present.
Boeing chose to adhere to MEA (More Electric Aircraft) concept with Boeing 787 Dreamiliner. A key change from traditional airliners is the electrical architecture of 787 flight systems, in particular the BOEING 787 is the first aircraft which adopted the bleed-less configuration. This configuration has some discriminating factors from a conventional commercial aircraft: the most relevant relies on the deletion of pneumatic system and bleed manifold. No-bleed systems in replacement of hydraulic, pneumatic and mechanical systems led to several benefits, e.g.:

1. Lower maintenance costs and fewer maintenance tasks, electrical systems are much faster and easier to replace than pneumatic, hydraulic and mechanical systems.
2. Increased engine efficiency, the use of “bleedless” systems will allow the engines to produce thrust more efficiently, all of the high-speed air produced by te engines goes to thrust [36].
3. Improved fuel consumption, due to a more efficient power extraction, transfer and usage.

From Fig. 2.13 it can be seen that the 787 Dreamiler uses more electricity, instead of pneumatics, to power airplane systems such engine start, APU start, wing ice protection, cabin pressurization and hydraulics pumps. There are six generators: two on each engine and two on the APU (Auxiliary Power Unit) in the tail. On the ground, the 787 can be started without any ground power since the APU battery starts the APU generators which start the APU to power the engine generators, which start the engines [37].

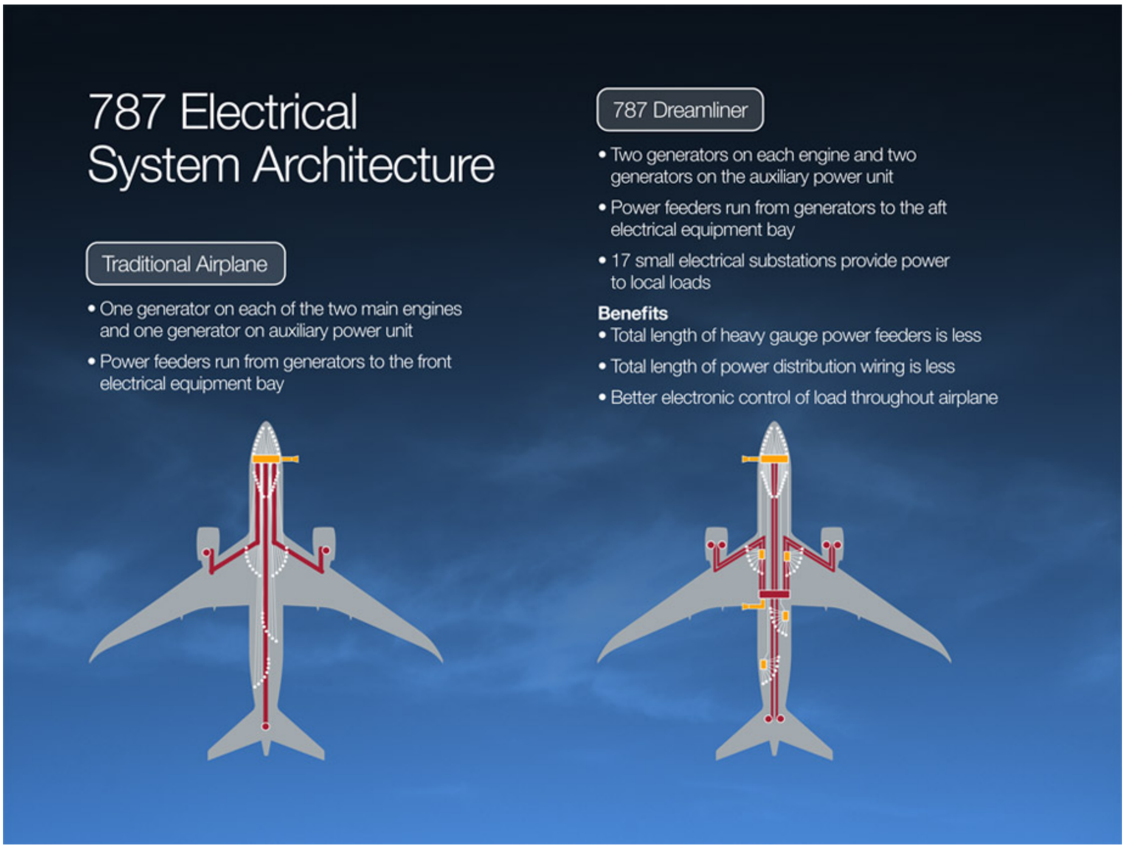


Figure 2.13: A comparison of the electrical system architectures between a traditional aircraft and the Boeing 787 Dreamliner [37].

2.4.3 Considerations on the retrofits consequences

The retrofitting decision needs of careful evaluation of whole related consequences. A study carried out by the Department of Aerospace Engineering of Delft University of Technology deals with this subject [38]. In this study the economical consequences

Reduced airport charges	If the new engine produces lower noise or lower emissions, for the airports that apply environmental charges, these costs will be lower.
Improved productivity of the fleet	The restrictions applied by some airports (for example closure at night) may be removed by performing the re-engine operation.
Decreased operational costs	When the engine on an aircraft is replaced by a less noisy and more modern engine, it is possible that the new engine is more efficient than the old one and optimized for thrust versus specific fuel consumption while minimizing total life cycle cost.

Table 2.4: Benefits associated to a re-engine program.

of a re-engine program for a fleet of 10 B747-200s are divided into benefits and costs, as shown in Tab. 2.4 and Tab. 2.5.

P. B. Coddington [39] did a comparison between re-engining aircraft versus purchasing new aircraft, specifically, re-engining a used B727-200 Advanced or buying a new B757-200. The need for a successor to the 727-200 Advanced was spurred by the oil crisis of 1973 and by increasing public demand for noise suppression. Boeing began considering further developments of its narrow-body 727 trijet. Two approaches were considered: a stretched 727 (a cheaper derivative using the 727's existing technology) or a twin-engine aircraft which made use of new materials and improvements to propulsion technology [40]. Only one company, Valsan Partners, has successfully re-engined a 727-200 Advanced, replacing only the two outboard engines and hush kitting the tail engine. The Valsan re-engining on the 727-200 Advanced has cut fuel costs by 12% [41]. From this study it appears that if an airline already owns a 727, the total cost, for the first year, to operate and modify the existing aircraft is $17.2 million. If, on the other hand, an airline operator scrapped its existing 727 for a new 757, the cost for the first year would be $57.2 million: a difference of $40 million. Even over a 15-year period, an operator who already owns a 727 and refurbishes it is going to save $32.7 million over buying a new 757.

Initial investment cost	The replacement engine itself but also spare parts.
Cost for maintenance purposes	Cost associated with additional training of maintenance personnel, additional ground and support equipment, documentation and tools.
Engineering cost	Cost related to the upfront engineering required for engine integration (for e.g. aerodynamic interference, pylons, nacelles) and system integration (especially related to engine control system, hydraulic system, electrical system).
Certification cost	Cost related to the upfront certification effort required.
Engine replacement cost	Costs associated with the modification of the airframe, the man hours spend on the modification and downtime associated with the modification.
Productivity loss	Costs associated with the reduced availability of the aircraft, depending on the downtime of the modification.

Table 2.5: Costs associated to a re-engine program.

For the next 15 years the refurbished 727 will be less expensive to purchase and operate than a new 757, but the 757 will have more range and payload capabilities. However, the savings must be weighed against an individual air carrier's need for range and payload in its route structure. The second drawback to be considered is that a new 757 will last longer than 15 years, while a refurbished 727 is unlikely to last any longer than 15 additional years. In conclusion, taking into account the immediacy of the mandated noise suppression of the 727s, refurbishing a 727-200 Advanced is a good and feasible option instead of buying a new 757-200, especially for the airlines whose current economic condition is not strong.

It is very difficult to obtain reliable indications about the costs of development and production of different future technologies, as costs are commercially sensitive information [26]. A standardized model through which the costs associated to the introduction of innovative characteristics can be estimated is not present in literature.

In this thesis these aspects have been supported and based on the experience of experts on aeronautics features, industrial partners and AGILE 4.0 consortium.

3
Methodologies for Cost Analysis

Contents

3.1 Introduction

The aim of this chapter is to describe the tools *NR Cost*, *AEA DOC* and *Retrofit*, used to perform different cost analysis in a collaborative framework for aircraft design.

ACRAFT	The main aircraft characteristics necessary for manufacturer costs estimation.
COST	Economic assumptions.
WEIGHT	Weight data for any aircraft component (e. g. structures, systems).
COEFF	Scaling coefficients.

Table 3.1: Groups into which *NR Cost* tool inputs are divided.

3.2 Recurring and Non-recurring Costs Estimation for Commercial Transport Aircraft

The first tool to be involved in the cost estimation automated process is *NR Cost* tool. It is an executable file in Fortran developed by Leonardo Company whose purpose is to provide an estimation of design, development and production costs (Recurring and Non-Recurring Costs) for commercial transport aircraft.

3.2.1 Inputs and Assumptions

The executable requires as input only one plain text file whose name is "nr-cost_inp". The syntax of this file is very simple but it must be respected. In the first line there is the possibility to specify the aircraft name, object of the cost estimation. The input values are organized in different groups. In the Fortran language, a series of variables or arrays can be grouped in a "namelist". The following rules describe these input records:

- It must included a start delimiter ($), it may be an ampersand (&).
- The data must start in or after column two. Column one is totally ignored and so, also the start delimiter must begin in column 2.
- The group-name begins immediately after the start delimiter.
- There must be at least one comma, space, or tab between variables.
- Insert "&END" or "$END" to signal the end of the data group.

The inputs necessary are organised in the groups shown in Tab. 3.1, further details are following exposed. As already stated in section 2.2.3, manufacturer costs estimation is based on the NASA sponsored study [14] in which the systems considered are the following:

1. Wing;
2. Tail;
3. Body;
4. Landing Gear;
5. Nacelle;
6. Pylon;
7. Engine (installation);
8. Fuel system;
9. Flight controls;
10. Hydraulic;
11. Electrical;
12. Pneumatic;
13. Air Conditioning;
14. Anti-Icing;
15. Auxiliary Power Unit;
16. Furnishings and Equipment;
17. Instruments;
18. Avionics (installation);
19. Load and Handling.

In the input file, the weights of each system previously listed must be included. Tab. 3.2 shows the complete set of input parameters chosen by the user to identify the problem.

An example of Cost Estimating Relationship for recurring costs (in particular, the wing production cost) is given in the Eq. 3.1.

$$C_W = 1730 D_{EF}\{[((1 - W_{RATIO,W})W_W)^{0.766} + (W_{RATIO,W}W_W)^{0.766} C_{SAVE,W}] Q^{AFLEARN}\} CF_W I_{DX_{INF}} LR_{DEF} \quad (3.1)$$

D_{EF}	Deflator coefficient computed since 1975 to 1991	-
$W_{RATIO,W}$	Ratio of wing weight made of composite to total wing weight	-
W_W	Wing weight	*lb*
$C_{SAVE,W}$	Cost saving factor when using composite material for wing structure	-
Q	Production units	-
$AFLEARN$	Learning factor for airframe	-
CF_W	Wing scaling coefficient to consider a variation in cost per pound as wing weight changes	-
$I_{DX_{INF}}$	Inflation index used for costs computation	-
LR_{DEF}	Deflator factor to update Labour Rate for year 1991	-

Group	Parameter	Description	Unit
ACRAFT	S	Maximum speed	kt
	NENG	Number of engines	-
	IMAT	Material index	-
	NPROP	Number of propellers	-
	ALTDE	Altitude at maximum speed	ft
COST	QTY	Production units	-
	QTYP	Pre-series quantity	-
	QTYTA	Test articles quantity	-
	QTYD	Development quantity	-
	PR	Production rate	-
	INF	Inflation	-
	ENGLRL	Engineering labour rate	$\$/hr$
	TOOLLR	Tooling labour rate	$\$/hr$
	YEAR	Year of cost estimation	-
	CSENG	Cost of one engine	$
	CSPROP	Cost of propellers	$
	CSAVION	Cost of avionics	$
	CSARMTS	Cost of armaments	$
	CSOPER	Cost of operational items	$
	CSAVE	Cost saving factor when using composite material for structural items	-
	AFLEARN	Learning curve exponent for airframe structure	-
	IALEARN	Learning curve exponent for instruments	-
	SYLEARN	Learning curve exponent for systems	-
	PFR	Profit for global recurring costs	-
	PFNR	Profit for non recurring costs	-
	PFRAF	Profit for recurring costs of airframe	-
	OVPERC	Overhead cost ratio	-
	CSFLOPS	Cost of flight tests	$
	OTHER	Cost of miscellaneous items	$
	TIF	Tooling improvement factor	-
	LABLR	Manifacturing labour rate	$\$/hr$
WEIGHT	W	Weight for each system listed at Pag. 32	lb
	WRATIO	Ratio of the structural item weight made of composite to total item weight	-
	WARMTS	Armaments weight	lb
	WOPER	Operational items weight	lb
	AMPRW	Aeronautical Manufacturers' Planning Report Weight coefficient	-
COEFF	CF	Scaling coefficient to consider a variation in cost per pound as weight changes for each system listed at Pag. 32	-

Table 3.2: *NR Cost* tool input parameters.

	Rate	Exponent
Structure	86	-0.218
Instruments	88	-0.184
Systems	94	-0.0896

Table 3.3: Learning curve factors adopted by NASA RC methodology [14].

This tool has been released in 1991 but the NASA study dates back to 1977, for this reason, deflator factors are included in each cost equation to apply 1991 economic conditions. There are several aspects which influence cost that will be discussed below.

- **Inflation.** The flexibility of the model makes it suitable to be used for any year by applying a simple inflation index. The inflation is an increase in the volume of money relative to available goods, the result is a rise in the general price level. The inflation is applied by the tool by multiplying each cost component in the model by $I_{DX_{inf}}$, calculated by the tool as a function of the consumer price index (INF) for the required year and the year of cost estimation (YEAR) , both quantities are up to the user and must be inserted in the input file (see Tab. 3.2).
- **Learning curve.** Another aspect that influences costs is the learning curve. The basic of learning-curve theory is that the direct labor man-hours necessary to complete a unit of production will decrease by a constant percentage each time the production quantity is doubled. The learning curve model adopted in this case is the Cumulative Average Model (see Eq. 3.2): for an 80% cumulative average learning curve rate, there is a 20% decrease in average cost each time that the cumulative quantity produced is doubled. NASA RC methodology suggests to adopt the learning curve rates in Tab. 3.3.

$$Y = aX^b \tag{3.2}$$

However, the user has the possibility to insert the exponents (slope of the function when plotted on log-log paper) of the learning curves for airframe

Y	Cumulative average cost per unit
a	Cost required to produce the first unit
X	Cumulative number of units produced
b	Exponent of the learning curve (= log of the learning rate/log of 2)

structure, instruments and systems. In this document, the parameters in Tab. 3.3 will always be chosen.

A similar concept in valid for tooling operations, i.e. the process of designing and engineering the tools that are necessary to manufacture parts. The input value TIF (Tooling Improvement Factor) is a measure of tooling hours and cost reduction due to technology improvements since 1970, date of the cost formulation. A 10% reduction in tooling hours and cost has been envisaged, hence it is suggested to choose TIF = 0.9.

- **Composite material.** Engineering studies have demonstrated that substantial weight savings can be realized through the use of composite materials. When NASA RC method was introduced, the effect of composite materials on the cost of aircraft structures was uncertain. However, the user has the possibility to consider both cost and weight structure variations due to the use of composite materials through the insertion of a cost saving factor CSAVE and a weight variation factor WRATIO for airframe items. The structural components interested by the composite effects are:
  1. Wing;
  2. Horizontal tail;
  3. Vertical tail;
  4. Fuselage;
  5. Landing Gear;
  6. Nacelle.
- **Profit.** The user can choose to include a manufacturer profit on both recurring costs and non recurring costs. A 10 percent profit can be a reasonably choice, as suggested by NASA RC study.

- **Other cost items.** There are some cost components whose estimation is not performed by the tool but these must be inserted by the user:
  - Propeller cost;
  - Engine cost;
  - Armaments cost;
  - Micscellaneous items cost;
  - Operational items cost.

  The user can decide to put equal to zero whatever parameter, if necessary, the important thing is not to omit them. In Tab. 3.2 there are also the following items:
  - Avionics cost;
  - Flight tests cost.

  In this case, these costs can be either assigned non-zero value (if known by the user) or directly estimated by the tool (setting them equal to zero in the input file).

  The input indicated as OVPERC is needed to take into account for overhead costs, i.e. costs on the manufacturer's income statement except for those that are directly related to manufacturing or selling the product, expenses associated with running a business that can't be linked to creating or producing a product. The overhead costs (as design costs) occur in the early years of the design and manufacture cycle. It is difficult to estimate well this cost item, in this context, it is modelled as a percentage of flyaway cost (recurring costs plus non-recurring costs). Therefore, the user is called to specify this percentage (divided by one hundred).

As already stated in section 2.2.3, NASA methodology does not provide an equation to compute the engine cost, as it happens for systems. The engine cost, therefore, is an input parameter that must be inserted by the user.

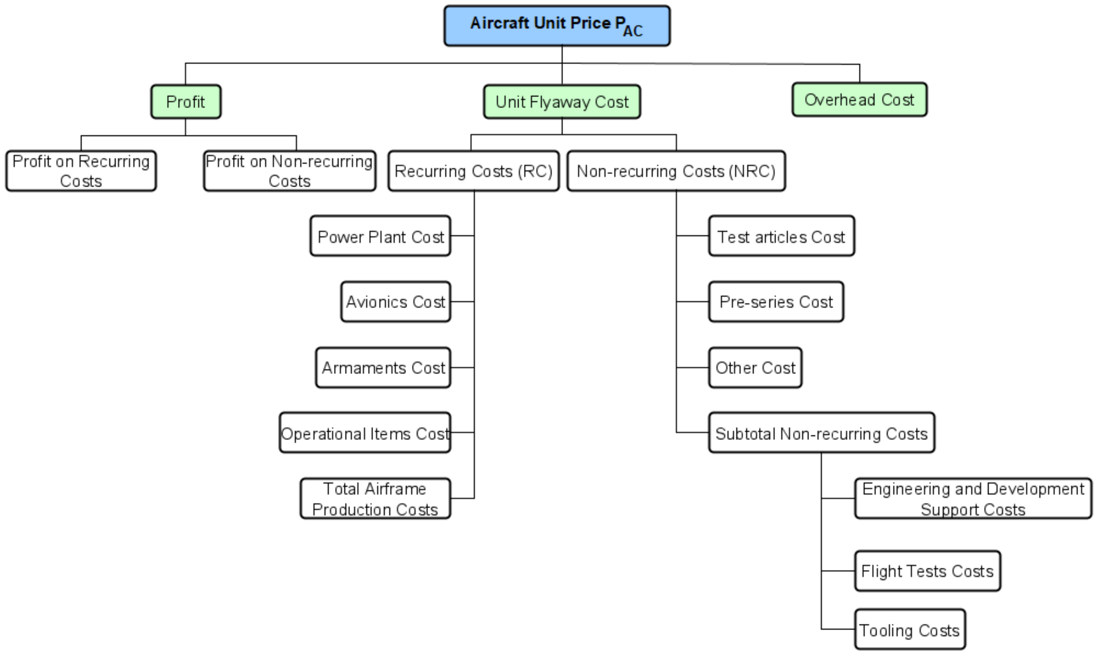


Figure 3.1: Aircraft Unit Price estimation schema.

3.2.2 Results and Validation

Once the tool is executed, it will automatically generate an output plain text file called "nrcost_out" from which different data can be extracted. The most important output is the Aircraft Price since it is necessary to perform Operating Costs estimations. In Fig. 3.1 it is clearly explained which are the items to be estimated and summed by the tool to reach the final result. Before executing the tool for the principal application of this thesis, i.e. the regional turbofan of AGILE 4.0 project, it has been validated performing cost estimations on already existing aircraft.

Embraer 190. The Embraer 190 is a commercial twin-engine jet manufactured by Brazilian aerospace manufacturer Embraer, it took its first flight on March 2004. For this application, the E190 single class configuration with 100 seats has been considered. The Embraer 190 is fitted with two underwing-mounted General Electric (GE) 34-8E-10 turbofan engines [1] whose cost is $7.3 millon each engine. In Tab. 3.4 and Tab. 3.5 the aircraft data (from Embraer website [2]) and the economic assumptions used for the cost analysis are respectively resumed.

[1]https://en.wikipedia.org/wiki/Embraer_E-Jet_family
[2]https://www.embraercommercialaviation.com/commercial-jets/e190/

Parameter	Value	Unit
Maximum speed	470	kt
Altitude at maximum speed	41000	ft
Number of engines	2	-
Composite material index	0	-
Number of propellers	0	-

Table 3.4: Data for E190 price estimation.

Parameter	Value	Unit
Production units	600	-
Pre-series quantity	2	-
Test articles quantity	2	-
Development quantity	1	-
Production rate	4	-
Year of cost estimation	2005	-
Inflation	0.02	-
Cost of one engine	7300000	\$
Cost of flight tests	8000000	\$
Cost of operational items	2000000	\$
Cost of avionics	1000000	\$
Engineering labour rate	100	$\$/hr$
Tooling labour rate	60	$\$/hr$
Manufacturing labour rate	49.22	$\$/hr$
Profit for global recurring costs	0.1	-
Profit for non-recurring costs	0.1	-
Overhead cost ratio	0.1	-

Table 3.5: Economic assumptions for E190 price estimation.

The year of cost estimation corresponds to the year in which the aircraft obtained the certification by FAA (Federal Aviation Authority). The cost of flight tests is an input value suggested by an expert by Leonardo Company and calculated by multiplying the cost for each hour of flight tests by an average number of flight test hours. From Fig. 3.1 it is clear that an important component of the recurring costs are the airframe production costs, influenced primarily by systems weights and the quantity of units produced. With regard to the weights data, since it is not possible to obtain for public sources, a detailed weight breakdown of a commercial aircraft, a CLASS-2 Weight Estimation Method has been applied. The weight

Weights		
Wing	14060	*lb*
Horizontal tail	1035	*lb*
Vertical tail	735	*lb*
Fuselage	19780	*lb*
Landing gear	3670	*lb*
Nacelle	0	*lb*
Pylon	1450	*lb*
Engine installation	10670	*lb*
Fuel system	475	*lb*
Flight controls	1270	*lb*
Hydraulic system	1390	*lb*
Electrical system	2220	*lb*
Air conditioning system	1141	*lb*
Anti icing system	75	*lb*
Auxiliary power unit	370	*lb*
Furnishings and equipment	4370	*lb*
Instruments	198	*lb*
Avionic installation	1135	*lb*
Tail	1466	*lb*
Total: MEM	65510/29715	*lb/kg*

Table 3.6: E190 weights data for price estimation (MEM: Manufacturer Empty Mass).

results have been compared and adjusted in function of a known weight breakdown of an aeroplane of the same category. The result of this assumption is provided in Tab. 3.6, the composite material are not considered for this analysis.

The results are shown in Table 3.7 in terms of costs associated to the single aircraft and not to the whole fleet produced. It is possible to see from Tab. 3.8 a good agreement between the result obtained and the public domain data. The difference is caused by the year of cost estimation since the estimation refers to the year in which E190 has been certificated. However, the external source is based on 2017 list prices [42].

A critical aspect is that the manufacturers do not know at the start of the project how many aircraft will be produced. It has been chosen, as input value, a production unit equal to 600 based on the total number of deliveries. The impact of changes in the number of aircraft produced can be observed from Fig. 3.2. This trend is mainly

Parameter	Value	Unit
Recurring costs	36.324	*mil.*$
Non-recurring costs	5.205	*mil.*$
Profit on RC	3.632	*mil.*$
Profit on NRC	0.521	*mil.*$
Overhead costs	4.153	*mil.*$
Aircraft price	**49.835**	***mil.*$**

Table 3.7: Results for E190 price estimation.

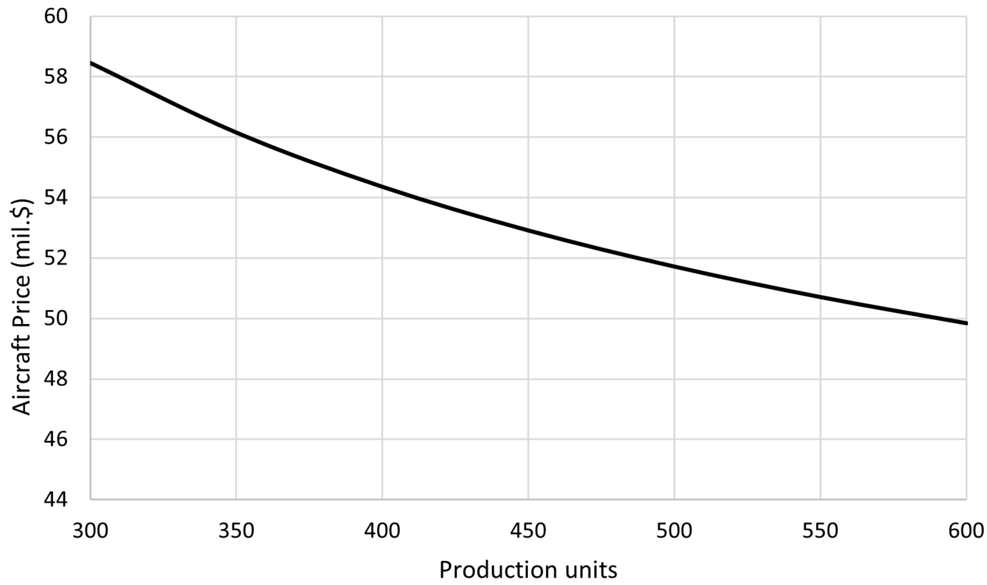


Figure 3.2: Variation of the estimated aircraft price with the number of aircraft produced.

due to the fact that, as the production quantity increases, the initial investment (non-recurring cost) is distributed among a bigger quantity of aircraft produced.

	NR Cost tool	External Source [42]
Unit Price (mil.$)	49.865	50.6

Table 3.8: Results comparison for E190 price estimation.

ACRAFT	The main aircraft characteristics necessary for operating costs estimation.
ECONOM	Economic assumptions.
EMISS	Data for the emission and noise charges calculation.
TBFAN	Engine data (for turbojet and turbofan engines).
PROPEN	Engine data (for propfan and turboprof engines).

Table 3.9: Groups into which *AEA DOC* tool inputs are divided.

3.3 Direct and Total Operating Costs Estimation for Short and Medium Range Aircraft

The second tool to be involved in the cost estimation automated process is *AEADOC* tool. It is an executable file in Fortran developed by Leonardo Company whose purpose is to evaluate Direct and Total Operating Costs for Short-Medium haul airliners and regional aircraft (jet and propeller driven). The theory behind, as the name suggests, is the AEA Method [20] for Short-Medium haul airliners. It is important to highlight that this methodology is valid for the early stage of a new aircraft programme, it is a fast and reliable tool for taking into account costs considerations since the conceptual phase.

3.3.1 Inputs and Assumptions

AEADOC has a similar structure to *NR Cost*, also in this case, the executable requires as input only one plain text file whose name is "aeadoc_inp". The rules to be respected while filling the input file are the same already exposed in section 3.2.1. The input values are organized in different groups (see Tab. 3.9) and listed in detail in Tab. 3.10 and Tab. 3.11. The author has amended the original executable file to allow noise and emissions charges estimation, not computed by AEA methodology. This modification was necessary since with the aim of encouraging the sustainable development of the air transport industry, there is a need to evaluate the social costs of the undesirable side effects, mainly aircraft noise and engine emissions, for different airports.

Therefore, the cost items estimated by the tool to reach the final DOC result are shown in Fig. 2.7. The equation 3.3 shows the calculation of the depreciation cost. The estimation method uses a simple amortization over a fixed period ($DYRS$), TI is the total investment obtained as the sum of aircraft delivery price and the spare costs that are related to aircraft spare parts (airframe and engine). R_{VAL} is the ratio between the value of the aircraft at the end of the operating life and the aircraft delivery price. The choice of depreciation period and the estimation of residual value is made by the purchasing airline (e.g. 15 years depreciation to 10% residual value).

$$DOC_{dep} = \frac{(1 - R_{VAL})TI}{DYRS} \tag{3.3}$$

TI	Total Investiment	$
R_{VAL}	Residual Value	-
DYRS	Depreciation Period (years)	-
DOC_{dep}	DOC of depreciation per year	$

The user has free choice on the inputs but in Tab. 3.12 some suggestions provided by AEA methodology [20] are listed. $RINSH$ is needed for the calculation of Insurance costs, shown in Eq. 2.1 where this parameter is represented by k_{ins}. $PERDOC$ is employed in the IOC computation, to be precise, it is multiplied by COC (Cash Operating Costs: DOC without depreciation) per trip to obtain Indirect Operating Costs.

It is worth going into details to better clarify which are the features that mainly influence DOC.

- **Aircraft price.** From Tab. 3.10 it is shown that the user can insert:
  - Aircraft delivery price (ADP)
  - Manufacturer standard study price (MSP)

  The two inputs are linked together since, from AEA theory, the Aircraft delivery price includes:
  - Manufacturer standard study price (the list price for a standard configuration);

Group	Parameter	Description	Unit
ACRAFT	MTOW	Maximum take-Off weight	t
	PLD	Maximum payload weight	t
	MEW	Manufacturer empty weight	t
	BENGW	Bare engine weight	t
	ADP	Aircraft delivery price	$mil.\$$
	BFE	Buyer furnished equipment	$mil.\$$
	MSP	Manufacturer standard study price	$mil.\$$
	ENPRI	Engine price	$mil.\$$
	EN	Engines number	-
	PAXN	Passengers number	-
	CREWC	Attendants number	-
	BT	Sector block time	hr
	BF	Sector block fuel	kg
	IENG	Engine type index	-
	SECTOR	Sector assumed for DOCs evaluation	NM
ECONOM	YEAR	Year of cost evaluation	-
	INF	Inflation	-
	AFSPARE	Airframe spares	-
	ENSPARE	Engine spares	-
	DYRS	Depreciation period	year
	RVAL	Residual value	-
	RINSH	Insurance rate	-
	YIELD	Sector yield	-
	FUELPRI	Fuel price	$/U.S. gal
	PERDOC	Coefficient for IOC evaluation	-
	UTIL	Aircraft annual utilization	bhr/year
TBFAN	THRU	Sea level static take-off engine thrust	t
	BPR	By-pass ratio	-
	CN	Number of compressor stages including fan stages	-
	OAPR	Overall pressure ratio	-
	SN	Number of shafts	-
PROPEN	SHP	Shaft horse power	hp
	BN	Blade number	-
	D	Propeller diameter	m
	CN	Number of compressor stages including fan stages	-
	OAPR	Overall pressure ratio	-
	SN	Number of shafts	-

Table 3.10: *AEA DOC* tool input parameters.

Parameter	**Description**	**Unit**
TD (T_d)	Departure airport threshold noise	$EPNdB$
TA (T_a)	Arrival airport threshold noise	$EPNdB$
L_APP ($L_{approach}$)	Aircraft certified noise level at the approach measure point	$EPNdB$
L_LAT ($L_{lateral}$)	Aircraft certified noise level at the lateral measure point	$EPNdB$
L_FLYOV ($L_{flyover}$)	Aircraft certified noise level at the fly-over measure point	$EPNdB$
CNOISE (C_{noise})	Unit noise rate	$
C_NOX (C_{NO_x})	Unit rate for NO_x	$
NOX_EM_VALUE ($EmValue_{NO_x}$)	Emission value of NO_x	kg
C_CO (C_{CO})	Unit rate for CO	$
CO_EM_VALUE ($EmValue_{CO}$)	Emission value of CO	kg

Table 3.11: *AEA DOC* tool input parameters for emission and noise charges estimation (in brackets how the parameters appear in the equations).

Input parameter	Value
AFSPARE	0.1
ENSPARE	0.3
RINSH	0.005
PERDOC	1.35

Table 3.12: Parameters for the calculation of DOC components suggested by AEA methodology.

– Change orders costs (surcharges for modifications);
– Buyer furnished equipment (the price for equipment components that the customer buys on its own responsibility, BFE);
– Capitalised interests on progress payments.

The user can choose to insert the ADP or the MSP and set the other one equal to zero as a consequence. In some cases, these payments can scarcely be determined due to the lack of publications. However, estimation methods do exist for determining the delivery price , see [15] for more details.

Strictly related to prices, is the spare cost: the sum of the cost of the engine and aircraft spare parts. The user is requested to enter:

– AFSPARE;

– ENSPARE.

The price for spares is calculated by the tool from a proportion AFSPARE of the price of the airframe and a proportion ENSPARE of the price of the engines. The engine price can be obtained from the manufacturer or estimated according to statistical equation (Jenkinson 1999 [15]).

- **Engine type.** The user is requested to indicate the type of engine the aeroplane in question is equipped with through the input value $IENG$.

$$IENG = \begin{cases} 1 & \text{if turbofan engine} \\ 2 & \text{if propfan engine} \\ 3 & \text{if turboprop engine} \end{cases}$$

This distinction in important especially in terms of estimation of maintenance costs.

- **Fuel costs.** For a correct estimation, it is important to first know fuel price P_{fuel} (usually given in dollars per gallon in US environment) for the year in which the cost estimation is required [22]. Then direct operating cost associated to fuel are then calculated by the tool applying Eq. 3.4.

$$DOC_{fuel} = \frac{P_{fuel} BF}{BT} \tag{3.4}$$

P_{fuel}	Fuel Price	$\$/kg$
BF	Block fuel	kg
BT	Block time	hr
DOC_{fuel}	DOC related to fuel	$/bhr

The Block Fuel BF, entered by the user, will be estimated according to flight phases A to G from Fig. 2.9, which shows the definition of the aircraft trip according to AEA 1989a.

- **Aircraft Utilization.** The number of flight hours flown annually gives the annual aircraft utilization $UTIL$. If the user does not know this value, it can be set equal to zero and the tool will estimate it.

3.3.2 Noise and Emissions Charges

As already stated in the previous section (sec. 3.3.1), noise charges and emission related charges estimations are included in this operating costs analysis. Generally, taxes increase according to the noise generated by the aircraft but also according to its weight, because the heavier airplane is usually the noisier. Some countries define a maximum noise threshold above which the aircraft pays a fee per single operation, while others divide aircraft into noise categories with different taxation or incentives. In most of cases, airlines meet, for the same aircraft, different taxes depending on the country where they operate. In AEA DOC tool, the methodology for calculating noise charges follow the ECAC approach (explained in detail in [43]).

Noise charges. The principle behind the noise related charge calculation is shown in the Eq. 3.5.

$$\Delta_a = \frac{L_{approach} - T_a}{10}$$

$$\Delta_d = \frac{\frac{L_{flyover} + L_{lateral}}{2} - T_d}{10}$$

$$DOC_{noise} = C_{noise}(10^{\Delta_a} + 10^{\Delta_d}) \tag{3.5}$$

The parameters present in this calculation are listed in Tab. 3.11, it has been assumed that unit noise rates for arrival and departure are equal (C_{noise}).

Emission charges. Airport tax on emissions of pollutants has been developed more recently than the noise charge. They have been introduced for the first time in Switzerland in 1997 and the following year in Sweden. The emission charge follows the standard landing and take-off (LTO) cycle and it is based on certified emission values of NO_x in the LTO cycle in accordance with International Civil Aviation Organization (ICAO) Annex 16, Volume II [44]. For jet aircraft, the following formula (3.6) allows us to calculate fees for NO_x (but also for other gaseous pollutant, in our case, CO).

$$DOC_{NO_x} = C_{NO_x} EmValue_{NO_x} \tag{3.6}$$

Parameter	Value	Unit
Maximum take-off weight	73.5	*t*
Maximum payload weight	13.6	*t*
Manufacturer empty weight	38.1	*t*
Bare engine weight	3.45	*t*
Aircraft delivery price	47.0	*mil*.$
Buyer furnished equipment	0	*mil*.$
Manufacturer standard study price	0	*mil*.$
Engine price	4.50	*mil*.$
Engines number	2	-
Passengers number	150	-
Attendants number	3	-
Sector block time	7.05	*hr*
Sector block fuel	15.5	*t*
Engine type index	1	-
Sector assumed for DOCs evaluation	2842	*NM*
Year of cost evaluation	2000	-
Fuel price	0.6	$/U.S. gal
Aircraft annual utilization	3504	*hr*

Table 3.13: Data for A320 DOC estimation [45].

3.3.3 Results and Validation

After the execution, the tool will automatically generate an output plain text file called "aeadoc_out". It shows each DOC item calculated per block hour (*bhr*) and the final total costs values in terms of $/bhr, $/seat-bhr, $/t-bhr, $/trip, ¢/seat-mile, ¢/seat-km, ¢/t-mile, ¢/t-km, ¢/seat-trip.

Airbus A320. This section is devoted to the comparison of the *AEA DOC* tool results with respect to data present in a study performed by Kundu [45] about A320 DOC estimation. In Table 3.13 the aircraft data and the economic assumptions suggested by Kundu [45] and used as inputs value for *AEA DOC* are listed. The remaining part of the inputs is shown in Tab. 3.14, where there is the definition of the economic scenario set by the author. The engines mounted by this A320 version are the CFM International CFM56-5B6 [46], whose characteristics are listed in Tab. 3.15. The results of the two direct costs calculations are shown in Tab. 3.16 and in pie charts in Fig. 3.3.

Parameter	Value	Unit
Inflation	0.02	-
Airframe spares	0.10	-
Engine spares	0.30	-
Depreciation period	15	years
Residual value	0.10	-
Insurance rate	0.005	-

Table 3.14: Economic assumptions for A320 DOC estimation.

Parameter	Value	Unit
Sea level static take-off thrust	10.7	t
By-pass ratio	5.9	-
Number of compressor stages including fan stages	19	-
Overall pressure ratio	32.6	-
Number of shafts	2	-

Table 3.15: Engine data for A320 DOC estimation.

It is possible to see that the orders of magnitude of the results are the same. DOC items like depreciation and interest do not agree perfectly due to the use of different economic inputs between the two methods. The difference between flight crew, cabin crew and maintenance costs may be due to the different labor rates per hour adopted. The lack of public domain data, both for engine and airframe, also does not contribute to obtain a more accurate methodology and a perfect agreement between the results.

The author would like to conclude this section by adding that the confidence gained in the model derives not only from the comparison just described, but also from the numerous discussions with Leonardo company throughout the AGILE 4.0 project.

3.4 Retrofit Costs Estimation

3.4.1 Introduction

The aim of this chapter is to describe the *Retrofit* tool, developed by the author, which simulates a retrofitting activity estimating recurring and non-recurring costs

	AEA DOC tool (\$/trip)	Kundu (\$/trip)
$DOC_{depreciation}$	6465	6923
$DOC_{interest}$	5710	5370
$DOC_{insurance}$	472	473
$DOC_{flight\ crew}$	4321	3482
$DOC_{cabin\ crew}$	2129	2854
$DOC_{navigation}$	3194	3194
$DOC_{landing\ fee}$	571	573
$DOC_{ground\ handling}$	1692	1365
$DOC_{maintenance}$	4899	4056
DOC_{fuel}	3109	3066
Total DOC	**32564**	**31356**

Table 3.16: Results comparison for A320 DOC estimation (\$/trip).

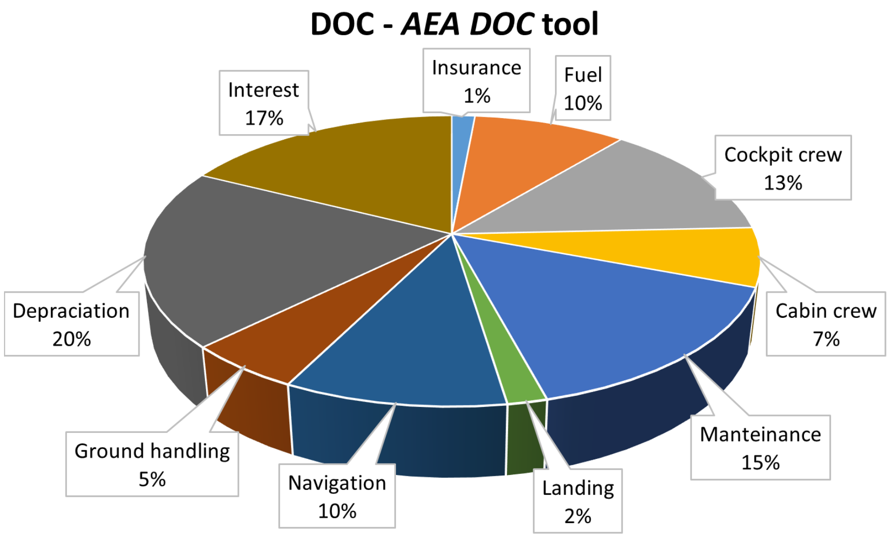
associated to the installation of innovative features on existing aircraft. Unlike the tools described above, this tool has been developed in Excel and it has been included in a collaborative framework for aircraft design to perform cost analysis. The purpose is to investigate if these potential retrofits would be cost effective and could be attractive, instead of addressing new technologies and processes at newly developed aircraft. Retrofits are not necessarily targeted to ageing and/or out-of-production aircraft only.

Reasons for aircraft upgrades are vary, in section 2.4 it is explained that one purpose may be the need to reduce emissions and fuel consumption. In addition to the previous there is also an emerging need to retain and modernize certain aircraft types to maintain certain segments and benefits of airlines [27].

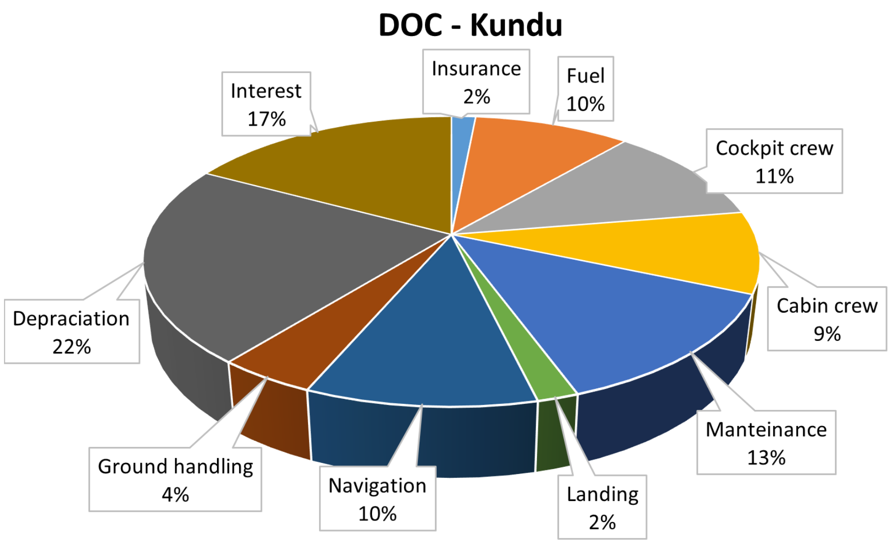
In this study, the retrofit operation has been assumed as conformed to a repair operation in order to have a better costs estimation basis. However, retrofits are different from Maintenance Repair and Overhaul (MRO) activities, as these involve inspection, maintenance, repair and overhaul of aircraft and aircraft components without including novel parts or modifying the aircraft or its components [27].

The objective of this study, accomplished with the development of the *Retrofit* tool, is to define suitable retrofit opportunities within the civil aviation sector by:

- Understanding the rationale behind a retrofit project;



(a) *AEA DOC* tool.



(b) Kundu.

Figure 3.3: Pie charts of DOC comparison for A320.

- Identifying suitable (sufficiently mature, economically feasible and certifiable) technologies to incorporate in existing civil aircraft;
- Giving the possibility to simulate different scenarios;
- Scheduling all the engineering studies followed by practical operations to be done on the existing aircraft to finalize the upgrade;
- Performing a cost benefit analysis on each new technology adopted.

Few possible retrofit options will be object of this study, these have been chosen as being worthwhile to investigate further. The candidate technologies for retrofit can be categorised in: re-engining and on-board-systems replacement. In the next section the aspirant upgrades are analyzed in details.

3.4.2 Candidate Retrofit Technologies

The agreed retrofit technologies for cost analysis are:

- New engines with higher BPR and improved fuel efficiency (Geared turbofan, bleedless), as shown in Fig.3.4;
- New on-board system (OBS) architectures: more electric and all electric (MEA/AEA) architectures.

The reasons behind the choice of these technologies have been explained in the previous sections. The factors that impact the decisions for executing retrofit activities are mainly the necessity to obtain a performance improvement, a reduction of operational costs and environmental impact. High BPR engines could offer an higher propulsive efficiency, lower specific fuel consumption (SFC) and also a considerable reduction in aircraft noise. In this work, the objective is to apply the retrofit improvements on the short medium range regional turbofan aircraft of the AGILE 4.0 project (see chapter 4).

New high BPR engines. Three different engines, with increasing BPR, have been designed to be mounted on this aircraft:

1. BPR 9;
2. BPR 12;
3. BPR 15.

In this work the engines, designed within the AGILE 4.0 project, have an advanced architecture (like the PW1000 series and following) with respect to the conventional engine (comparable to the GE-CF34) with BPR=5.4, see Fig. 3.4 for a comparison between the different engine architectures. It is important to highlight that each engine has its own and defined geometry, performance, masses, and fluid dynamic conditions. Due to different engine architectures, different engine specific fuel consumption and emission index will be taken into account in the retrofit cost analysis.

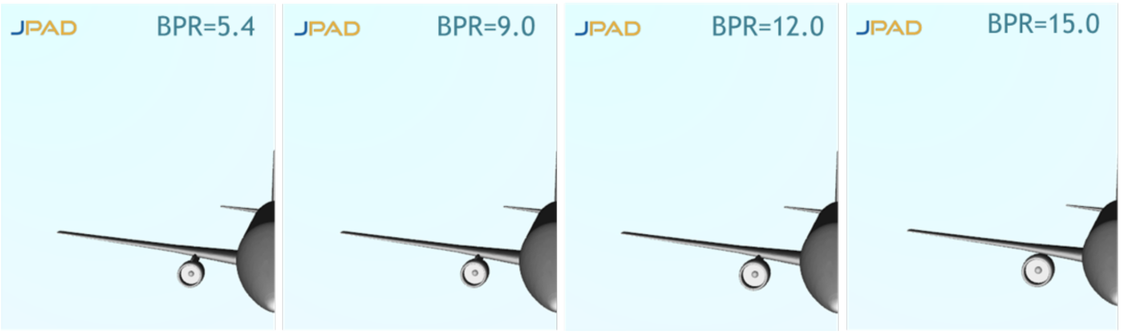


Figure 3.4: Reference engine (to the left) compared with the advanced engines suitable for AGILE regional turbofan aircraft.

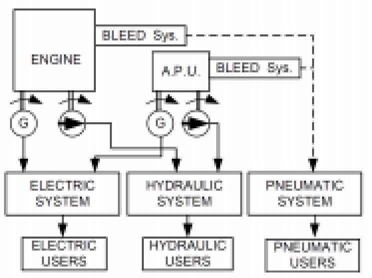


Figure 3.5: Conventional architecture.

The second variable involved in the retrofit program is the system architecture. The idea is to start from a conventional architecture, in which the power generation and distribution systems are: hydraulic, pneumatic and electric systems. From this layout, the idea is to move toward the more electric concept, explained in section 2.4.2.

New OBS architectures. The architectures considered are the one adopted for the AGILE 4.0 project [1]. The starting point is the:

- CONVENTIONAL. The conventional systems architecture, shown in Fig. 3.5, is equipped with hydraulically drive Flight Control System (FCS) and landing gear actuators. The Environmental Control System (ECS) and the Wing Ice Protection System (WIPS) are supplied by pneumatic system (bleed air from engine compressor). Electric system is a traditional 115 V AC and the electric system consists in two generators.

  From this layout, the method consists in moving toward the more electric architectures:

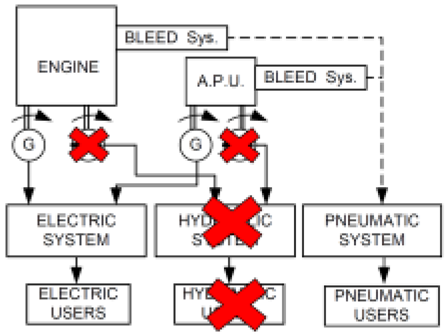


Figure 3.6: More electric 1 architecture.

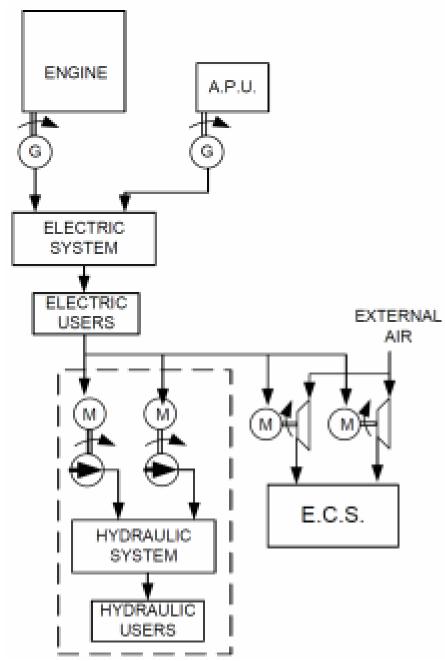


Figure 3.7: More electric 2 architecture.

- **MORE ELECTRIC 1 (MEA1).** In this configuration the hydraulic system is completely removed along with its distribution system. All actuators are electric. Electric system requires the generation in 235 V AC. See Fig. 3.6 for further details.
- **MORE ELECTRIC 2 (MEA2).** The peculiarity of this architecture is represented by the electrification of the WIPS and the ECS. Electric system requires the generation in 235 V AC. It is a bleedless configuration with compressors electrically drive and hydraulic pumps supplied by electric motors (see Fig. 3.7).

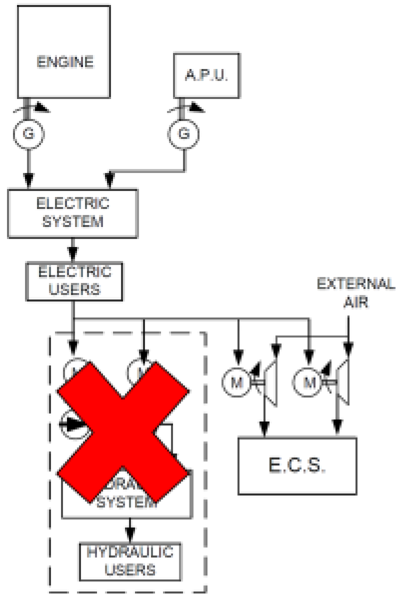


Figure 3.8: All electric architecture.

- **ALL ELECTRIC (AEA).** All electric architecture adopts the innovative features of MEA 1 and MEA 2, thus neither hydraulic nor pneumatic system are present. No bleed air is required, the pneumatic power is produced by dedicated compressors. Electric system requires the generation in 235 V AC and the electric system consists in four generators (see Fig. 3.8).

The third point of the list at Pag. 50 means that the user has the possibility to combine the different upgrades (among those just listed) in order to choose the most suitable. In the next sections this opportunity to switch the kind of technology will be shown in details.

Once the technologies to be retrofitted have been indicated, it is important to understand how the costs associated with a retrofit operation can be estimated (fifth point of the list at Pag. 50). The theory behind the *Retrofit* tool has been developed together with experts of Leonardo Company. It consists in listing all the operations involved in this procedure and after evaluating the costs due to each operation. Going into more detail, the major cost items managed by the tool are:

- **Engineering.** It coincides with the non-recurring costs, the initial investment to be computed to support the retrofit project.

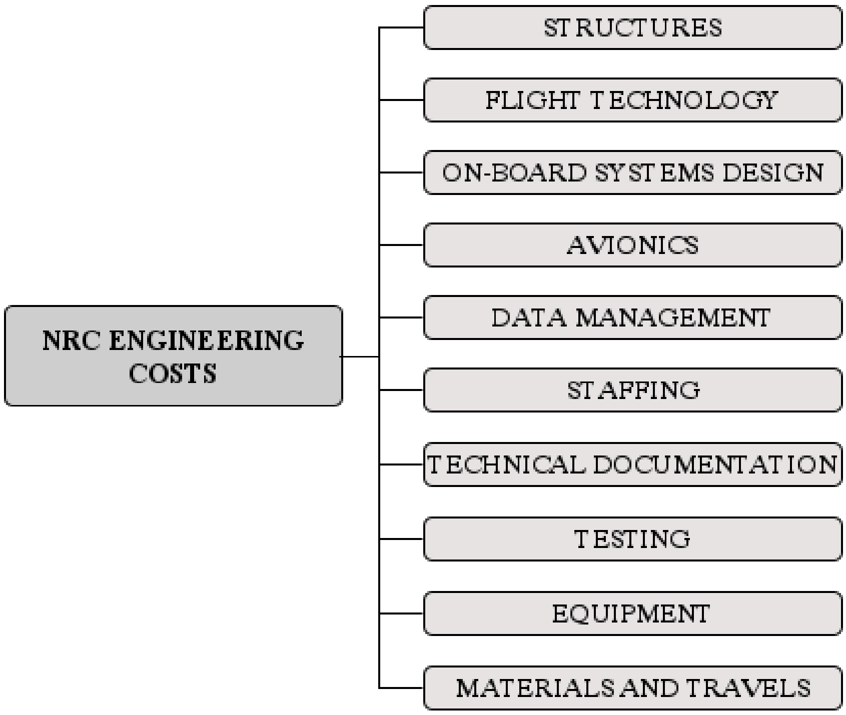


Figure 3.9: Engineering effort considered by *Retrofit* tool.

- **Operations.** It corresponds to the recurring costs. This cost item is associated with the practical actions, the execution of the aircraft modifications.
- **Equipment.** Expenditure on the purchase of new engines, systems, but also additional ground and support equipment, every kind of supply.

3.4.3 Engineering Effort

Non-recurring costs include, for example, any costs of research, testing, evaluation effort associated with aircraft modification, systems architecture redesign, other subsystems redesign. The major engineering costs items involved in a retrofit program and estimated by the tool are listed in Fig. 3.9 and analyzed in details:

- **Structures.** Before installing the new technologies on an existing aircraft, the operations must be supported with en engineering effort focused on the modification on the airframe structure. The choice to keep same characteristic weights implies that fuselage, tail plane and landing gears structure does not need any modifications (i.e. reinforcements/re-design). The studies deal with the following aspects:

- **New engine attachment points.** New engines may have new attachment points on the wing. Higher by-pass ratio means that the fan size is increased, as a result, mounting these engines under a wing is a challenging task that requires a strong engineering effort.
- **Entire wing stress analysis.** Due to the different geometries and characteristics of the new engines, their inertia, force and thrust produced change. Static aeroelastic deformation of the wing structure and load distributions, bending moment and torque need to be studied. For this purpose, structural finite element model of the wing/engine system is established.
- **Fuselage modification.** The hydraulic and pneumatic circuits run across the wings and the fuselage to connect the energy sources to the various users. If the on-board systems change, it is necessary to remove the fuselage panels and reinstall them after the replacement. An engineering effort will be focused on the planning of the operations of fuselage panels disassembly and assembly.
- **Floor panels removal and installation.** It is necessary to schedule this operation since the access to some on board systems is possible exclusively passing through the cabin floor. A striking example are the extraction/retraction, steering and braking systems of the aircraft landing gear.

- **Flight Technology.**
  - **Aerodynamics.** A CFD (Computational Fluid Dynamics) analysis must be carried out to predict the drag, lift, noise, structural and thermal loads, performance for the updated aircraft systems. Initial validation of such software is typically performed using experimental apparatus such as wind tunnels. A final validation is often performed using full-scale testing, such as flight tests.

  - **Performance.** The distribution of the aircraft mass along the body is important 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 have an higher contribution to the rolling moment of inertia of the aircraft.
  - **Flight quality.** A certain engineering effort is involved in the study and evaluation of the longitudinal and lateral-directional stability and control characteristics of the retrofitted aircraft.
  - **Weight and center of gravity analysis.** 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 c.g. location at any point in time.
  - **Flutter analysis and structural load analysis.** Moving the engine module along spanwise and chordwise directions can influence the flutter characteristics. Natural vibration modes of the structure may change also with the adoption of new actuators. The structure shall be capable of supporting at critical loads present on the manoeuvring diagram.
  - **Wind tunnel and flight tests support.** After wind-tunnel test campaign a relevant engineering effort is required to process the tests data and to obtain the new drag polar curves.
- **On-board systems design.** The partial or total electrification of the on-board systems architecture requires an intense engineering work to design it. The following activities are considered:
  - Load and failure analysis, new installation drawings;
  - Electrical generation and distribution;
  - ECS electrical pack;
  - Thermal IPS design;
  - Air conditioning distribution;
  - FCS electrical actuation;

  - OBS architecture design.
- **Avionics.** The retrofit involves an engine replacement, as a result it is necessary to install a new FADEC (Full Authority Digital Engine Control) system and also a new autopilot software. FADEC works by receiving multiple input variables of the current flight condition including air density, throttle lever position, engine temperatures, engine pressures, and many other parameters.
- **Data management.** This cost item includes the engineering effort required to control the configuration and manage data. People who handle information like on-board equipments serial numbers, the way these systems interface with structure.
- **Miscellaneous activities.** This item includes the costs associated to these activities:
  - Acoustic and vibration;
  - Materials and processes;
  - Airworthiness and safety;
  - Chief engineering;
  - Design quality assurance;
  - Cost and planning;
- **Technical documentation.** After such a relevant innovation, it is essential an engineering effort to update various aircraft manuals: Repair manual, Aircraft Flight Manual (AFM), Flight Crew Operating Manual (FCOM) and Weight and Balance Manual (WBM).
- **Testing.**
  - **Wind tunnel tests.** Once the new engine has been chosen, the combination airframe and new engine must be tested since for the design of new aircraft configurations the wind tunnel experiment is an indispensable tool in order to predict the aerodynamic performance of single aircraft components as well as the overall configuration. To validate numerical procedures (CFD analysis) a wind-tunnel test campaign has

to be organized and carried out. A scaled model reproducing the engine and part of the wing must be produced in order to study the resistance and the aerodynamics.

  - **Flight tests and engineering support.** After the retrofit updates, a flight test campaign is carried out to determine the new aircraft characteristics (previously estimated through wind tunnel tests), to assist the engineering design and developmental process and verify the attainment of technical performance specifications and objective, to establish the system's operational effectiveness and operational suitability. For certification and safety purposes, the subsystems shall always be tested in flight.
  - **Static and fatigue tests.** If some wing structural element is modified or reinforced after the installation of heavier engines, static load tests may be conducted in order to determine the wing's ability to handle loads.
  - **Rig tests.** Several test rigs must be performed to analyse the behaviour of the new on-board systems starting from the standalone component up to its integration into the aircraft. An example is the FCS Test Rig whose purpose is to verify and validate the Flight Control System, in the same way, there is also the propulsion system test ring or the avionics one.

- **Equipment.** Avionics software development process is required by law. This cost item has to be considered since the engine FADEC and the autopilot are changed, as a consequence, a new software will be adopted.
- **Materials and travels.** In this cost item are allocated the materials to support engineering researches and the costs to sustain every kind of travel (e.g. movements of good and supplies).

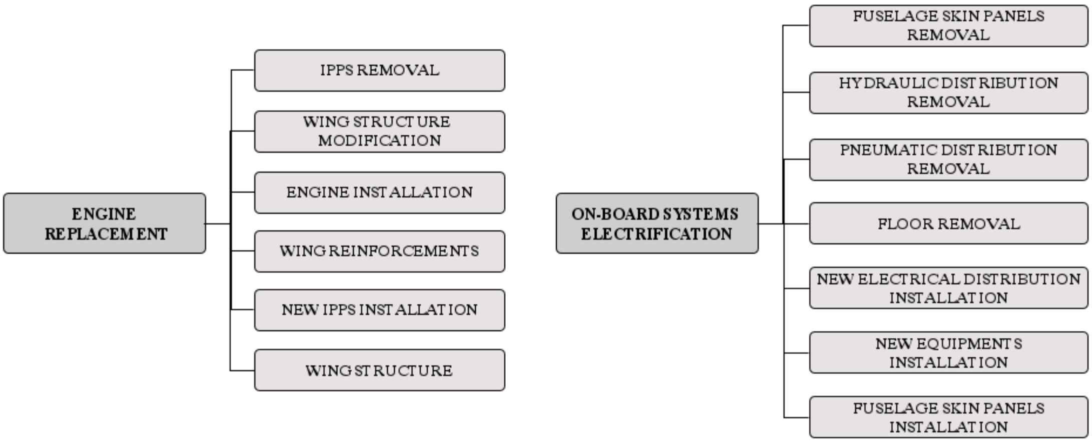


Figure 3.10: Operation costs handled by *Retrofit* tool.

3.4.4 Operations to Update the Fleet

The appropriate modifications and updates to be applied on the fleet are defined and scheduled during the engineering phase. The aim of this section is to present the recurring costs necessary to sustain the practical operations to be executed on the aircraft. The major operations cost items involved in a retrofit program and estimated by the tool are listed in Fig. 3.10.

As already explained in section 3.4.1, this work aims to investigate if it is worth installing potential innovative technologies on existing commercial aircraft fleets. However, an hypothetical scenario is where the airline is forced to modernise its fleet, or purchase new aircraft, due to stricter emission constraints. In this scenario, it is expected an aggressive emissions restriction by Governments, pushing the airliners to update, through a retrofit program, existing heritage fleets. The Airliners will refer to the aircraft OEM (Original Equipment Manufacturer) to reduce emissions, improving fuel consumption. The investment in retrofitting must be carefully evaluated, considering acquisition costs for equipment (engines, OBS) but also engineering costs, certification. It has been outlined a scenario using the Model Based System Engineering (MBSE) technology through the use of Capella tool [47]. This approach allows us to have both a functional view of the system as well as traceability right up to the physical components. In this general scenario it has

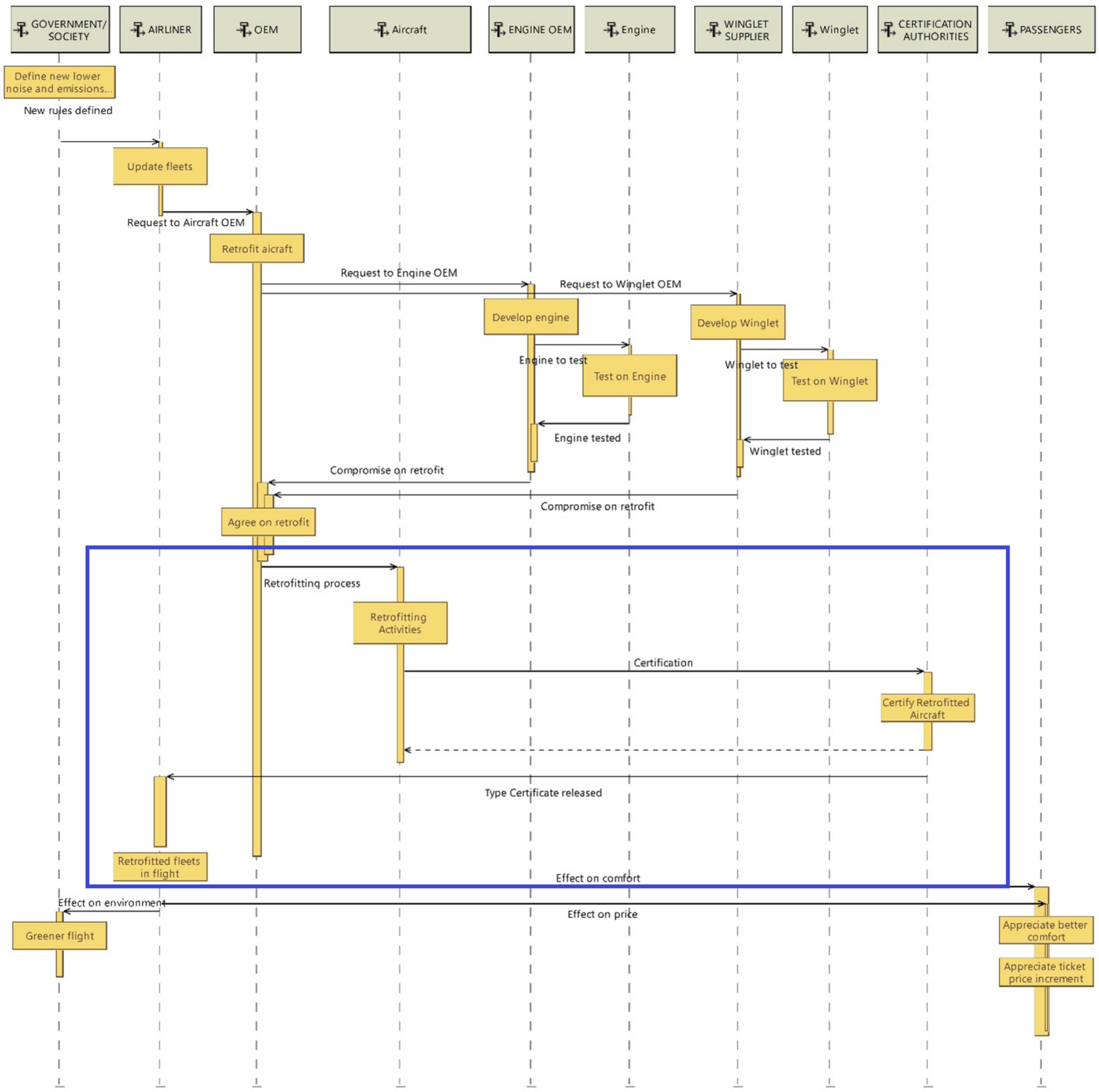


Figure 3.11: Sequence diagram developed in Capella tool to model the general retrofit scenario.

been considered also the possibility to add winglets as further retrofit technology, therefore, this aspect is not implemented in the *Retrofit* tool.

The scenario reported in Fig. 3.11 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 the Winglet supplier. The retrofitted aircraft, subject to in force rules, can be operated after certification process, aiming for fuel, emissions, and noise reductions. The benefits are appreciated from operators (Airliners) and passengers.

The blue box in Fig. 3.11 contains the activities whose costs are estimated by the *Retrofit* tool. and sub-scenario shown in Fig. 3.12 in detail. As stated before, the retrofitting operations are mainly carried out by OEM, distributed between several of its Departments.

- Engineering Department. It focuses on the engineering effort required for engine integration and system integration.
- On-board Systems and Avionic Department. The activities of this department concerns with the design of the on-board systems and the new avionic to be integrated.
- Production Department. After the research studies, the activities listed also in Fig. 3.10 are performed. In Fig. 3.13 there is an example of engine removal performed on an Airbus A340-600, necessary for maintenance purposes.
- Costs Department. This department performs cost estimates, in parallel with the progress of the program, and it concludes the agreements with suppliers.
- Flight Test Department. It carries out the flight test campaign for both research and certification purposes.
- Certification Authority. It is the regulatory authority that verifies if the retrofitted aircraft is in compliance with applicable airworthiness requirements established by the national air law. The updated fleet must be compliant with the environment restriction rules.

3.4.5 The Rationale behind the Tool

Retrofit tool objective is the calculation of the costs associated with a retrofit program. The logic behind the tool consists in estimating recurring and non-recurring costs through the hours and people needed to carry out the operations and their hourly costs.

Non-recurring costs. For each engineering activity described in section 3.4.3 the tool associates it a number of hours necessary to accomplish it. By multiplying

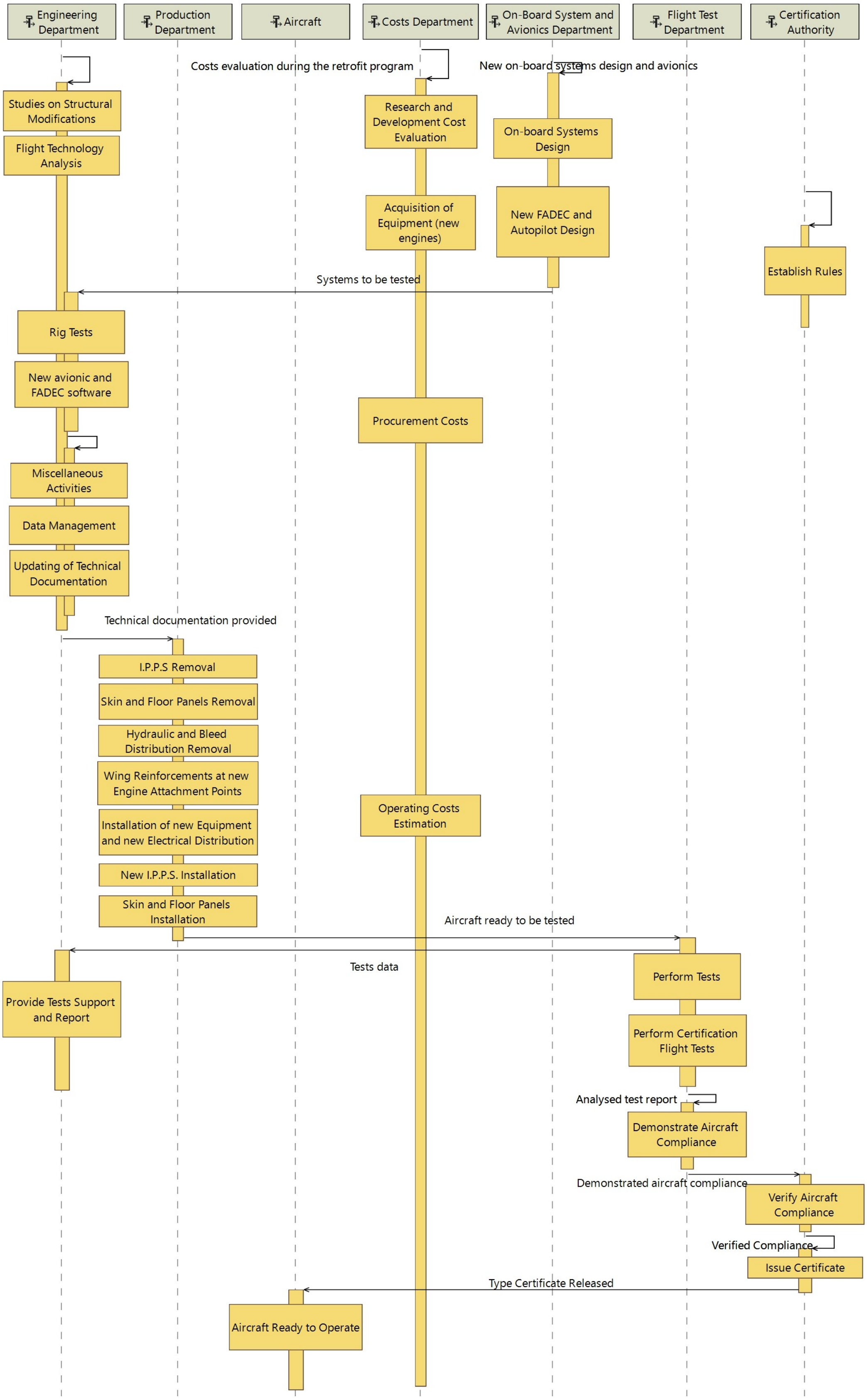


Figure 3.12: Sequence diagram developed in Capella tool to visualize the main events that occur in a retrofit program, whose costs associated are estimated by the *Retrofit* tool.

Figure 3.13: Removal of the Rolls Royce Trent 500 engine on an Airbus A340-600 [48].

the total number of hours by the engineering hourly cost, the result is the total engineering cost to carry out the aircraft modification.

Operations cost. In a similar way, the tool correlates every practical activity (shown in section 3.4.4) with the months necessary to carry them out. By multiplying the number of months by the operations hourly cost and the number of workers involved, the result is the total operations cost to realize the aircraft improvement.

By looking at the list of input parameters, in Tab. 3.17, it is possible to understand more in details the logic behind the *Retrofit* tool.

There is the possibility to simulate different scenarios, depending on the type of technology upgrade to be performed, through the variation of the input value, indicated in Tab. 3.17, as "Retrofit index", whose possible values are:

$$Retrofit\ index = \begin{cases} 1 & \text{if engine replacement} \\ 2 & \text{if engine replacement + MEA1 architecture} \\ 3 & \text{if engine replacement + MEA2 architecture} \\ 4 & \text{if engine replacement + AEA architecture} \end{cases}$$

If the user decides to upgrade the engines keeping the conventional on-board system architecture, the index to be inserted is equal to one. If the user decides to replace the engines and also to choose a more electric system architecture, the index corresponds to two or three. The main scenario corresponds to the more extreme innovation, which is the engine replacement with the adoption of the all

Description	Unit
Engineering hourly cost	€/hr
Wind tunnel tests hourly cost	€/hr
Flight tests hourly cost	€/hr
Operations hourly cost	€/hr
Hours per month required for operations	hr
Engine replacement workers needed	-
OBS replacement workers needed	-
New OBS architecture cost	€
New engines cost	€
Equipment costs for engine replacement	€
Learning curve rate - Recurring costs (%)	-
Minimum number of aircraft sold to obtain discount on equipment costs	-
Minimum discount on equipment costs (%)	-
Number of aircraft to be retrofitted	-
Retrofit index	-
Number of aircraft among which non-recurring costs are initially apportioned	-
Profit margin on non-recurring costs	-
Converter EUR/USD	-
List price of the aircraft to be retrofitted	€
Value of the aircraft at the retrofitting moment over value at the beginning of the operative life	-
Number of cycles done until retrofit over total operating number of cycles	-

Table 3.17: *Retrofit* tool input parameters.

electric architecture (index equal to 4). The other three intermediate solutions are subcases. The tool is developed to calculate the costs associated to the main scenario. The subcases cost components are treated as a percentage of those involved in the main case. There are several reasons and assumptions behind each percentage chosen, based mainly on the comparison between the different system architectures. For some of the non-recurring cost items listed in section 3.4.3, the percentages assumed for each retrofit scenario are shown in Tab. 3.18. The choice to adopt an higher by-pass ratio engine by maintaining a conventional architecture requires a modification of the engine-system interface. However, a certain amount of engineering study is necessary to plan a removal of fuselage

Non-recurring cost item	Retrofit type: Engine (%)	Engine + MEA1 (%)	Engine + MEA2 (%)	Engine + AEA (%)
Fuselage skin and floor panels removal and installation	10	60	30	100
Electrical generation	20	50	50	100
ECS electrical pack	0	0	100	100
Air conditioning distribution	0	0	100	100
FCS electrical actuation	0	100	0	100
RIG tests	0	50	30	100

Table 3.18: Example of *Retrofit* tool assumptions on Non-recurring costs estimation.

panels to access the systems and to change part of the electrical generation. A significantly larger amount of the fuselage panels disassembly cost is reserved for the other two scenarios. In MEA1 architecture, the flight control and landing gear actuators are electrically supplied, thus, FCS electrical actuation engineering cost is taken as a whole. All the pipes that transfer the hydraulic fluid must be replaced. The pipes travel from the nose landing gear up to the elevators, for this reason, the corresponding panels removal and installation cost percentage is high but not one hundred percent since it is not requested to remove the pipes from the engine to ECS PACKs. The ECS PACKs (Pressurization Air Conditioning Kit) and air conditioning distribution are not changed in this system architecture, as a consequence the corresponding percentages are equal to zero. The MEA 2 configurations is bleed-less like; while hydraulic power is still necessary to feed the actuators. The fuselage panes removal activity requires less effort than MEA1 since the ECS and Air conditioning PACKs and distribution are usually located near the wing-to-body fairing, beneath the fuselage. A fair division, between the two intermediate architectures, of the electrical generation cost was assumed. Rig tests are necessary since the new systems must be tested before being installed on board, the effort is proportionate to the magnitude of the proposed change.

In the following equation (3.7), an example of non-recurring cost computation is presented.

$$NRC_{Floor\,panels} = HR_{Floor\,panels} L_{eng} PERC_{arch} \tag{3.7}$$

$HR_{Floor\,panels}$	Hours for the design of floor panels removal and re-installation activities (hr)
L_{eng}	Engineering hourly rate (€/hr)
$PERC_{arch}$	Percentage factor to account for a reduction in hours (cost) depending on system architecture
$NRC_{Floor\,panels}$	Total non-recurring costs involved in the design of floor panels removal and re-installation activities (€)

A non-recurring cost is a capital expenditure, it is sustained prior to the first unit of production. Generally, non-recurring costs are initially apportioned over the first few units produced, as a consequence, the first upgraded aircraft will have an higher price than the rest. With the aim of determining the aircraft operating costs to perform a cost-benefit analysis of a retrofit program, it was chosen to distribute uniformly the capital cost among all aircraft of the retrofitted fleet, adding also a gain for the manufacturer through a profit margin (a percentage factor) that can be inserted as input. The amount of total engineering cost to be allocated to each refurbished aircraft is calculated through the expression 3.8.

$$NRC_{aircraft} = \frac{NRC_{total}}{Q}(1 + PRF_{NRC}) \tag{3.8}$$

NRC_{total}	Total retrofit program non-recurring costs (€)
Q	Number of aircraft retrofitted
PRF_{NRC}	Profit margin on non-recurring costs
$NRC_{aircraft}$	Non-recurring costs per aircraft (€)

A difference between different retrofit scenarios was also considered for the operation costs whose percentages reflect what has already been said for non-recurring costs. For the intermediate retrofit solutions, some activities require less time (are cheaper) since it is not necessary to operate massively on the entire aeroplane. In the following equation (3.9), an example of operation cost computation in presented.

$$RC_{Equip\,install} = MTH_{Equip\,install} HRS_{MTH} L_{ops} PPL_{sys} PERC_{arch} \tag{3.9}$$

$MTH_{Equip\,install}$	Months necessary to install new equipment on board (i.e. ECS, IPS, cables) ($month$)
HRS_{MTH}	Average monthly hours for operation activities (hr)
L_{ops}	Operations hourly rate (€/hr)
PPL_{sys}	Number of workers involved in the OBS replacement activities
$PERC_{arch}$	Percentage factor to account for a reduction in hours (cost) depending on system architecture
$RC_{Equip\,install}$	Total recurring costs involved in the installation of new equipment on board (€)

Operation costs, unlike non-recurring costs, are expenses to be sustained for the activities that take place on each single aircraft. The tool provides a learning curve for these costs to consider the phenomenon of increasing productivity as production accumulates. The user can insert the learning curve rate (see Tab. 3.17), the theory at the basis is the same adopted in *NR Cost* tool, showed in section 3.2.1. An example of learning curve with a rate equal to 95% is showed in Fig. 3.14.

The third cost item handled by the *Retrofit* tool to determine the total cost due to a retrofit program is reserved to equipment. Within the tool, equipment costs are composed of three main components, to be inserted as input values (see Tab. 3.17):

- **Engine**. The cost of new engines to be fitted.
- **Systems**. The cost of new on-board systems to be fitted.
- **Additional equipment**. Cost associated with additional ground and support equipment.

The *Retrofit* tool provides the possibility to consider a reduction of the equipment acquisition costs by simulating a possible agreement between manufacturer and supplier. This is the reason why, between the inputs of the tool (Tab. 3.17) there are also:

- Minimum number of aircraft sold to obtain discount on equipment costs (N_{DISC});

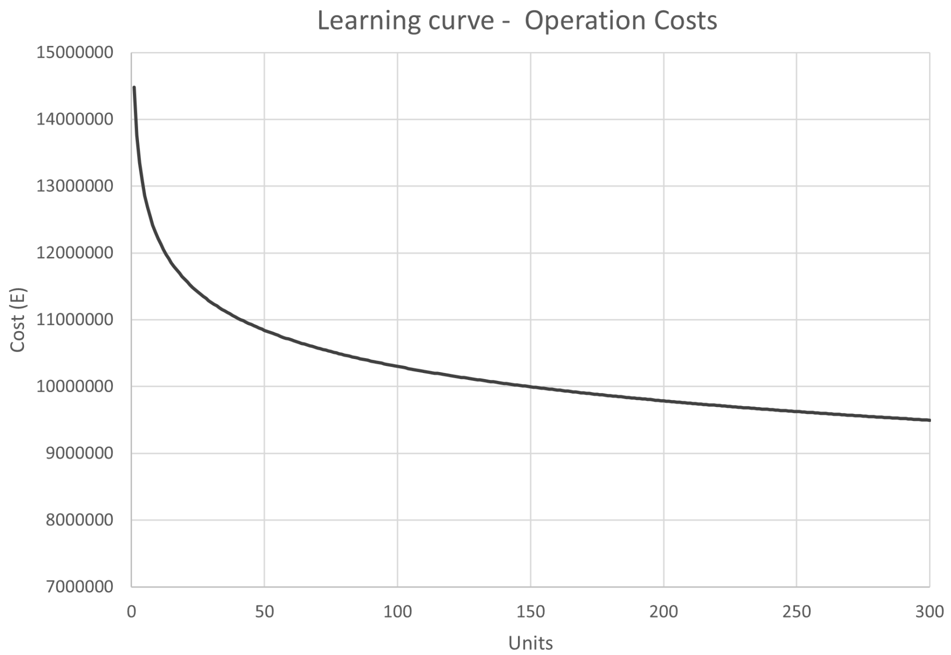


Figure 3.14: Example of learning curve adopted for the retrofit operation costs.

N_{DISC}	$DISC$ (%)
50	5

Table 3.19: Example of input values for modeling an agreement between manufacturer and equipment supplier.

- Minimum discount on equipment costs ($DISC$).

These two parameters allow the user to build the rule that regulates the manufacturer-supplier agreement. In Tab. 3.19 there is an example of possible input values through which it is assumed that every 50 aircraft to retrofit (every 100 engines purchased) the manufacturer applies 5 percent discount.

The final cost due to retrofit to be allocated to each aircraft is the sum of the three major costs previously explained. The final step to calculate the purchasing cost of the refurbished aircraft is to add its actual value to the retrofit costs. If the airline already owns the fleet before the retrofit program, the only expenditure to be incurred is due to the introduction of new technologies on the fleet. Therefore, with the aim of determining operating costs it is necessary to account for the value of the aircraft at the time it has been upgraded. From Tab. 3.17 it is shown that the user is

Cycles (% of lifespan)	Actual Value (% of acquisition value)
25	40
50	20
75	10

Table 3.20: *Retrofit* tool depreciation method parameters.

called to insert the list price of the aircraft to be retrofitted. Assuming that the fleet may not be upgraded at the beginning of the operative life, it is necessary to actualize the value of the aircraft at the moment of the retrofit program since it reduces as a result of wear and tear, age (deterioration) or obsolescence. Depending on whether the user knows the actual value of the aeroplane or not, among the inputs there are:

- Value of the aircraft at the retrofitting moment over value t the beginning of the operative life;
- Number of cycles done until retrofit over total operating number of cycles.

If the user does not know the value of the aircraft at the time of retrofit, the first input between the two listed above is set equal to zero. In this case, it is sufficient to indicate the number of cycles already carried out by the aircraft as an indication of the remaining aircraft lifespan, through which the tool is able to estimate the actual value. The cycle corresponds to one takeoff and landing, meaning engine start, climb, cruise, landing and shutdown. The method of apportioning the cost over such life behind the tool is an accelerated method of depreciation that allows greater deductions in the earlier years of the life. A depreciation curve through three points, suggested by the Leonardo Company, has been adopted (see Tab. 3.20), with a residual value (the expected salvage value) equal to 10% of acquisition value.

The most important *Retrofit* tool output, for operating cost estimations purpose, is the retrofitted aircraft price whose components are shown in Fig. 3.15.

3.5 Technologies as part of Multidisciplinary Design Analysis and Optimization

In this work, the preliminary cost studies are performed in the context of the multidisciplinary process developed inside the AGILE project. AGILE has

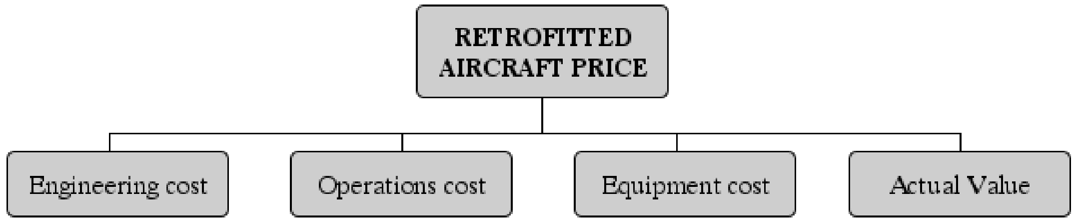


Figure 3.15: Components of the retrofitted aircraft purchasing cost.

shifted the focus on accelerating the deployment and the operations of collaborative, large-scale design and optimization frameworks [49].

3.5.1 Collaborative Design

Aircraft design account for the interaction of various disciplines such as structural mechanics, aerodynamics or flight mechanics. One method to control and manage the complexity of conceptual system engineering is through collaboration. The collaborative design approach ensures that the product is designed by experts from different backgrounds, able to give their contribution regarding the area in which they are specialized. The modern evolution of this way of working is the Collaborative Remote Design. It allows people from different locations to communicate and exchange their tools, methods and results through server connection.

The design tasks must be distributed among different teams and each team must have the possibility to use the tools generated by other teams to obtain data needed for their own tool. These are the basis for Multidisciplinary Design Optimization (MDO). MDO uses optimization methods to solve design problems; the innovative idea is to found the optimum by optimizing each discipline sequentially and exciting the interactions between the teams. So, in this way, the optimum of the simultaneous problem is superior than the optimum of each team [50].

Aiming at advancing the interdisciplinary collaboration between the various disciplines and realizing decentralized MDO architectures, the process efficiency can be enhanced by an open, central data model that serves as a common language [51]. This hypothesis has been proven by applying the Common Parametric Aircraft Configuration Schema in advanced preliminary aircraft design tasks including MDO.

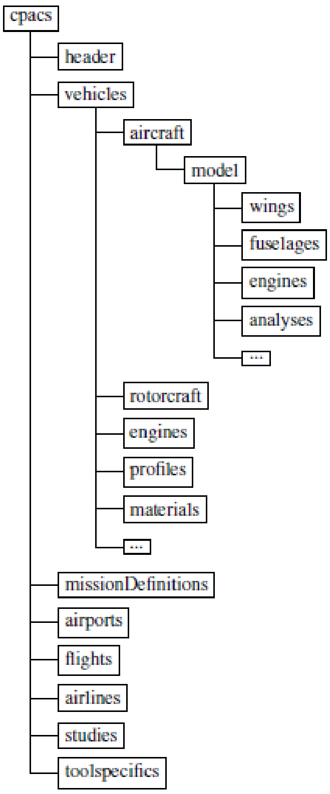


Figure 3.16: CPACS schema [52].

3.5.2 CPACS

The Common Parametric Aircraft Configuration Schema (CPACS) has been introduced and developed at the German Aerospace Center (DLR) since 2005. It is an Extensible Markup Language (XML)-based data format for the description of aeronautical systems [52].

In AGILE, CPACS is the means through which the partners efficiently communicate, exchange informations between their design and simulation tools. All the AGILE aircraft configurations are modeled using CPACS, and all the partners' simulation tools are CPACS compliant. The structure of CPACS mainly follows a top-down approach which decomposes a generic concept (e.g., an aircraft) into a more detailed description of its components (see Fig. 3.16).

CPACS offers information on aircraft operations such as on airports and airlines, missions and flights. To support the integration of tools in collaborative design environments the library TiXI [53] has been developed at DLR. It could be used

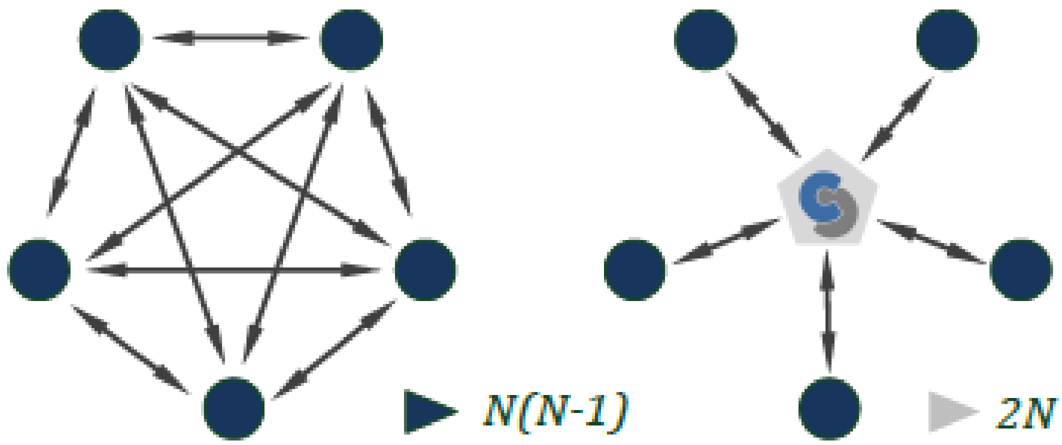


Figure 3.17: Tool interfaces without (left) and with (right) CPACS [52].

from applications written in C, C++, Fortran, JAVA and Python. Through this library the user can, for example, create documents, create and delete nodes, and add and remove element attributes of CPACS file.

The geometry library TiGL [54] provides the interface between the parametric CPACS description of the aircraft and the simulation tools. The library provides interfaces C, C++, Python, Java and MATLAB. In addition, the TiGL software package includes the TiGL Viewer that enables also the visualization of the aircraft geometries and other CAD files.

The full parametrization of the aircraft, obtained through the use of the central data exchange format, reduces a lot the possible directions of data exchange between N tools involved. As depicted in Fig. 3.17, by using this data format, the amount of data interfaces reduces from N(N-1) to 2N.

3.5.3 RCE

In AGILE the MDO processes are integrated as MDO workflows and executed by making use of PIDO (Process Integration and Design Optimization) environments [49]. One integration environment used in AGILE is the “Remote Component Environment” (RCE) [55], developed by DLR. The generic workflow is composed of built-in and user-defined components, the tools are merely viewed as black-boxes comprised of inputs and outputs, but no description of their internal behavior.

The tools are integrated as standalone components, with defined inputs and outputs. While executing the workflow, data dependencies between the components are automatically detected, and a component is executed as soon as all its input data are available [56].

The components of a multidisciplinary process can also be executed in a distributed manner, where the tools are located on different machines with different operating systems. In addition to user-integrated tools, RCE provides a number of predefined tools which can be used in conjunction with integrated tools to construct complex workflows. These predefined tools supply a multitude of basic functionalities such as reading and extracting data from files, manipulating XML, executing user-defined Python scripts. After integrating the tools required for the execution of the workflow, the user may compose them into a workflow.

To this end, RCE offers a Graphical User Interface (GUI), it is composed of different views and editors (besides standard GUI elements such as the menu bar, status bar) allowing the user to construct practically a workflow and do other operations.

3.5.4 Implementation of RCE Workflow

In order to perform an automatic cost analysis, the tools previously shown have been integrated in a workflow-driven environment (RCE) with python based codes. In the integration concept of RCE, an integrated tool is treated as a black box. It produces a CPACS output file having as input an initial CPACS file. To integrate a tool into RCE, the following requirements must be fulfilled:

- The tool must be executable without any user interaction during execution;
- The input data must only be command line parameters and files;
- All input files must be located in a specific folder;
- All output files generated by the tool must be written in a specific folder.

For this purpose, the tool directory must be copied in the RCE default tools directory. In particular, a generic tool directory contains the following files/folders:

- '*tool.py*'. It is necessary to allow the tool to work;

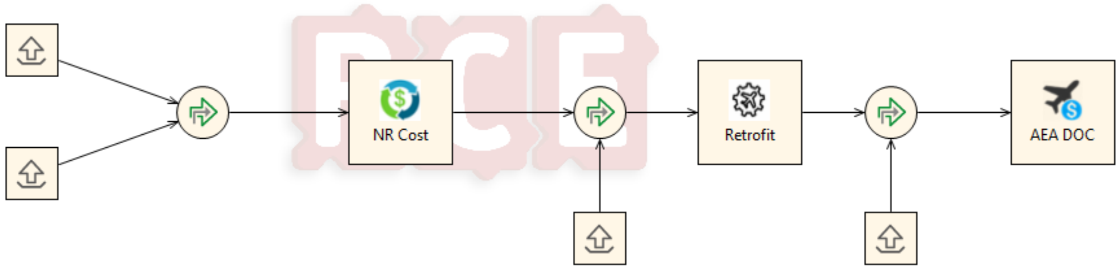


Figure 3.18: Visualization of the workflow implemented in RCE in order to perform cost analysis.

CPACS file	XML file that describes the geometry and main data of the configuration under analysis. It is merged with "Toolspecific" file.
Toolspecific file	XML file in which input parameters of the correspondent tool have to be inserted.

Table 3.21: Inputs required in order to execute the cost analysis workflow.

- '*mappingInput.xml*'. Through which RCE generates the tool input XML file as a subset of the incoming CPACS file XML structure, specified by a mapping file;
- Folder called '*ToolInput*' with '*toolInput.xml*' file which contains input data useful to launch the calculation;
- '*mappingOutput_tool.xml*'. Through which RCE merges the content of the tool output XML file into the origin incoming CPACS file, based on a mapping file;
- Folder called '*ToolOutput*' with '*toolOutput.xml*' file in which output data are written;
- Folder called '*ReturnDirectory*' to store some output after the run;

In Fig. 3.18 the workflow integrated by the author in RCE is presented while it Tab. 3.21 the inputs required to execute the workflow are listed.

The components indicated with an arrow that points up are the input providers, at the beginning of the workflow there are two input providers since one is used

```xml
<analyses>
  <massBreakdown>
  <trajectories>
  <monetaryValues>
    <nonRecurringCost>6.264e+06</nonRecurringCost>
    <recurringCost>
      <costDescription>
        <cost>4.0847e+07</cost>
        <description>Recurring costs per single aircraft ($)</description>
      </costDescription>
      <productionQuantity>500.</productionQuantity>
      <systems>
        <airConditioningSystems>
          <airConditioningSystem>
            <cost>637296.</cost>
            <description>Air conditioning system cost ($)</description>
          </airConditioningSystem>
        </airConditioningSystems>
        <auxilaryPowerUnits>
          <auxilaryPowerUnit>
            <cost>190481.</cost>
            <description>Auxilary Power Unit system cost ($)</description>
          </auxilaryPowerUnit>
```


Figure 3.19: Some costs data added in the CPACS file through *NR Cost* tool.

to collect the initial CPACS file while the other is necessary to add important auxiliary information to execute the tool (in this case *NR Cost* tool), included in the Toolspecific file. Some of this information concern some data that aren't present yet in the initial file (i.e. economic assumptions). The data included in this additional file will be added to initial CPACS thanks to another workflow component, the merger. It is represented as two arrows that seems to address a common direction of merging. Thanks to its mapping file it is possible to decide which tags of the CPACS file are desired to be moved or which tags have to be updated. The output of the merger component will be a new CPACS file that will be the input to the *NR Cost* tool. The main core of this tool is a python code whose function is to extract values from CPACS and transform that in an input file for the executable that will estimate recurring and non-recurring costs. The library that allows to find the data of interest analyzing the structure of the CPACS file is called TiXI Library (explained in section 3.5.2). The same python code will extract the cost data from the executable output file and add them in specific tags of CPACS file, an example is showed in Fig. 3.19.

The output CPACS file of the *NR Cost* tool become input file for the next *Retrofit* tool, to which the additional input data present in the toolspecific file will be added through another merger component. Also in this case, a python code allows the tool to work properly and without any user interaction. The *Retrofit* tool is developed in an Excel file, the python code accesses the excel file and updates it with data from the CPACS file. The output produced by the tool will be extracted from the Excel file through the python code and added in specific tags of the CPACS file. The retrofitting tool is located between *NR Cost* and *AEA DOC* tools. It calculates the new aircraft version unit price, from which the updated operating costs will be estimated. The way the *AEA DOC* tool is integrated in the framework, the structure of the python code and the way in which information is exchanged are the same described for *NR Cost* tool.

4

Application of the Cost Analysis Process

Contents

4.1 Introduction

In the previous chapter, the cost tools have been validated and applied to determine the capital and operating costs of existing aircraft (respectively, Embraer E190 and Airbus A320). As stated previously, the proposed methodologies turn out to be crucial in the early stage of a new aircraft program. In this respect, the aim of the work here presented is to offer a fast and reliable way for taking into account costs considerations since the conceptual phase.

The baseline of the analysis shown in this Chapter has been designed during the AGILE project. In the following sections the estimation of recurring, non-recurring and operating costs of the baseline aircraft is provided, then the retrofit candidates will be applied on it and subjected of a cost-benefit analysis.

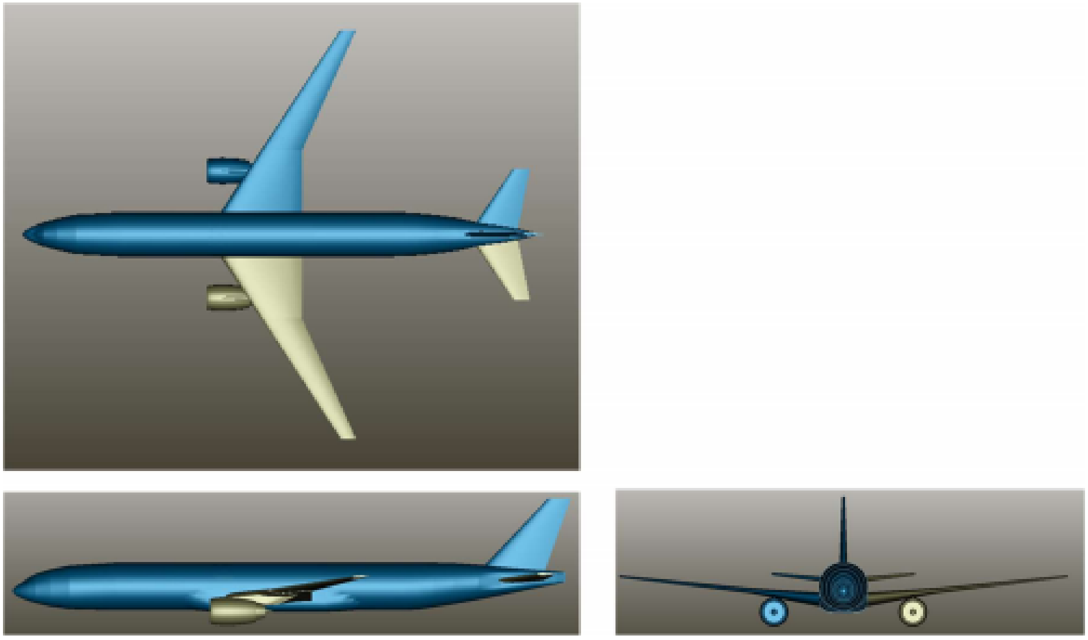


Figure 4.1: Baseline aircraft 3-Views.

Parameter	Value	Unit
S	81.4	m^2
b	21.18	m
AR	9.09	-
MAC	3.796	m
l_f	34	m

Table 4.1: Baseline aircraft geometries.

4.2 Test Case: Baseline Aircraft

The reference aircraft is a short-medium range regional turbofan of 90 passengers. The aircraft mounts two turbofan engines with a BPR = 5.4 (like GE-CF34) and EIS = 2010. The representation of its geometry, described through CPACS file, is shown in Fig. 4.1.

The main geometrical dimensions are summarized in Tab. 4.1. The main aircraft masses estimated in the AGILE project are listed in Tab. 4.2. For the DOC estimation, two scenarios have been analysed: a design mission and a typical mission.

Parameter	Value	Unit
OEM	23445	kg
$MTOM$	39480	kg
PL	9180	kg
m_{fuel}	6434	kg
m_{oper}	2091	kg

Table 4.2: Baseline aircraft mass data.

Maximum speed	460	kt
Altitude at maximum speed	36000	ft
Number of engines	2	-
Composite material index	0	-
Number of propellers	0	-

Table 4.3: Data for Agile baseline aircraft price estimation.

4.2.1 Cost evaluation

Recurring and Non-recurring costs. The objective of this first cost analysis, performed through the use of *NR Cost* tool is the determination of the aircraft price. The proposed methodology is fully integrated into a framework for preliminary aircraft design studies, which allows for multidisciplinary design optimization (see section 3.5.4). In Tab. 4.3 and Tab. 4.4 the aircraft data and the economic assumptions are respectively resumed. The cost of flight tests is an input value suggested by an expert by Leonardo Company and calculated by multiplying the cost for each hour of flight tests (7000 $/hr) by an average number of flight test hours. The cost of the engine, whose architecture is like the General Electric CF34 and a BPR=5.4, has been assumed within the AGILE project, equal to three million dollar. The number of production units has been chosen based on the number of deliveries of similar regional aircraft (Embraer E-190 and Bombardier CRJ900 [1] [2])

As described in the previous chapter, each aircraft component recurring cost is a function of the component weight and the targeted units (Beltramo et al. [14]). Therefore, this cost tool takes in input a CPACS file in which the geometry and

[1]https://en.wikipedia.org/wiki/Embraer_E-Jet_family
[2]https://en.wikipedia.org/wiki/Bombardier_CRJ700_series

Production units	500	-
Pre-series quantity	2	-
Test articles quantity	1	-
Development quantity	1	-
Production rate	4	-
Year of cost estimation	2020	-
Inflation	0.02	-
Cost of one engine	3000000	\$
Cost of flight tests	11000000	\$
Cost of operational items	2000000	\$
Cost of avionics	1000000	\$
Engineering labour rate	100	$\$/hr$
Tooling labour rate	60	$\$/hr$
Manufacturing labour rate	49.22	$\$/hr$
Profit for global recurring costs	0.1	-
Profit for non-recurring costs	0.1	-
Overhead cost ratio	0.1	-

Table 4.4: Economic assumptions for AGILE baseline aircraft price estimation.

weights data of the aircraft are well established. The detailed weight breakdown is presented in Tab. 4.5. The results are shown in Tab. 4.6.

DOC. The estimation of the operating costs has been carried out by means of the *AEA DOC* tool, as usual for this kind of assessment, it is necessary define the economic scenario (see Tab. 4.7). Table 4.8 summarizes the weights and performance data necessary for the calculation. The manufacturer standard study price corresponds to the result of *NR Cost* tool, previously executed. Fuel price is updated to November 2020 and obtained from IATA website. The Certificated noise levels have been assumed looking at data from similar aircraft while the rates for both noise and emission charges calculation refer to Stockholm Arlanda Airport [44] updated to 2020, except for the rate for carbon monoxide assumed by the author equal to the one for NO_x. The quantities of NO_x and CO exhausted in the Landing and Take-Off Cycle are the result of the *Engine Retrofit* tool, inserted in the workflow before the costs tool.

The results are shown in Table 4.9 and Table 4.10.

Weights		
Wing	10706	*lb*
Horizontal tail	931	*lb*
Vertical tail	696	*lb*
Fuselage	13100	*lb*
Landing gear	2707	*lb*
Nacelle	0	*lb*
Pylon	1111	*lb*
Engine installation	6995	*lb*
Fuel system	407	*lb*
Flight controls	1179	*lb*
Hydraulic system	1465	*lb*
Electrical system	1385	*lb*
Air conditioning system	628	*lb*
Anti icing system	105	*lb*
Auxiliary power unit	181	*lb*
Furnishings and equipment	4837	*lb*
Instruments	438	*lb*
Avionic installation	1013	*lb*
Tail	1466	*lb*

Table 4.5: AGILE baseline weights data for price estimation.

Parameter	Value	Unit
Recurring costs	28.92	*mil.*$
Non-recurring costs	6.226	*mil.*$
Profit on RC	2.892	*mil.*$
Profit on NRC	0.623	*mil.*$
Overhead costs	3.514	*mil.*$
Aircraft price	**42.17**	***mil.*$**

Table 4.6: Results for AGILE baseline aircraft price estimation.

4.3 Retrofitting activity

The retrofitting activity simulated in this document aims to retrofit the AGILE 90-pax regional jet aircraft presented in section 3.1. The candidate retrofit technologies, designed and analysed within AGILE project, have been showed in details in section 3.4.2. The objective of this study is to show which are the consequences of the modernization of the fleet on the aircraft operations. The way the aircraft operates is a direct consequence of its performances, for this reason, the workflow

Manufacturer standard study price	42.17	$mil.\$$
Engine price	3.0	$mil.\$$
Passengers number	90	-
Attendants number	2	-
Year of cost estimation	2020	-
Depreciation years	15	$years$
Inflation	0.02	-
Residual value	10.0	% of TI
Yield	0.45	$\$/pax.nm$
Fuel price	1.05	$/U.S. gal
Departure airport threshold noise	82.0	$EPNdB$
Arrival airport threshold noise	89.0	$EPNdB$
Certified noise level at the approach measure point	91.0	$EPNdB$
Certified noise level at the lateral measure point	97.0	$EPNdB$
Certified noise level at the fly-over measure point	94.0	$EPNdB$
Unit noise rate	3.49	$
Unit rate for NOX	11.6	$
Unit rate for CO	11.6	$

Table 4.7: Economic assumptions for DOC estimation of AGILE regional turbofan aircraft.

Performance		
	Design mission	Typical mission
Sector (NM)	1820	720
Block fuel (kg)	5641	2752
Block time (hr)	4.29	1.83
Emission value of NOX (kg)	14.87	15.02
Emission value of CO (kg)	0.29	0.31
Weights		
MTOW (kg)	39480	
PLD (kg)	9180	
MEW (kg)	21730	
BENGW (kg)	1100	
Engine Data		
Thrust (t)	7.97	
BPR	5.4	
Number of compressor stages	13	
Overall pressure ratio	29	
Number of shafts	2	

Table 4.8: Data for DOC estimation of AGILE regional turbofan aircraft.

	\$/bhr	\$/flight
DOC_{dep}	921	3951
DOC_{int}	813	3488
$FINANCIAL\,COSTS$	**1734**	**7439**
DOC_{ins}	68	292
DOC_{fuel}	462	3951
$DOC_{cockpit\,crew}$	911	3908
$DOC_{cabin\,crew}$	299	1283
DOC_{maint}	799	3428
DOC_{lnd}	72	309
DOC_{nav}	349	1497
DOC_{grd}	395	1694
DOC_{noise}	20	86
DOC_{emiss}	41	176
$CASH\,DOC$	**3416**	**14655**
DOC	**5150**	**22095**

Table 4.9: Agile4.0 Baseline DOC estimation for the 1820 NM design mission.

	\$/bhr	\$/flight
DOC_{dep}	1050	1921
DOC_{int}	927	1696
$FINANCIAL\,COSTS$	**1977**	**3617**
DOC_{ins}	78	119
DOC_{fuel}	528	966
$DOC_{cockpit\,crew}$	911	1667
$DOC_{cabin\,crew}$	299	547
DOC_{maint}	1012	1852
DOC_{lnd}	168	271
DOC_{nav}	324	593
DOC_{grd}	926	1694
DOC_{noise}	46	84
DOC_{emiss}	97	177
$CASH\,DOC$	**4389**	**8032**
DOC	**6366**	**11649**

Table 4.10: Agile4.0 Baseline DOC estimation for the 720 NM typical mission.

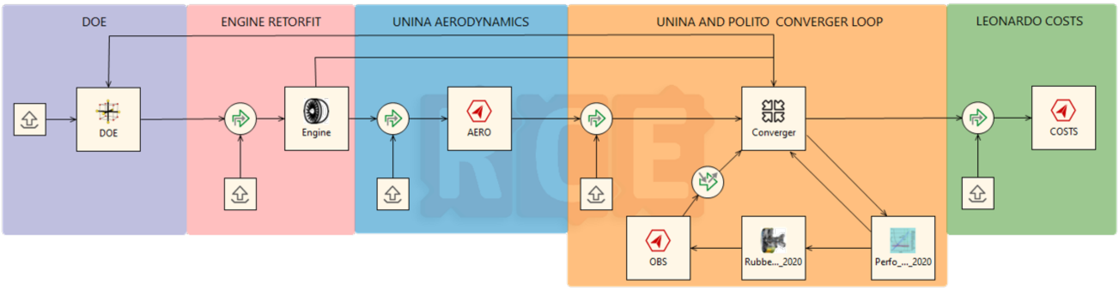


Figure 4.2: DOE process in RCE.

described in 3.5.4 is implemented in a Design of Experiments (DOE) process in order to evaluate the dependence of the retrofit technologies on the aircraft performances.

4.3.1 Design of Experiments

Through the AGILE 4.0 project technologies there is the possibility to create trade-off studies in a fast and efficient way. The workflow showed in Fig. 3.18 is implemented in a Design Of Experiments process in order to evaluate the dependence of the engine BPR and OBS architectures variation on the aircraft performances. The presence of the DOE module in the workflow reported in Fig. 4.2 permits to execute the sequence for each discrete value assumed by the independent variables (BPR, OBS).

Varying the BPR, the Engine module will estimate the new engine characteristics that will directly have an influence on the aircraft aerodynamics, calculated by the AERO module. In the Converger loop there is the Perfo tool whose function is to calculate the aircraft performances and the OBS tool that will size the correspondent architecture. A new OBS architecture means a new weight and a new engine SFC. The specific fuel consumption influences the performances and also the WTO will directly change. It is clear that in the Converger loop there is a snowball effect until the convergence is reached. The updated CPACS file is the input for the COSTS module, in which *NR Cost*, *AEA DOC* and *Retrofit* tools work.

Engineering hourly cost	80	€/hr
Wind tunnel tests hourly cost	5000	€/hr
Flight tests hourly cost	7000	€/hr
Operations hourly cost	80	€/hr
Hours per month required for operations	160	hr
Engine replacement workers needed	50	-
OBS replacement workers needed	60	-
Equipment costs for engine replacement	2.0	$mil.$€
Learning curve rate - Recurring costs (%)	95	-
Minimum number of aircraft sold to obtain discount on equipment costs	50	-
Minimum discount on equipment costs (%)	5	-
Number of aircraft to be retrofitted	300	-
Number of aircraft among which non-recurring costs are initially apportioned	10	-
Profit margin on non-recurring costs	0.10	-
Converter EUR/USD	1.22	-
List price of the aircraft to be retrofitted	34.6	$mil.$€
Number of cycles done until retrofit over total operating number of cycles	0.50	-

Table 4.11: *Retrofit* tool general input parameters for AGILE baseline regional aircraft.

4.3.2 DOE Application: Different Retrofit Scenarios

Since the *Retrofit* tool allows the choice of different technologies to be retrofitted, the user has performed several combination between the possible scenarios in terms of engines and on-board systems architectures. Different solutions can be taken into account and as a consequence, the operation, engineering and equipment costs are different in case of partial or total electrification of OBS architecture and different engines. Therefore, in Tab. 4.11 the general inputs common to all scenarios are listed.

A great part of the input data has been suggested by Leonardo Company as these are information concerning industrial processes, difficult to find from public sources. The list price of the aircraft to be retrofitted corresponds to the AGILE regional turbofan price estimated through *NR Cost* tool (see section 4.2.1), expressed in Euro instead of Dollars using the converter EUR/USD in Tab. 4.11. A number of 300 aircraft to be converted has been selected based on a mean value of the

	BPR = 9	BPR = 12	BPR = 15
New engines cost ($mil.$\$)	8.0 (x2)	8.5 (x2)	9.0 (x2)

Table 4.12: Assumption on the advanced engines costs.

($mil.$\$)	Conventional	MEA1	MEA2	AEA
BPR = 9	19.62	31.35	31.60	34.49
BPR = 12	20.32	32.06	32.31	35.20
BPR = 15	21.02	32.77	33.02	35.91

Table 4.13: Retrofit investment for each combination of engine and OBS architecture.

number of similar regional aircraft in service (e.g. Embraer E170, E190, E195, Bombardier CRJ900). As first choice, the existing fleet is upgraded at 50% of operating life. For this specific aircraft category, the possible number of cycles per operative life is one hundred, it means that the retrofitted fleet has at least other fifty thousand cycles to operate.

The rest of the inputs, which concerns the equipment costs, changes with the type of technology that has been decided to implement. In Tab. 4.12 the assumptions on the high BPR engine costs are listed. The last components of equipment costs, as already explained in section 3.4.5, is the cost of the new on-board systems to be fitted. This parameter is taken directly through the Python code from the output CPACS file of *NR Cost* tool which computes the OBS costs through Beltramo et al. methodology [14] (as a function of each component weight). The main result is the estimation of the retrofit investment on each aircraft of the existent fleet and, as a consequence, the new aircraft purchasing cost. From Tab. 4.13 it is clear that the more advanced is the retrofit technology the higher is the investment on each aircraft. A re-engining program replaces the two engines at a cost of \$21 million. The total cost of all retrofits is at least \$31 million up to \$36 million.

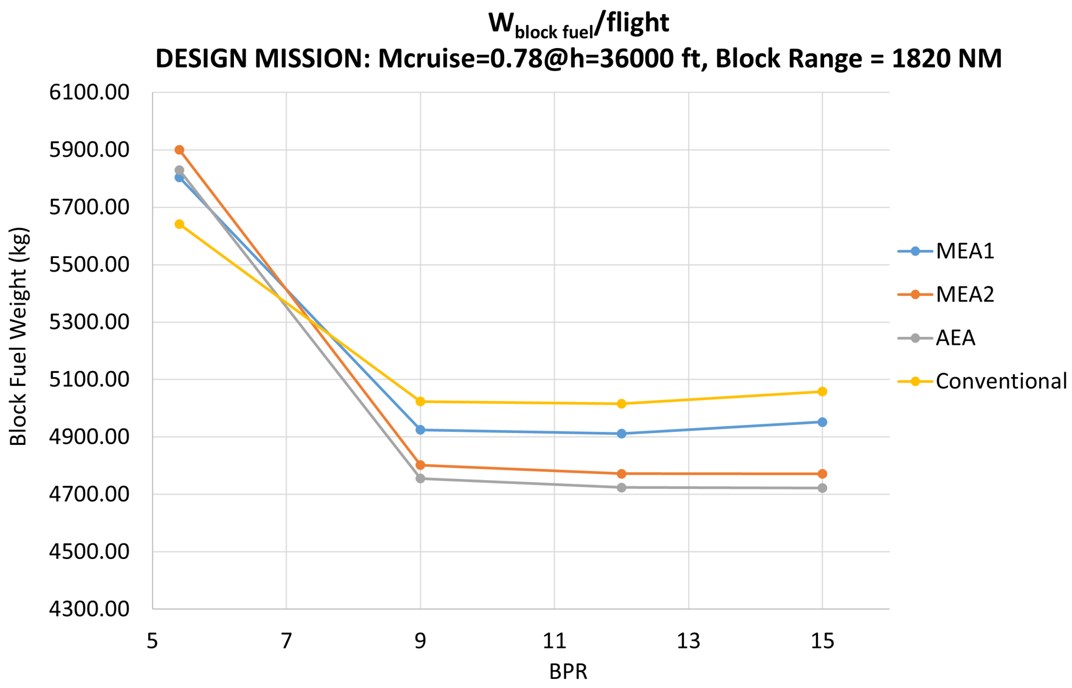
At this point, the performance and economic consequences of the retrofit program on the existing fleet can be presented.

4.3.3 Performance and Operating Cost Comparison

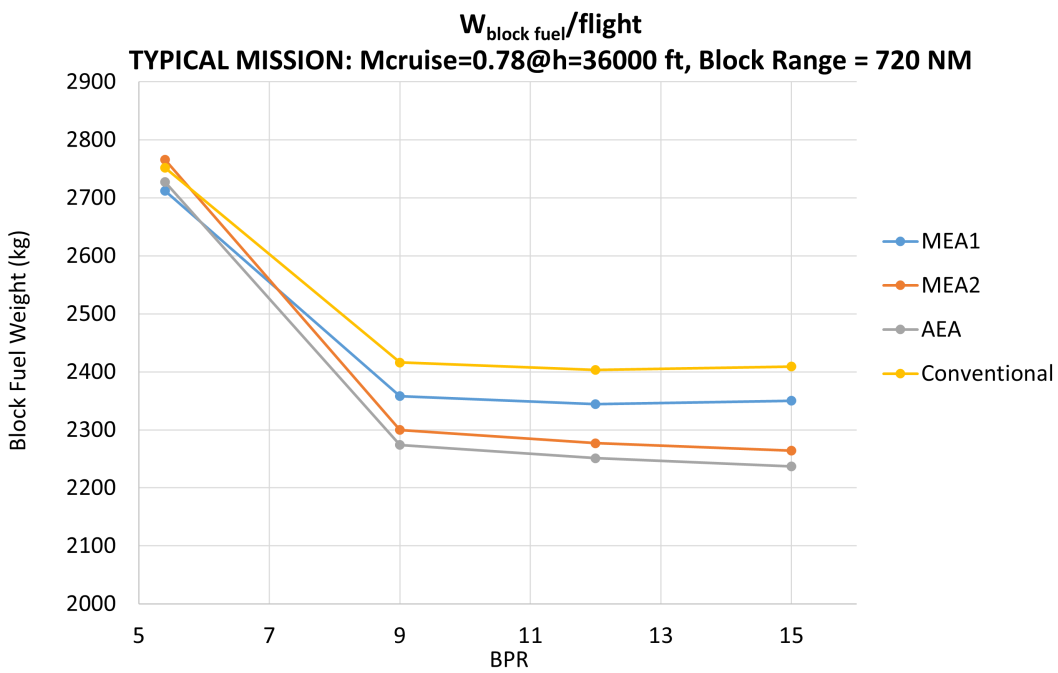
The rationale behind the high bypass ratio engines is to achieve a greater propulsive efficiency and lower SFC with the increasing of by-pass to core air. On the negative side it increases engine physical size, weight and drag for a given thrust. To reduce fuel burn, the contribution to fuel burn from SFC reduction has to be greater than the increase from the weight and drag increases. However, also the innovative on-board systems architectures produce a saving in fuel consumption. This saving ascribes to the innovative high voltages actuators, with the removal of hydraulic power. The analysis have been computed for both design and typical missions, already cited in section 4.2.

The 9 by-pass ratio geared turbofan engine brings to a 13 percent reduction of SFC in cruise relative to the conventional 5.4 by-pass ratio engine. Further increasing the BPR from 9 to 15 involves an additional 5 percent reduction of SFC. From Fig. 4.3 it is clearly shown that the reduction of specific fuel consumption results in a consistent reduction of the block fuel weight with the increase of bypass ratio. It is interesting to notice that maintaining constant the bypass ratio, there is a variation of the fuel consumed during the mission by varying exclusively the OBS architecture. All the innovative architectures produce a saving in fuel consumption. The examination of the results brings to the fact that the MEA 1 architecture is less fuel efficient than the two other bleed-less innovative configurations considered. AEA architecture is the one which brings the highest advantage: this ascribes to both the removal of bleed air and the hydraulic distribution systems. Considering the typical mission, with the retrofitted fleet, there is a reduction of fuel consumed per flight that goes from 12% up to 19% (see. Fig. 4.4). The lower reduction corresponds to the less extreme modification that is adoption of BPR 9 engines, the greater fuel reduction is achievable by completely electrifying the systems and mounting BPR 15 engines.

Another aspect to highlight is the overall emission of CO_2. By assuming an emission index of 3.180 kg of CO_2 per 1 kg of fuel burned, the saved fuel per flight of about 515 kg implies a reduction of about 1638 kg of CO_2 per flight. Furthermore,



(a) *Design mission*



(b) *Typical mission*

Figure 4.3: Block fuel weight variation with BPR and different OBS architectures.

%	Conventional	MEA1	MEA2	AEA
BPR = 9	-12.2	-14.3	-16.4	-17.4
BPR = 12	-12.7	-14.8	-17.3	-18.2
BPR = 15	-12.5	-14.6	-17.7	-18.7

Figure 4.4: Heatmap showing block fuel savings achievable with the retrofit options, typical mission.

	Baseline	RE-1	RE-2	RE-3
Block Fuel Weight (t/year)	6897	5699	5641	5606
CO_2 emitted (t/year)	21931	18122	17938	17827

Table 4.14: Block fuel weight and CO_2 emission comparison between baseline and the retrofitted configuration, typical mission. RE-1: AEA+BPR=9, RE-2: AEA+BPR=12, RE-3: AEA+BPR=15.

from Tab. 4.14 it is possible to consider that there is a decrease of more than 4100 tonnes per year in terms of emitted CO_2 mass.

The installation of the new engines coupled with a partial or total electrification of the on-board systems has an impact on the mass at take-off, see Fig. 4.5. At fixed BPR, the MEA1 architecture brings to the higher maximum take-off mass reduction. This result is due to the absence of hydraulic generation and distributions which brings to a considerable total systems weight reduction (- 27%). The MEA2 architecture seems to be the less convenient in terms of WTO reduction because the absence of bleed air systems results in a reduction of the total power plant weight compensated by a slight increase of the total system weight because of an heavier electrical generation. In the end, AEA architecture couples the characteristics of both intermediate ones. Moving towards higher by-pass ratios, the minimum WTO is reached at BPR=9 mainly because of the diminution of fuel mass to accomplish the mission (with respect to the baseline). At higher by-pass ratios, the advantage due to the further reduction of fuel mass (showed in Fig. 4.4) is dampened by the inevitable increase in engine mass.

It is well known that turbofan engines technology advances towards higher bypass ratios, driven by fuel efficiency, but also with the acoustic benefit of lower jet noise levels from the reduced jet exhaust velocity. At the actual moment a tool to estimate the reduction of noise levels due to new technologies is not yet

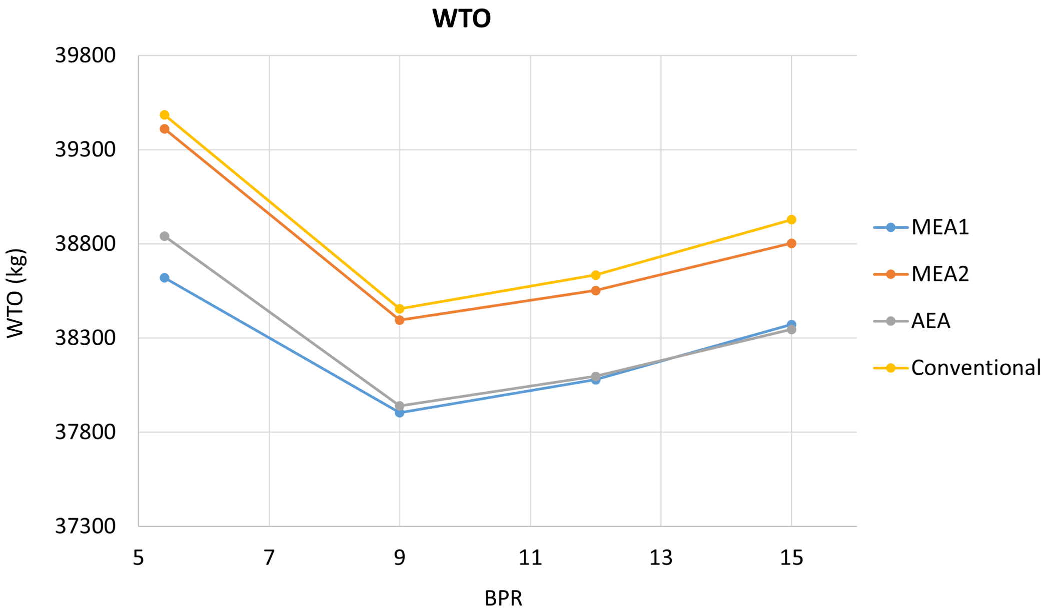


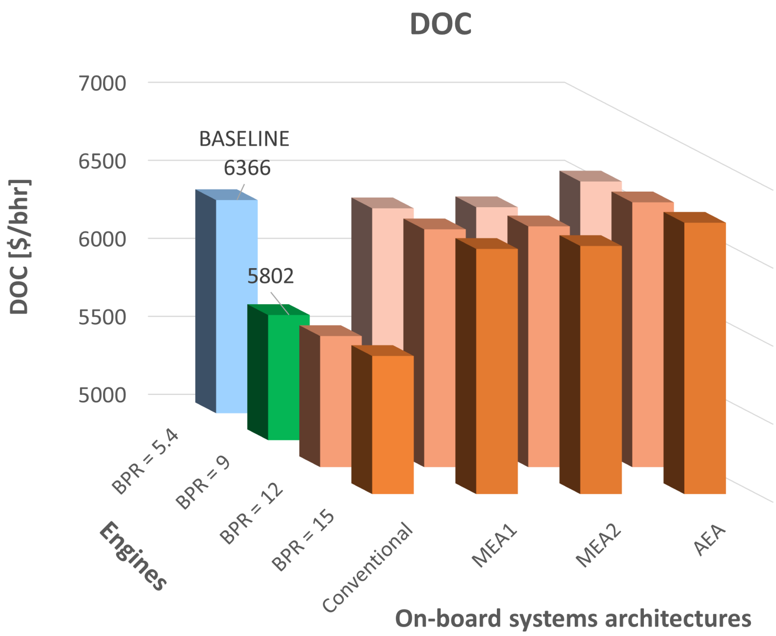
Figure 4.5: Maximum take-off mass variation with BPR and different OBS architectures.

available in the RCE framework, but it is in progress. However, EASA publishes a database of certification noise levels containing all approved aircraft configurations. The database covers aircraft for which EASA has issued a type certificate data sheet for noise [57]. Within this database, the data have been filtered in order to consider the noise levels related exclusively to Embraer E190 and E190-E2. These two regional aircraft, mount respectively two turbofan General Electric CF34-10E (BPR = 5.4) and two geared turbofan Pratt and Whitney PW1919G/21G/22G/23G (BPR = 12). Given the strong similarities between these engines and those mounted on the AGILE aircraft in conventional and advanced configurations, it is worth mentioning the Embraer noise certificated levels. Tab. 4.15 clarifies that increasing the by-pass ratio from 5.4 to 12 results in a reduction of 14 EPNdB (cumulative). With a simple linear regression apllied on EASA database, it turns out that with a BPR=15 engine an additional reduction of 6 EPNdB on the cumulative noise level is reached. However, it is necessary to highlight that the noise sources, as the techniques for noise reduction, are not all due to the engine technology but they are also linked to airframe and control surfaces.

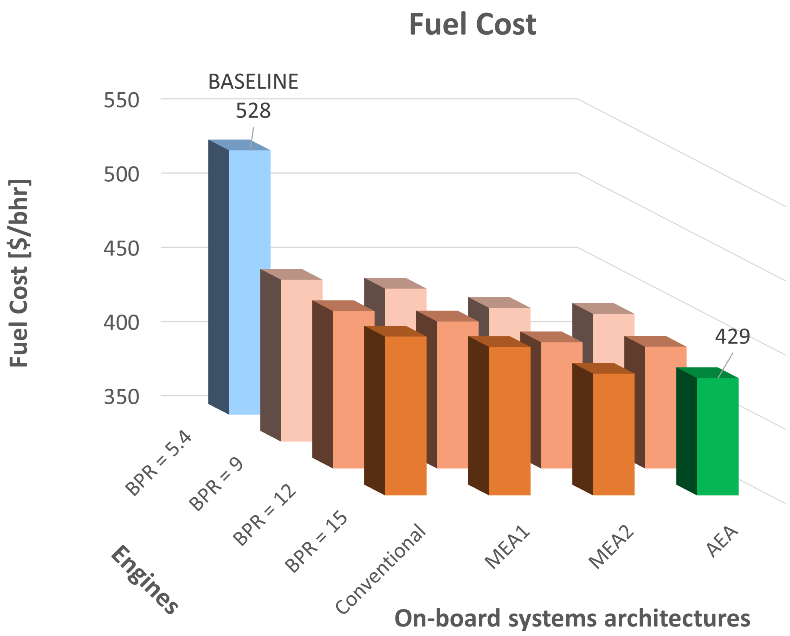
	Noise Levels (EPNdB)			
	Lateral	Flyover	Approach	Cumulative
E190 (GE CF34-10E)	92	84	93	269
E190-E2 (PW1919G)	86	77	92	255

Table 4.15: E190 and E10-E2 certification noise levels [57].

The operating costs of the retrofitted aircraft can now be estimated, after the evaluation of the retrofit investment computed by the *Retrofit* tool. For this specific aircraft category, the lifespan in terms of cycles is around one hundred thousand. It has been assumed that the existing fleet is retrofitted after the first half of the operative life and the remaining operative life will be approximately the 67 percent of the total one. An additional percentage has been allowed because it is hoped that with the retrofit intervention the fleet operative life gets a bit longer. This concept has a direct effect on the depreciation period: recovery time period in which the aircraft manufacturer recoup the initial cost via tax deductions to be sustained by airlines. A refurbished aircraft is not likely to last as a new one so the depreciation period chosen is ten years, instead of 15 years used for new aircraft. As a consequence the financial part of DOC is significant. In terms of direct operating costs, the technologies bring surely a reduction in fuel costs. However, many of the revolutionary aircraft technology concepts offer other benefits than fuel efficiency. An important motivation to adopt a more electric system architecture is the more intelligent and ease maintenance coupled with an increased aircraft reliability. There is reason to think that the maintenance costs can be reduced also with the installation of new, more innovative engines. *AEA DOC* tool computes a slight reduction of maintenance costs with the increase of BPR. Nevertheless, the theory behind *AEA DOC* tool dates back to the year 1989, it is clear that some operational benefits from the adoption of such innovative technologies are not taken into account. The 3D bar graph showing the DOC value per block hour for each retrofit option is reported in Fig. 4.6.



(a) *DOC per block hour*



(b) *Fuel cost per block hour*

Figure 4.6: DOC and Fuel Cost variations with BPR and different OBS architectures, Typical Mission (green columns represent the minimum values).

Conclusions and Future Developments

For this specific aircraft category, the possible number of flights per day could be equal to 7 and it could work per 358 days per year, assuming 7 days for maintenance check A and B. From Tab. 4.16 it is clear that refurbished aircraft,

	Baseline	RE-BPR=15	RE- AEA+BPR=15
DOC (\$/bhr)	6366	5885	6739
DOC (*mil.*\$/year)	23.93	22.12	25.33

Table 4.16: Direct Operating Cost comparison between baseline and two retrofit options, typical mission.

featured with new high bypass ratio engines, is less expensive to operate. This is due mainly to its low purchasing cost and lower fuel costs. The re-engine aircraft can operate for approximately 67000 cycles, period in which the airline operator is going to save \$48 million over operating the baseline configuration. The huge retrofit investment involved in a program which consists in a modification of both powerplant and OBS architecture, implies an increase in operating costs caused by high depreciation and interest costs.

The re-engine retrofit solution seems to be a very attractive solution for the airlines who want to modernise their existing fleet to benefit from a reduction in operating costs and at the same time face with emission trading, new noise rules, increasing fuel prices, new ATM environment and passenger expectations to enjoy and higher level of comfort.

With the integration of the automated cost process in the distributed design environment (RCE) it has emerged that aircraft design has to be driven by a well-balance trade-off between performance and cost that leads to an affordable and suitable product life cycle for the operators. Thanks to CPACS, the common parametric language file format, it is possible to easily exchange the information between different disciplines or modules. Within the collaborative design structure, all the information generated by the developed process are stored in a CPACS file accessible to anyone belonging to the same collaborative structure.

As future development, a more rigorous operating cost methodology to better support designers in making reasonable decisions at early design stage can be matured. While technology, in aerospace industry was the main driver in the past, nowadays there is demand of cost reduction to satisfy customers' needs. However the *Retrofit* tool can be further applied to implement several technologies, as winglets or enhancements of cabin design.

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