# POLITECNICO DI TORINO

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**Master of Science degree**
**in Aerospace Engineering**

M.Sc. Thesis

# RAMS and Maintenance cost assessment in a Multidisciplinary Design Optimization environment

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# Contents


1. Introduction ..... 1
  1.1 Maintenance efficiency by design ..... 1
  1.2 Problem statement and aim of the thesis ..... 4
  1.3 Research scope ..... 6
    1.3.1 Composite structure ..... 6
    1.3.2 Laminar flow wing ..... 10
    1.3.3 Electro-hydrostatic actuators ..... 12
  1.4 Thesis outline ..... 14
2. State of the art: literature review ..... 15
  2.1 RAMS ..... 15
    2.1.1 Definition and terminology ..... 15
    2.1.2 State of the art ..... 16
  2.2 Maintenance, Repair and Overhaul in civil aviation ..... 26
    2.2.1 Objectives and prescriptions ..... 26
    2.2.2 State of the art ..... 28
3. Research methodology ..... 32
  3.1 Overview ..... 32
  3.2 Theoretical modification of the models for conventional aircraft ..... 33
    3.2.1 RAMS model update ..... 33
    3.2.2 Maintenance cost model update ..... 36
  3.3 Modification of the models for innovative aircraft ..... 38
    3.3.1 Maintenance process modelling ..... 38
    3.3.1 Qualitative and quantitative analyses ..... 65
    3.3.2 Equations modification ..... 69
4. Implementation and execution ..... 72
  4.1 Simulation environment ..... 72

4.2 Models set-up in RCE ... 73
4.2.1 RAMS set-up ... 73
4.2.2 Maintenance cost set-up ... 74
4.2.3 Operating costs tool: definition and set-up ... 76
4.2.4 Overview of the workflow ... 77
4.3 Reference aircraft ... 81
4.4 Conventional execution ... 82
4.4.1 Inputs ... 83
4.4.2 Outputs ... 85
4.5 Innovative test ... 91
4.5.1 Impact of singular solutions ... 91
4.5.2 Impact of combined solutions ... 112
4.6 RAMS and Maintenance influence in Aircraft Design ... 115
5. Future work ... 116
5.1 New approach for MMH/FH estimation ... 116
5.2 Improved allocation of Structure in Maintenance cost model ... 116
5.3 Improved fidelity of DMCs estimation at subsystem level ... 117
5.4 Deepening of SysML diagrams ... 117
5.5 Modification for MEA2 and AEA system architectures ... 117
Aknowledgments ...
Bibliography ...

# Figures

**Figure 1**: Maintainability methods adopted for A380 [4] .......... 3
**Figure 2**: Composite usage over last two decades [12] .......... 8
**Figure 3**: Electro-Hydrostatic Actuator (EHA) scheme [22] .......... 13
**Figure 4**: Overview of the chapters .......... 14
**Figure 5:** Reliability failure rate estimation and allocation at subsystem level [8] .......... 22
**Figure 6**: Safety failure rate estimation at system level [8] .......... 22
**Figure 7**: Estimation and allocation of the safety failure rate [8] .......... 23
**Figure 8**: LCC breakdown [3] .......... 27
**Figure 9**: Classification of maintenance costs (modified from [9]) .......... 28
**Figure 10**: Flow chart of the whole methodology .......... 33
**Figure 11**: From the cleaning intervention to the full extent characterisation of the damage .......... 47
**Figure 12**: From the repair process selection to the repair materials selection .......... 53
**Figure 13**: From the identification of the correct fibre type and weight to the preparation for final cure .......... 55
**Figure 14**: From the repair process action to the protective coatings restoration .......... 56
**Figure 15**: From the paint restoration to end of the repair process .......... 57
**Figure 16**: Overview of the composite maintenance repair process activity diagram .......... 58
**Figure 17**: Aileron EHA and electro-hydraulic actuator [23] .......... 58
**Figure 18**: Flight control actuator removal simulation .......... 59
**Figure 19**: Activity diagram EHA and HA, first and second phase .......... 60
**Figure 20**: Activity diagram EHA and HA, third phase .......... 61
**Figure 21**: Activity diagram EHA and HA, fourth phase .......... 62
**Figure 22**: Activity diagram EHA and HA, fifth phase .......... 63
**Figure 23**: Overview of the activity diagram for removal/installation of flight control actuator .......... 64

**Figure 24**: Maintenance Man Hours improvement for composite vertical tail [5] ....... 67
**Figure 25**: RAMS tool set-up in RCE ........................................................................ 73
**Figure 26**: Example of RAMS toolspecific ................................................................ 74
**Figure 27**: Maintenance cost tool set-up in RCE ....................................................... 75
**Figure 28**: Example of Maintenance cost toolspecific ................................................ 75
**Figure 29**: Workflow used for the MDA ..................................................................... 77
**Figure 30**: Workflow for the DOE launch to evaluate different design configurations in a single run ............................................................................................................. 80
**Figure 31**: Example of set-up values for conventional aircraft in technologies CPACS xml toolspecific ............................................................................................................ 80
**Figure 32**: Visualization of baseline aircraft [42] ...................................................... 81
**Figure 33**: Reliability failure rate breakdown ........................................................... 85
**Figure 34**: Maintenance manhours rate breakdown .................................................. 87
**Figure 35**: Direct maintenance cost breakdown at subsystem level ............................ 88
**Figure 36**: Distribution of direct labour costs among subsystems ............................... 90
**Figure 37**: Distribution of maintenance material costs among subsystems ................. 90
**Figure 38**: CONV and MEA1 on-board system architectures ..................................... 92
**Figure 39**: MEA1 and MEA2 on-board system architectures ..................................... 93
**Figure 40**: Comparison of operating costs per flight hour between CONV/CONV and COMP/CONV ............................................................................................................ 101
**Figure 41**: Comparison of operating costs per flight hour between CONV/CONV and LAM/CONV ............................................................................................................... 106
**Figure 42**: Comparison of operating costs per flight hour between CONV/CONV and EHA/MEA1 ............................................................................................................... 112
**Figure 43**: Comparison of DMCi between CONV/CONV and LAM+COMP/CONV 113
**Figure 44**: Comparison of operating costs per flight hour among combined solutions ................................................................................................................................ 114

# Tables

**Table 1**: Technological Age Index [8] ........ 19
**Table 2**: Complexity Index [8] ........ 19
**Table 3**: Role Index [8] ........ 19
**Table 4:** Examples of failure rates, at subsystem level, calculated for existing aircraft [8] ........ 20
**Table 5:** IRM and CDTM values [8] ........ 25
**Table 6**: Examples of MMH/FH estimation at subsystem level [8] ........ 26
**Table 7**: Table containing the coefficients of the DMC equations (CERs) (modified from [9]) ........ 31
**Table 8**: Estimation Ki provided by [8] from a statistical database ........ 34
**Table 9**: Fractions assigned for improved consistency ........ 35
**Table 10**: Identification of MMH/FHnn% vectors for different civil aircraft categories ........ 36
**Table 11**: Comparison between RAMS and Maintenance cost PBS ........ 38
**Table 12**: Qualitative investigation for RAMS and Maintenance cost ........ 65
**Table 13**: Coefficients for Composites in RAMS ........ 70
**Table 14**: Coefficients for NLFW in RAMS ........ 70
**Table 15**: Coefficients for EHAs in RAMS ........ 70
**Table 16**: Coefficients for Composites in Maintenance cost ........ 71
**Table 17**: Coefficients for NLFW in Maintenance cost ........ 71
**Table 18**. Coefficients for EHAs in MC ........ 71
**Table 19**: Key aircraft design characteristics ........ 81
**Table 20**: Specific inputs in RAMS toolspecific file for Reliability failure rate estimation at A/C level ........ 83
**Table 21**: Specific inputs in RAMS toolspecific file for Maintenance manhour per flight hour estimation at A/C level ........ 83

**Table 22**: Manual inputs provided in Maintenance toolspecific for maintenance cost assessment ........................................................................................................ 84
**Table 23**: Reliability failure rate results at subsystem level ........................................ 85
**Table 24**: Maintenance man hours per flight hour results at subsystem level .............. 87
**Table 25**: Direct maintenance cost at subsystem level ................................................. 88
**Table 26**: Total labour and material cost breakdown at A/C level .............................. 89
**Table 27**: Labour and material costs results at subsystem level .................................. 89
**Table 28**: Total maintenance cost breakdown at A/C level ......................................... 89
**Table 29**: Operating costs breakdown per flight hour .................................................. 91
**Table 30**: All possible aircraft solutions given by combination of TECH and OBSA . 95
**Table 31**: Comparison of the structure weights due to introduction of composites in COMP/CONV ................................................................................................................ 96
**Table 32**: Comparison between reliability failure rate allocation of CONV/CONV and COMP/CONV ................................................................................................................ 97
**Table 33**: Comparison between maintenance man hours of CONV/CONV and COMP/CONV ................................................................................................................ 98
**Table 34**: Direct maintenance costs savings due to composites in COMP/CONV compared to CONV/CONV ........................................................................................... 99
**Table 35**: Comparison of DLC and MC of the structure between CONV/CONV and COMP/CONV .............................................................................................................. 100
**Table 36**: Comparison of operating costs between CONV/CONV and COMP/CONV .................................................................................................................................. 100
**Table 37**: Comparison of the structure weights due to introduction of NLFW in LAM/CONV ................................................................................................................. 102
**Table 38**: Comparison between reliability failure rate allocation of CONV/CONV and LAM/CONV ................................................................................................................. 103
**Table 39**: Comparison between maintenance man hours of CONV/CONV and LAM/CONV ................................................................................................................. 104
**Table 40**: Direct maintenance costs savings due to composites in COMP/CONV compared to LAM/CONV ............................................................................................ 105
**Table 41**: Comparison of DLC and MC of the structure between CONV/CONV and LAM/CONV ................................................................................................................. 105
**Table 42**: Comparison of operating costs between CONV/CONV and LAM/CONV 106

**Table 43**: Comparison of the structure weights due to introduction of EHAs in EHA/MEA1 ........ 107
**Table 44**: Comparison between reliability failure rate allocation of CONV/CONV and EHA/MEA1 ........ 108
**Table 45**: Impact of MEA1 on subsystems weight ........ 108
**Table 46**: Comparison between maintenance man hours of CONV/CONV and EHA/MEA1 ........ 109
**Table 47**: Direct maintenance costs savings due to composites in COMP/CONV compared to EHA/MEA1 ........ 110
**Table 48**: Comparison of DLC and MC between CONV/CONV and EHA/MEA1... 111
**Table 49**: Comparison of operating costs between CONV/CONV and EHA/MEA1. 111
**Table 50**: Changes of DMCi in COMP+LAM/CONV ........ 112
**Table 51**: Changes of DMCi rate in combined solutions ........ 113
**Table 52**: Comparison of operating costs per flight hour among combined solutions 114

# Abbreviations

| | |
|---|---|
| AC | Advisory Circulars |
| A/C | Aircraft |
| AD | Airworthiness Directives |
| AGILE | Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts |
| AOG | Aircraft On Ground |
| ASTRID | Aircraft On Board Systems Sizing and Trade-Off Analysis in Initial Design |
| CER | Cost Estimating Relationship |
| CPACS | Common Parametric Aircraft Configuration Schema |
| DLC | Direct Labor Cost |
| DMC | Direct Maintenance Cost |
| DOE | Design of Experiment |
| EASA | European Aviation Safety Agency |
| EHA | Electro-Hydrostatic Actuator |
| EMA | Electro-Mechanical Actuator |
| FAA | Federal Aviation Administration |

| | |
|---|---|
| FEM | Finite Element Method |
| FH | Flight Hour |
| FMEA | Failure Modes and Effects Analysis |
| FR | (Reliability) Failure Rate |
| FY | Financial Year |
| HA | Hydraulic Actuator |
| IDGs | Integrated Drive Generators |
| LCC | Life Cycle Cost |
| LR | Labour Rate |
| MB | Maintenance Burden |
| MBSE | Model Based System Engineering |
| MC | Material Cost |
| MCA | Medium Civil Aircraft |
| MDA | Multidisciplinary Design Analysis |
| MDO | Multidisciplinary Design Optimization |
| MEW | Maximum Empty Weight |
| MMH | Maintenance Man Hour |
| MMH/FH | Maintenance Man Hours per Flight Hour |

| | |
|---|---|
| MPD | Maintenance Planning Document |
| MRB | Maintenance Review Board |
| MRO | Maintenance Repair and Overhaul |
| MSG | Maintenance Steering Group |
| MTBF | Mean Time Between Failure |
| MTOW | Maximum Take-Off Weight |
| NASA | National Aeronautics and Space Administration |
| NDI | Non-Destructive Inspection |
| NLFC | Natural Laminar Flow Control |
| NLFW | Natural Laminar Flow Wing |
| OEM | Original Equipment Manufacturer |
| PBS | Product Breakdown Structure |
| QC | Quality Control |
| RAMS | Reliability Availability Maintainability Safety |
| RCE | Remote Component Environment |
| W&B | Wheels And Brakes |

# 1. Introduction

## 1.1 Maintenance efficiency by design

Aircraft are highly complex systems that have a service life of 30 or more years, during which they require a high level of operational availability to meet their customers' needs. Regular maintenance is therefore essential to ensure aircraft' *airworthiness* and thus availability (quality) through its extended lifecycle [1].

*Aircraft design* is a process whose aim is to select a specific configuration of the aircraft, further design specifications in respect of some given top-level requirements that are considered as guide criteria. This process includes sizing and analyses necessary to obtain a parametric description of the aircraft's general arrangement and its performance data. Several disciplines are involved in this long process, reason why it is difficult to find a unique solution satisfying the top-level requirements in each field: the strong interaction of each discipline with each other often takes to a non-convergent solution.

In this context *Multidisciplinary Design Optimization* (MDO) is used to overcome the problem by obtaining the global optimal solution in respect of the top-level requirements.

High performance and low production cost are some of the main goals of an aircraft design, but the aircraft manufacturers have realised that also cost assessment has to be taken into account at the design stage in order to be cost effective at the maintenance phase. The design parameters such as geometry and/or material could have direct effect on the maintenance costs, as well as, reliability of each subsystem can improve or worsen the maintenance repair intervals, and, consequently, the maintenance costs.

For this reason, *Reliability, Maintainability, Availability and Safety* (RAMS) have become system design requirements that have significant effects on the safety of an aircraft and its longevity. RAMS discipline dictates the duration of the scheduled maintenance interventions, consequently it constitutes the main trade-off factor of the maintenance program development and therefore the maintenance cost prediction. As a

result, it is evident that RAMS, in order to minimize maintenance costs is an important driver for aircraft design.
During the aircraft design process RAMS assessment helps to make decisions regarding risk, efficiency, repair and maintenance. Moreover it is fundamental for improving assembly/disassembly operations when maintenance actions are required.

*Aircraft maintenance* is a complex socio-technical system that requires coordination, cooperation and communication among aircraft maintenance engineers, crew managers, inspectors and hangar managers, commercial and quality engineers as well as the manufacturer, the customer and the airline, in order to provide a fully serviceable aircraft when required by an airline at minimum cost [2].

Maintenance cost is the price paid for the whole process, which is required to perform regular inspections and to bring the aircraft into serviceable condition according to airworthiness regulations. Its estimation can be defined as the process of predicting the cost of all maintenance activities [3].

Related to maintenance costs, there are the aspects of maintainability. Aircraft such as Airbus A380, Boeing 787 and Airbus A350 have been designed from the beginning in view of improved maintainability and reliability.

Starting from the A380 design (2003), Airbus had included a team of maintenance specialists with maintainability and reliability skills in the design team [4].
They adopted a maintenance philosophy according to which they developed advanced technology operations. These include: setting of new standards for maintenance costs; more efficient maintenance program; high operational reliability; high component reliability.
Very proper maintenance assessment methods have been developed with the objective of verifying accessibility, testability, remove/replace, human factors, servicing/lube, reparability and handling. Furthermore, the time taken to remove and replace the components through maintenance task analysis has been planned to be monitored (**Figure 1**).

A V model approach had been used to achieve operational reliability. The first part is a top-down approach to assign aircraft level targets to system and components. The second part is a bottom-up approach going in order to arrive back from components to aircraft system level and to verify that design meets the target. With regard to the maintenance program, it has been designed to allow maximum flexibility by allocating the task intervals into the use of flight time (flight hours, flight cycles, calendar time).

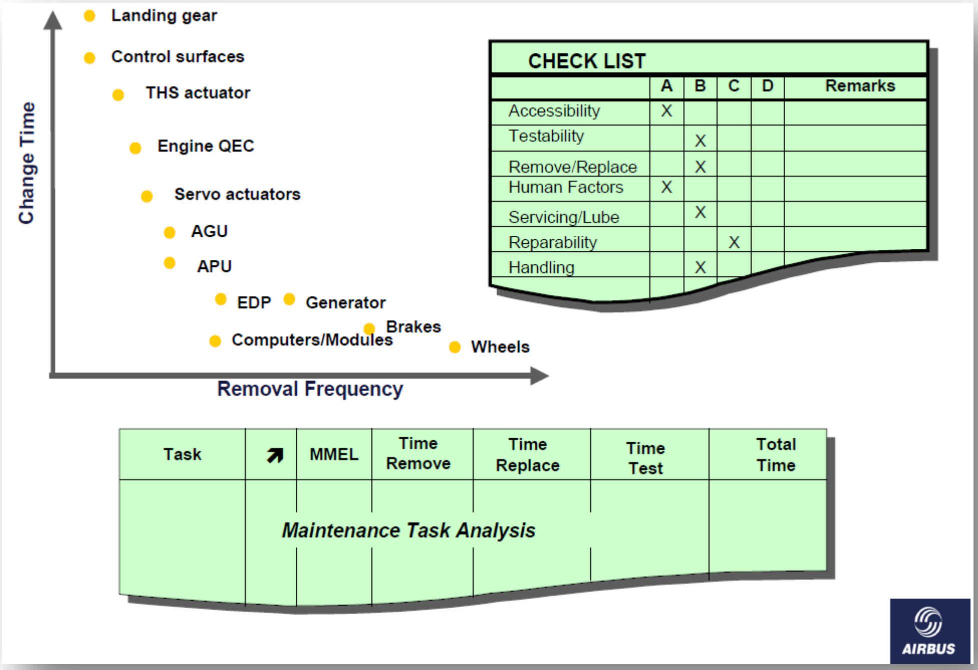



**Figure 1**: Maintainability methods adopted for A380 [4]

Another example of aircraft designed from an improved maintenance perspective is the Boeing 787 (2008). Boeing claims to have chosen composites because among the many advantages there is the reduced scheduled maintenance burden. In facts the B787 structure is optimized for reduced scheduled maintenance burden. Furthermore, B787 design approach minimizes overall fuselage joints, reduces weight and drag, has lower structural maintenance burden, and, consequently reduced inspection intensity. Improvements have been also reached from a system view through better mean-time-between-failures (MTBFs): B787 systems are optimized to reduce scheduled maintenance [5].

Further sample is given by the Airbus A350 XWB (2013) where many design features have been put in place to reduce the maintenance cost and to improve the A350 XWB component reliability. Less maintenance by design has been reached through intelligent airframe using 53% composite materials; new 4-panel concept fuselage; robust more efficient systems building on A380 new generation systems [6]. An example is the hydraulic system. The A350 XWB (as with the A380) has only two hydraulic systems (each running at 5,000 psi) compared to the current aircraft and to the 787.

The A350 XWB maintenance program is based on a "usage parameter" concept which is now adopted on all Airbus programmes. The most appropriate usage parameter ((Flight Hours (FH), Flight Cycles (FC) or calendar times (days, months or years)) and its associated interval are defined for each maintenance task. This prevents the development of a too conservative approved maintenance programme, driven by task planning considerations (that may differ from one airline to another).
With this concept the operator has the flexibility to choose the timing of the tasks to be performed depending on the aircraft utilisation, having the possibility to split the work during different night shifts for example, or keep the tasks package concept if preferred. This allows maintenance to be performed only when necessary, to package tasks according to aircraft actual utilisation, airline maintenance policy and practices, rather than having to adhere to pre-defined block-checks.
Airbus' target for the A350 is to have a reduction of around 40 percent MPD Maintenance Man-hour (MMH) compared with current-generation aircraft (e.g. the 767) [7].

These examples show that the common goal of manufacturers as well as of airlines is to minimize maintenance costs. In order to reach it more efficiently, it is necessary to consider this goal from the early stages of the design process.

## 1.2 Problem statement and aim of the thesis

Several research studies deal with the estimation of reliability and maintenance cost of the aircraft. However, detailed estimations at subsystem level and assessment on the impact that maintenance man-hour have on maintenance costs have been omitted so far.

The purpose of this master thesis is to provide a methodology that estimates RAMS and maintenance costs of a civil aircraft, both at system and subsystem level, at the early design phase in case of conventional and of new generation aircraft.

In this research study, a RAMS estimation model from Prof. Sergio Chiesa (Politecnico di Torino) [8] has been taken as the main basis for failure rate (FR) and maintenance man hour per flight hour (MMH/FH) estimation. It needed to be updated for two reasons. First, because the way of designing, producing and maintaining aircraft systems is completely evolved in a ten-year period since the model had been presented. Hence the model is based on statistical data that are obsolete. Second, new technologies that could be installed on the aircraft are not taken into account.

Concerning the aircraft maintenance cost estimation, the model from [9] provides the basis method in case of civil conventional aircraft. This model, based on equations for the maintenance cost assessment at a subsystem level, needed to be updated only for new generation aircraft.

Therefore the methodology has been created combining the two models and improved including renovated database. After being validated for a conventional aircraft, it has been extended to innovative technologies in order to assess the impact of technology changes on the two models within the scope of maintenance costs comparisons with the present conventional aircraft.

Thanks to the work done on the two models during this research, it is now possible to first evaluate the potential maintenance costs of a specific configuration (conventional or innovative), second to compare different alternative configurations in order to identify the maintenance cost saving potentials. It is possible to highlight advantages and disadvantages of every configuration in terms of maintenance cost and direct operating costs in general (e.g. fuel cost, crew cost).

The limiting conditions of this research are the lack of some data. Since the technologies on which is paid attention are recent or future, the available data are very limited, reason why the present research work is not intended to cover any detailed development but to focus on the conceptual aspects.

All data collected have been entirely used with appropriate assumptions if necessary, in order to provide a methodology that can already be applied.

The level of fidelity is not detailed, it is only for a preliminary assessment, since the goal of this study is to provide a tool to identify ranges and evaluate the tendencies of the outputs of the models. By contrast, the principal advantage is that this approach can be used in very early design phases when information is missing or is limited.

## 1.3 Research scope

The models above mentioned consider only conventional technologies installed on civil aircraft.

The contribution of aviation to global warming phenomena and environmental pollution has led to on-going efforts for the reduction of aviation emissions. Approaches to achieve the emissions reduction target include developing clean energy such as solar power, as well as increasing energy efficiency. An effective way to increase energy efficiency and reduce fuel consumption is reducing the mass of aircraft, as a lower mass requires less lift force and thrust during the flight [10].

The aeronautical industries are opting for more radical changes and improvements to today's aeronautical design philosophies to achieve these new ambitious goals. The variations in aircraft design concept are mainly centred on three new technologies that bring radical changes. They are:

- Composite structure;
- Natural Laminar Flow Wing (NLFW);
- Electro-Hydrostatic Actuators (EHAs).

Composites and EHAs are already in use. NLFW is not used yet but it may have promising results in terms of fuel efficiency. These technologies ideally allow optimizing aircraft performance and reducing fuel consumption.

The aircraft choice of the airlines depends mainly on the maintenance costs that is influenced by design parameters such as material and geometry. Direct maintenance cost (DMC) of civil aircraft is one of the important ways to assess the impact of different technologies and, consequently, to improve economy. DMC prediction can provide decision support for the optimization of the design parameters in order to realize the DMC reduction.

### 1.3.1 Composite structure

Aluminium structures have been a cornerstone in the design of commercial airplanes for many years. When the evolution of aluminium designs has improved the strength to-weight ratio, the industry started seeking doubled performance improvements in fuel efficiency for new airplanes. Composites, applied on numerically optimised structures, combined with system improvements, helped to provide the path to obtain such improvements.

A composite is made by a combination of two or more materials differing in form or composition on a macroscale. The constituent materials belongs to two main categories: matrix and reinforcement. The matrix material surrounds and supports the reinforcement to maintain their relative positions. Meanwhile, the reinforcements provide special mechanical and physical properties to enhance the overall property. The wide variety of matrix and strengthening materials allows structure designers to optimise the combination [11]. The constituents maintain their identities: while they act in simultaneous, they do not dissolve or merge completely into one another.

Composites, by offering strength-to weight ratios that enable lighter weight structures, allow the airplane design to feature items such as larger windows and lower altitude pressures in the cabin. Furthermore composite airplane structures include improved fatigue resistance, corrosion resistance and moisture resistance, as well as the ability to tailor lay-ups for optimal strength and stiffness in required directions [10].

Composites are not new to commercial aviation. In 1940 radar domes were the first applications of composites to commercial aircraft. Since then, they have been used in airframe structures, and their use has been steadily increasing over the last 45 years, by gradually replacing their metallic counterparts. In 1975, NASA developed a series of composite parts for research purposes, and the elevators of the Boeing 727 and Boeing 737 and the vertical fin of the DC-10 were redesigned. In 1995 the Boeing 777 entered in service with secondary structures (e.g. the leading edge, trailing edge, flaps, ailerons and rudder) made of carbon fibres for a total of 10 percent of the structural weight.

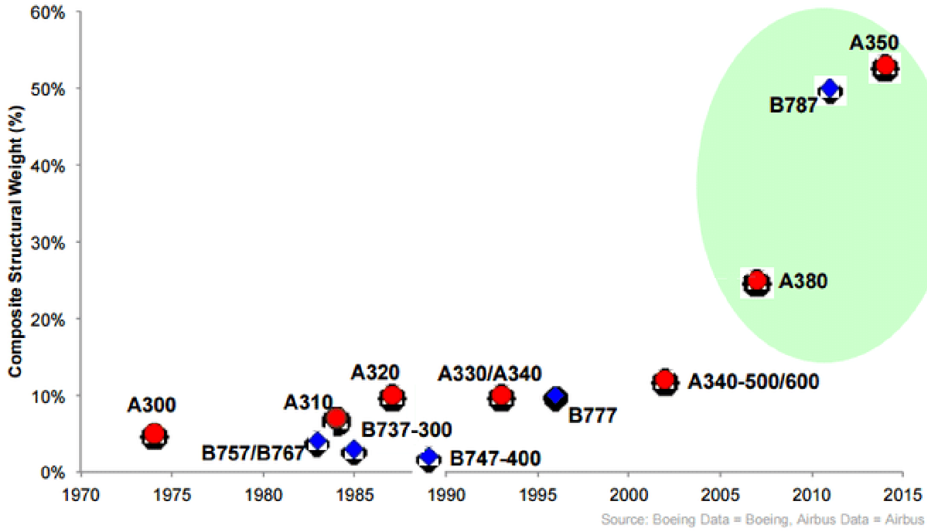



**Figure 2**: Composite usage over last two decades [12]

Over the time, tougher composite materials and enhanced, robust designs have been developed and, with the centre wing box of the A380, composites were even used for primary (load-carrying) structures. Airbus introduced a 25 percent of composite structure in A380-800 [3]. The latter enabled savings of 1500 kilogram compared to the aluminium counterpart [13].

Composite structures on commercial airplanes can be all fibreglass layers, all carbon layers, a mixture of the two (often referred to as hybrid parts), or cured with honeycomb core.

In 2008 the composite percentage reaches 50 percent of the structure weight with Boeing's Dreamliner 787. Their application reached new proportions (53 percent) with the A350 XWB, in 2013, which boasts a significant application of composites throughout.

Nowadays composite materials are dominant in areas that were traditionally aluminium.

Airbus and Boeing justify the usage of composites by an improvement of the aircraft performances during design and a reduction of the maintenance cost during its usage.

To reach these proportions many studies, tests, and demonstrations were performed to validate the strength and impact resistance of the composite material, particularly in comparison to aluminium structures. Additionally, in conjunction with airline partners, many damage scenarios were reviewed and the time and effort required to repair each type of damage were evaluated. The areas prone to damage, such as passengers and cargo doors, have been evaluated through damage scenarios and impact testing in order to be strengthened and designed to enable easier repairs if damaged. It should be also considered that, due to its use of toughened carbon materials, solid laminate composite structure is inherently very durable. During Boeing 787 design, tests have shown the fuselage can resist damage that would easily occur in an aluminium fuselage. Indeed, the usage of composites in these percentages allows to greatly reduce the maintenance of the fuselage because the effect of fatigue is reduced compared to the conventional aluminium, especially in the highly tension-loaded environment [14]. The good fatigue behaviour is justified also by the fact that a composite component that is designed for stiffness will therefore have a higher safety factor against material failure than its metallic counterpart [13]. This approach offered weight savings on average of 20 percent, for Boeing 787 compared to more conventional aluminium designs.

Through a comparison between B767 and B777, Boeing shows how the effect of the introduction of composites is translated into less scheduled maintenance than non-composite structures. The 777's composite tail is 25 percent larger than the 767's aluminium tail, yet requires 35 percent fewer scheduled maintenance labour hours. This labour hour reduction is due to the result of a reduced risk of corrosion and fatigue of composites compared with metal [14].
From Boeing perspective, a composite structure also results in less non-routine maintenance.

Another strong point is the possibility to adjust the orientation of the fibres or to unify the shape and therefore to reduce the number of parts in order to customize the composites specifically for a desired function [13].

However, it has some disadvantages, for instance the higher cost of composites in comparison to metals is one of the major obstacles for application of composites [10].

Furthermore, unlike aluminium the composites are not as efficient in dealing with compression loads. In fact, even if sensitive to tension loads, aluminium handles compression very well. Another disadvantage of composite structures is that, due to their anisotropic properties, compared to metallic structures they have more intricate damage mechanisms. One of the serious disadvantages is the susceptibility to accidental impacts due to presence of runway debris, hail, as well as to tool dropping during maintenance and repair operations. Object impacts are delicate because they can cause internal damage such as delamination or de-bonding requiring intrusive inspections and repair activities [15].

### 1.3.2 Laminar flow wing

Since fuel prices have become higher, it is no longer just a matter of minimizing maintenance costs but also reducing fuel burn related costs.

Beside the economic aspects, airlines and aircraft manufacturers are pushed towards more environmental friendly aircraft: the climate impact of aircraft can be reduced since less emission are produced. Indeed, planning for the expected increase in air traffic, the European Commission has issued the VISION 2020 document [16], requiring a reduction of the $CO_2$ emissions by 50 percent and of the NOX emissions by 80 percent [17].

Natural laminar flow is a passive technology improvement, i.e. no further systems need to be installed. Looking at the aircraft components, in order to achieve more fuel efficiency, the wing is particularly applicable for natural laminar flow technology. The application of Natural Laminar Flow Wing (NLFW) on civil aircraft is one of many promising fuel efficiency increase technologies [18], which could be integrated in a next generation short-to-medium range aircraft.

The principle of this technology is based on an aircraft drag reduction that is the primary impact, implicating more fuel efficiency and less carbon dioxide emissions. As outlined in a number of studies, a fuel burn improvement in the order of 10-12% is possible by generating laminar flow on an aircraft wing. This in turn leads to decreased fuel costs and ideally to an increased economic operation.

However, even though research and development around this topic is ongoing for some decades, NLFW has not been commercially deployed yet.

One major factor is the insecurity of operators regarding the overall efficiency, especially due to the additional maintenance of the system or the laminar effectivity under realistic operational conditions [19]. In fact, aircraft with NLFW are much more sensitive to environmental and operational boundary conditions such as insect contamination during take-off or cloud encounter in high altitudes.

Two are the negative impacts. First, factors or circumstances lessening the drag reduction, i.e. the laminar effectiveness, and second, aspects that lead to a (partial) increase of operating costs, i.e. weakening the economic effectivity [19].

One of the factors threatening the operational laminar effectiveness of aircraft is wing leading edge contamination with insect debris during take-off and landing. Insect debris can cause premature transition of the laminar boundary layer during cruise flight. This in turn reduces the laminar flow benefit and aircraft economic viability. In order to preserve the laminar flow benefits from insect contamination, additional cleaning intervention is required. The risk is that, in conjunction with a specific maintenance of NLFW surfaces, it may reduce the overall cost savings.

Another factor, after insect debris, is the presence of clouds during the flight. It undermines the laminarity of the flow and therefore decreases the positive effects of drag reduction of the wing itself.

Moreover, in order to consider transonic effects and to maintain the cruise speed of today's civil transport aircraft, a certain wing sweep is required. With respect to the application of NLFC, the design of a swept wing is constrained by three primary transition mechanisms, namely transition caused by Tollmien-Schlichting instabilities and cross-flow instabilities as well as attachment line transition. To prevent boundary-layer instability effects at high Reynolds numbers, the leading edge sweep angle for a standard medium sized aircraft equipped with NLFW is limited to values around 10°-15°. This limitation would result in an undesirable reduction of cruise speed [20].

As a consequence, it is clear that designing a wing with NLFW becomes a trade-off between different contradictory requirements, since the existing numbers are only valid for optimum boundary conditions like operation at design range [21].

In addition, the turn-around time of laminar flow aircraft might increase e.g., due to a change of the aircraft configuration or increased maintenance effort, which affects aircraft utilisation in network operations.

Hence, the technology exhibits some drawbacks which might limit its future operability. For example, laminar flow condition leading to the drag advantage is unlikely to be preserved in all flight phases. That is, laminar flow is approximately limited to cruise flight conditions. From an airline perspective, the network benefits of this future technology concept are of particular interest but still need to be studied. Network benefits include e.g., changes in airline network profit or network fuel consumption due to the introduction of laminar flow aircraft in network operations [20].

### 1.3.3 Electro-hydrostatic actuators

Actuators innovation is another direction along which aircraft designers and researchers are centred within the main objective of saving energy.

The conventional actuation techniques pressurise the actuator whether or not there is any demand. In reality for much of the flight, actuator demands are minimal and this represents a wasteful approach as lost energy ultimately results in higher energy off-take from the engine and higher fuel consumption [22].

Electro-hydrostatic actuators (EHAs) technology is being used as the basis of the revolutionary electric flight control system on Lockheed Martin's F-35 Lightning II and has been selected by Airbus for the A380, A400M and A350 XWB. The implementation of EHAs achieves improvements of the MTBF and dispatch reliability through the reduction in the total number of hydraulic components. For instance the A380 '*More electric*' flight control actuation concept consists in eliminating one hydraulic system and replacing it with a set of electrically powered actuators, with no damaging impact to the probability of losing the flight control actuation system. The hydraulic actuators are normally active while the electrically powered actuators are normally stand-by and become operative in the event of a failure of the normal, hydraulically supplied, control lane [23].

This type of actuator uses state-of-the-art power electronics and control techniques to provide more efficient flight control actuation. It seeks to provide a more efficient form of actuation where the actuator only draws significant power when a control demand is sought; for the remainder of the flight the actuator is quiescent.

The EHA accomplishes this by using the three-phase AC power to feed power drive electronics which in turn drive a variable speed pump together with a constant displacement hydraulic pump. This constitutes a local hydraulic system for the actuator (**Figure 3**). When there is no demand the only power drawn is that to maintain the control electronics [22].

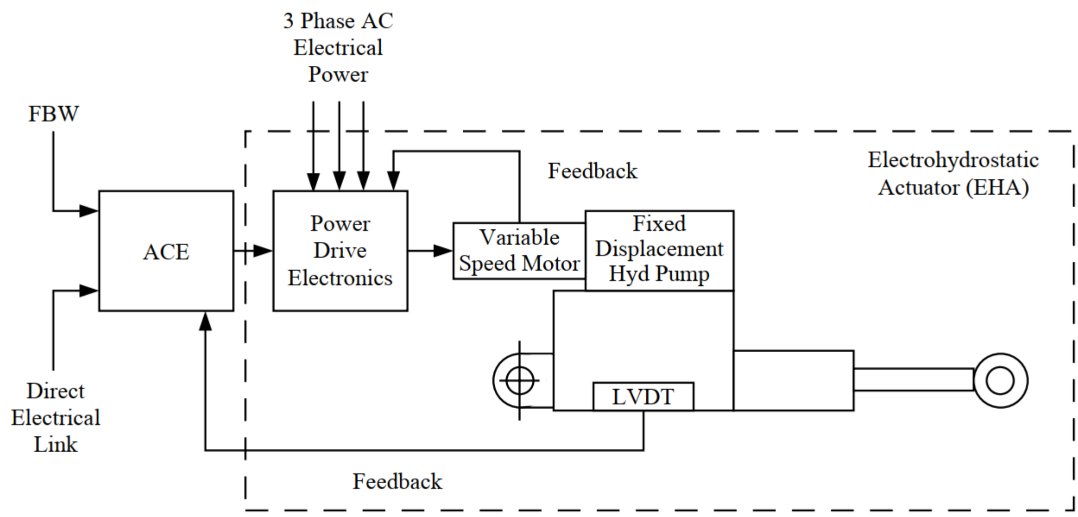



**Figure 3**: Electro-Hydrostatic Actuator (EHA) scheme [22]

All potential failure conditions in an aircraft have an acceptable probability of occurring which corresponds to the severity of the outcome. During the design process this is considered in the *Failure Modes and Effects Analysis* (FMEA) and any new devices must be designed to meet these failure probabilities.

In the case of a control surface, a failure which will result in loss of the aircraft is considered the most severe and must therefore have an exceedingly low probability of occurrence. Safety requirements will determine the architecture of the flight control system and the proposed solution must attain the reliability levels of conventional aircraft systems. In this case any failure resulting in a catastrophic failure of the aircraft has a failure probability of $< 10^{-9}$ per flight hour. Primary flight control surfaces are critical to an aircraft remaining airborne, so failure probabilities can be considered of the order of $10^{-9}$ per flight hour.

To understand the existing arrangements of actuators, the reliability of a single actuator can be considered. Accurate failure probability data is difficult to find and predicted component reliabilities may vary between sources and also between commercial and military actuators; however, a failure probability assigned to a single EHA of $1.98\times10^{-4}$ per flight hour is many orders of magnitude greater than the required $10^{-9}$ for a primary control surface and indicates a single EHA would not be suitable [24]. To overcome this reliability shortfall, there are many possibilities for connecting EHAs in parallel to drive a single surface and probabilities of 'loss of control' can be reduced to values of the order of $10^{-15}$ using dual EHA mechanisms on a surface, each driven by two independent sets of hydraulic pumps and control electronics, resulting in a quadruple control arrangement, capable of tolerating 3 faults.

## 1.4 Thesis outline

Chapter 1 is the introductory chapter where the thesis background has been presented. In Chapter 2 the state of the art will be shown giving particular attention on the RAMS and Maintenance cost estimation models that have formed the starting point for the equations present in the methodology that has been developed. Following, in Chapter 3, the methodology will be presented in its structure and development, going into detail according to each technology. In Chapter 4 the implementation and execution of use case studies will be shown, together with the interpretation of the results. Finally, a series of proposals for possible future developments will be included in Chapter 5.

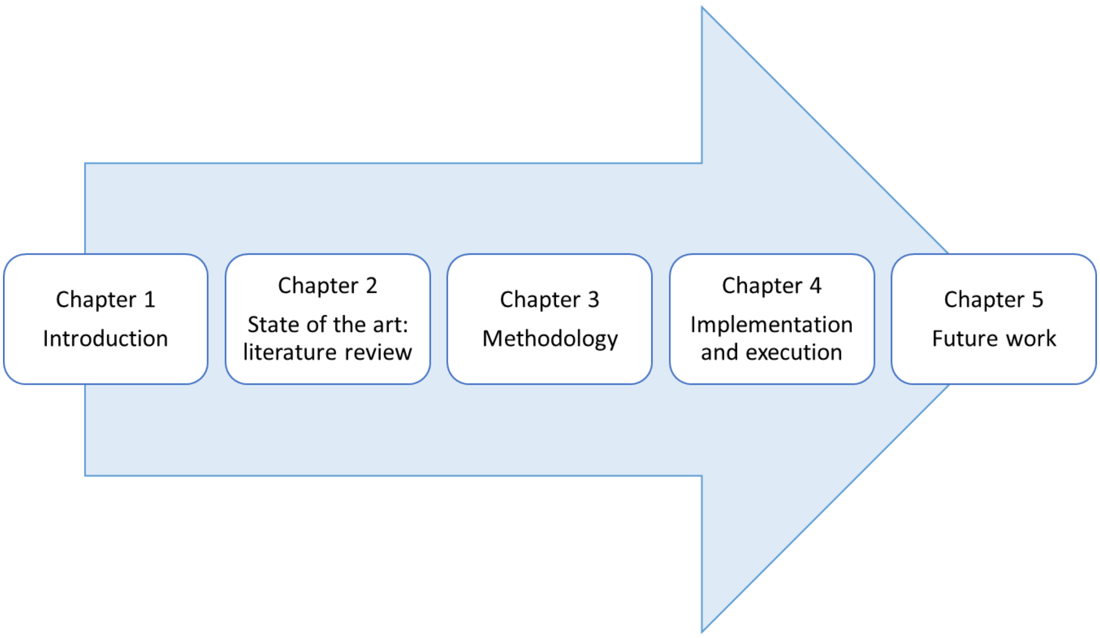



**Figure 4**: Overview of the chapters

# 2. State of the art: literature review

## 2.1 RAMS

### 2.1.1 Definition and terminology

RAMS stands for Reliability, Availability, Maintainability and Safety is a long-term operating characteristic of a system and is achieved by applying engineering data, concepts, methods, techniques and tools throughout the life cycle of the system.

Beginning with *Reliability*, it is a term used to describe quantitatively how failure-free a system is likely to be during a given period of operation. The ability to express reliability numerically is crucial, because it enables to concretely identify the user's need, contractual specifications, test guidelines and performance assessment. The main representative number of this discipline is *Failure Rate* (FR), defined as the number of failures of an item per measure-of-life unit. This measure is more difficult to visualise from an operational point of view than the MTBF measure, but is a useful mathematical term which frequently appears in many engineering and statistical calculations.

The reliability allocation process allocates the reliability 'budget' for a given system or subsystem to the individual components of that system or subsystem [25].

*Maintainability*, instead, is defined as a characteristic of design and installation. This characteristic is expressed as the probability that an item will be retained in, or restored to, a specific condition within a given period if prescribed procedures and resources are used [25]. A maintainability performance figure is Maintenance Man Hours per Flight Hour (MMH/FH), calculated by dividing the labour hours spent to maintain a particular aircraft fleet during a given period, by the flying hours during that period.

Maintainability and reliability are the two major system characteristics that combine to form the commonly used effectiveness index: *Availability*. It is a parameter that translates system reliability and maintainability characteristics into an index of effectiveness. It is based on the question ‘‘Is the equipment available in a working condition when it is needed?’’ as is evident by its proper nature, approaches to availability are time related [25].

*Safety* is the state where an acceptable level of risk is not exceeded. It characterizes the absence of catastrophic consequences on the user(s) and the environment. Safety is actually reliability with respect to catastrophic failures. The *Safety Failure Rate* is typically imposed by the normative. Risks Assessment & Management are safety related.

### 2.1.2State of the art

Several research studies have been carried out concerning reliability estimation in the aircraft field.

For example, the work [25] presents in detail the procedure of allocation of reliability in the systems and the various reliability functions, but despite being very reliable, it refers to generic systems and not specific systems on board an aircraft. It does not match well to be combined with a maintenance cost estimation model.

The same goes for the reliability study for general aviation [26]: even if it has an overall view of the plane, the output is precisely the reliability and is therefore not very easy to connect to an estimation of maintenance costs.

These two models only estimate reliability and do not assess RAMS outputs.

The Application of Reliability Methods for Aircraft Design Project Management [27], goes in great detail in the components and does not have an overall view of the aircraft in its subsystems.

Moreover, a model that estimates maintenance man hours exists [28], but it is based on the assumption that the preventive maintenance of unit is the age replacement, and it is a non-repairable unit. The repair method is replaced, restored to the new product after repair, and the situation of repair and reuse is not considered.

Globally the available models have the following shortcomings:

- Limited: not a subsystem level, but rather evaluate a certain system at the level of its components;
- Only for conventional aircraft, no new technologies considered;
- Based on obsolete statistical data.

Therefore the objectives of this thesis are to obtain a new updated RAMS estimation model and to develop a modification of it for new technologies.

### *RAMS estimation model*

Nevertheless, among all, RAMS estimation model [8] from Prof. Chiesa results to be the most complete. It is perfectly suitable to the connection with aircraft Maintenance cost estimation model that has been adopted (Par. 2.2.2). For this reason, particular attention is paid to the presentation of the estimation strategy provided by the model. Subsequently it will be possible to restrict the focus on the updates that will be made to the model (Par. 3.2.1) in order to actualise it to the typical current output values and on the changes introduced in case of new technologies implementation (Par. 3.3).

RAMS model constitutes the basis model for the estimation of Reliability Failure rate ($\mathrm{FR}$ $[\mathrm{failures/1000FH}]$), Safety Failure rate ($\mathrm{FR_S}$ $[\mathrm{failures/1000FH}]$) and Maintenance man hours per flight hour ($\mathrm{MMH/FH}$) of a new aircraft at the early design phase, when the detailed definition of the magnitudes, at system and at subsystem level is still lacking both in case of civil and military aircraft.

### Reliability Failure Rate estimation

*System level*

The estimation could occur only basing on the already defined magnitudes both for the system (aircraft) and the subsystems, such as total weight and partial weight of subsystems, aircraft role, sophistication level, complexity level and technological aircraft age and finally the opportunity to take aircraft maintenance into account since the design process.

The estimated values will continuously be reviewed and corrected through ulterior refinements during the whole design process, beginning with the preliminary design and ending with the detailed process.

As reported in the book, the traditional approach (*bottom-up*) for the reliability estimation of an aircraft under development foresees that a first failure rate estimation can be obtained through the knowledge of the architecture, although preliminary, of the various subsystems composing the aircraft. Once the failure rate of the equipment of each subsystem, $\lambda_{E_i}$, has been estimated it is possible to:

- estimate the failure rate of the whole system, λ, through the following relation:

$$\lambda = \sum_{i} \lambda_{E_i}$$

- request offers to the potential suppliers of the identified components, specifying them the reliability requirement.

The value obtained for the failure rate of the system can be compared with the correspondent design requirement: if the failure rate requirement is satisfied there are no problem, otherwise it is necessary modify (reduce) the failure rate values of the expected equipment and/or review the entire system configuration, in terms of number and type of equipment.

A difference between the estimated value and the required value of the failure rate at system level can be tolerated, because an excessive gap can be compensated by a wider maintainability level.

Another approach is *top-down*: the failure rate of each subsystem can be obtained through "allocation" of the system failure rate value, known as the requested requirement. In this case it is necessary to define first the system failure rate, basing on the few available data, second define the criteria for the allocation of it at subsystem level. Since there is a lack of data the model is based on available statistical data: seven existent aircraft with some relative information, three are combat and four are civil. Professor Chiesa analysed the data and established three coefficients:

1) IA (*Technological Age Index*) based on the years in which the design process took place and on the context in which the project has been developed.

| **Technological age (years)** | **Technological Age Index, IA** | **Reference aircraft** |
|---|---|---|
| 2010 | 0.9-0.6 | F22, F35 |
| '90-2000 | 1.0 | EF2000, A320 |

| Technological age (years) | Technological Age Index, IA | Reference aircraft |
|---|---|---|
| ‘80 | 1.5 | AMX, ATR42 |
| ‘70 | 2.0 | TORNADO, DC-9 |
| ‘60 | 2.5 | F104S, Caravelle |
| ‘50 | 3.0 | FIAT G91, F86 |

**Table 1**: Technological Age Index [8]

2) IC (*Complexity Index*) introducing the complexity level of the aircraft. This effect is evident in the civil aircraft field between two airplanes of different complexity like a jet liner and a regional turboprop.

| Complexity level | Complexity Index, IC | Reference aircraft |
|---|---|---|
| Very low | 0.6 | FIAT G91 |
| Low | 0.8 | S211 |
| | 0.9 | ATR42 |
| Medium | 1.0 | AMX, G222 |
| High | 1.4 | TORNADO, EF2000, F35 CTOL, A320 |
| Very high | 1.6 | F22, F35 VTOL |

**Table 2**: Complexity Index [8]

3) IR (*Role Index*), reporting the importance of the role played by the aircraft.

| Role | Role Index, IR |
|---|---|
| Hunting aircraft | 16.6 |
| Military aircraft | 2.1 |
| Civil aircraft | 1.0 |

**Table 3**: Role Index [8]

Made these definitions, it is possible express the failure rate of any aircraft depending on its maximum empty weight MEW:

$$\lambda = \left(\frac{\lambda}{\mathrm{MEW}}\right)_{\mathrm{MCA}} \cdot \mathrm{IR} \cdot \mathrm{IC} \cdot \mathrm{IA} \cdot \mathrm{MEW}$$

Where MCA stands for Medium Civil Aircraft actualised during years 1990-2000 whose failure rate is calculated when all the three coefficients assume unit value:

$$\left(\frac{\lambda}{\mathrm{MEW}}\right)_{\mathrm{MCA}} = 1.8 \left[\frac{\mathrm{failures}/1000\mathrm{FH}}{\mathrm{t}}\right]$$

| **Aircraft** | $\left(\frac{\boldsymbol{\lambda}}{\mathbf{MEW}}\right)_{\mathbf{MCA}}$ | **IR** | **IC** | **IA** | **MEW, [t]** | $\boldsymbol{\lambda}, \left[\frac{\mathbf{failures}}{\mathbf{1000FH}}\right]$ |
|---|---|---|---|---|---|---|
| EF2000 | 1.8 | 16.6 | 1.4 | 1 | 9.6 | 402 |
| TORNADO | 1.8 | 16.6 | 1.4 | 2.0 | 13.8 | 1155 |
| AMX | 1.8 | 16.6 | 1.0 | 1.5 | 6 | 269 |
| JAS 39 GRIPEN | 1.8 | 16.6 | 1.4 | 1.2 | 6 | 301 |
| C130 | 1.8 | 2.1 | 1.0 | 2.5 | 35 | 331 |
| A400 | 1.8 | 2.1 | 1.0 | 0.7 | 45 | 119 |
| C17 | 1.8 | 2.1 | 1.4 | 0.8 | 120 | 508 |
| G222 | 1.8 | 2.1 | 1.0 | 2.0 | 15 | 113 |
| A320 | 1.8 | 1.0 | 1.4 | 1 | 42 | 106 |
| B747 | 1.8 | 1.0 | 1.4 | 2.0 | 170 | 857 |
| ATR42 | 1.8 | 1.0 | 1.0 | 1.5 | 10 | 27 |

**Table 4:** Examples of failure rates, at subsystem level, calculated for existing aircraft [8]

*Subsystem level*

The allocation occurs considering the aircraft as constituted by subsystems in series without any redundancy at subsystem level.

The failure rate allocation at subsystem level has been effectuated basing on one of the few parameters know in early design phase: the weights of subsystems. The statistical data are collected in two different tables: one for hunter aircraft and the other for military and civil aircraft. From these tables Chiesa calculated an average value of subsystem $i$ percentage failure rate, $\lambda_{i_{avg}}\%$ and an average value of subsystem percentage weight $W_{i_{avg}}\%$. It derives a coefficient $K_i$ expressing their ratio:

$$K_i = \frac{\left(\frac{\lambda_i}{\lambda}\right)_{avg}}{\left(\frac{W_i}{MEW}\right)_{avg}} = \frac{\lambda_{i_{avg}}\%}{W_{i_{avg}}\%} \qquad i = 1, \dots, \#subsystems$$

Consequently, depending on whether it is combat or transport aircraft, different will be the vector K.

To allocate the failure rate of a new aircraft during preliminary design, at subsystem level, whose weights are already known, it is possible to proceed in first approximation by calculating first a non-normalised value of $i_{th}$ subsystem:

$$\lambda_{i_{nn}}\% = 100 \cdot K_i \cdot \left(\frac{W_i}{MEW}\right) = K_i \cdot W_i\%$$

Then it is possible to normalise this value:

$$\lambda_i\% = \lambda_{i_{nn}}\% \cdot \frac{100}{\sum_i \lambda_{i_{nn}}\%}$$

It follows that the allocation is given by:

$$\lambda_i = \lambda \cdot \frac{\lambda_i\%}{100} = \lambda \cdot \frac{\lambda_{i_{nn}}\%}{\sum_i \lambda_{i_{nn}}\%} = \lambda \cdot \frac{K_i \cdot W_i\%}{\sum_i \lambda_{i_{nn}}}$$

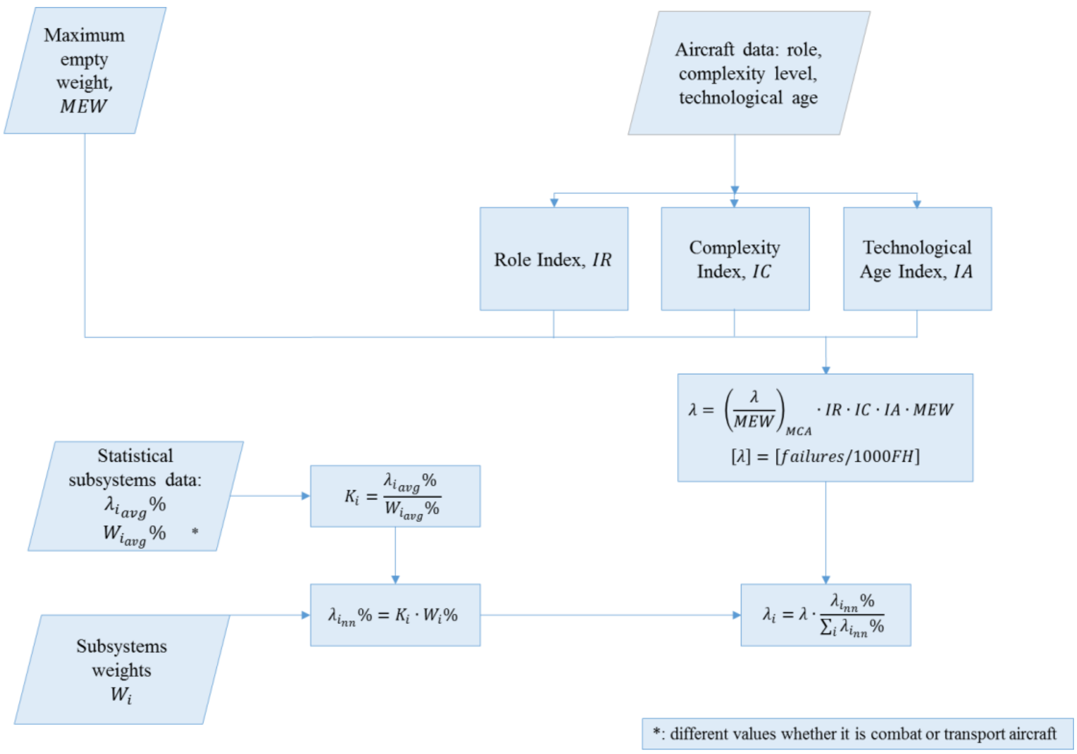



**Figure 5:** Reliability failure rate estimation and allocation at subsystem level [8]

## Safety Failure Rate estimation

*System level*

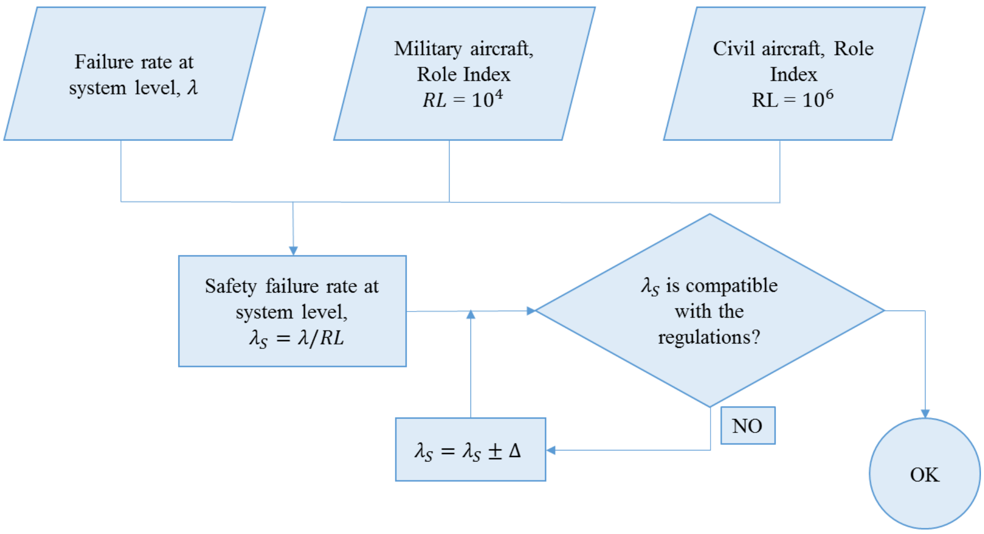



**Figure 6**: Safety failure rate estimation at system level [8]

The safety failure rate, which is the dangerous failure rate of a system is imposed by regulations and it must be respected. As proceeded with FR, also for the safety failure

rate it is possible to use a *top-down* approach in which, starting from the safety failure rate at system level, it is possible to allocate the others at subsystem level.
The estimation of the safety failure rate, at system level, is given by:

$$\lambda_S = \frac{\lambda}{RL} < \lambda_{S_{max}}$$

where RL represents the *Role Index* ($10^4$ for military aircraft, $10^6$ for civil aircraft), **Figure 6**.

*Subsystem level*

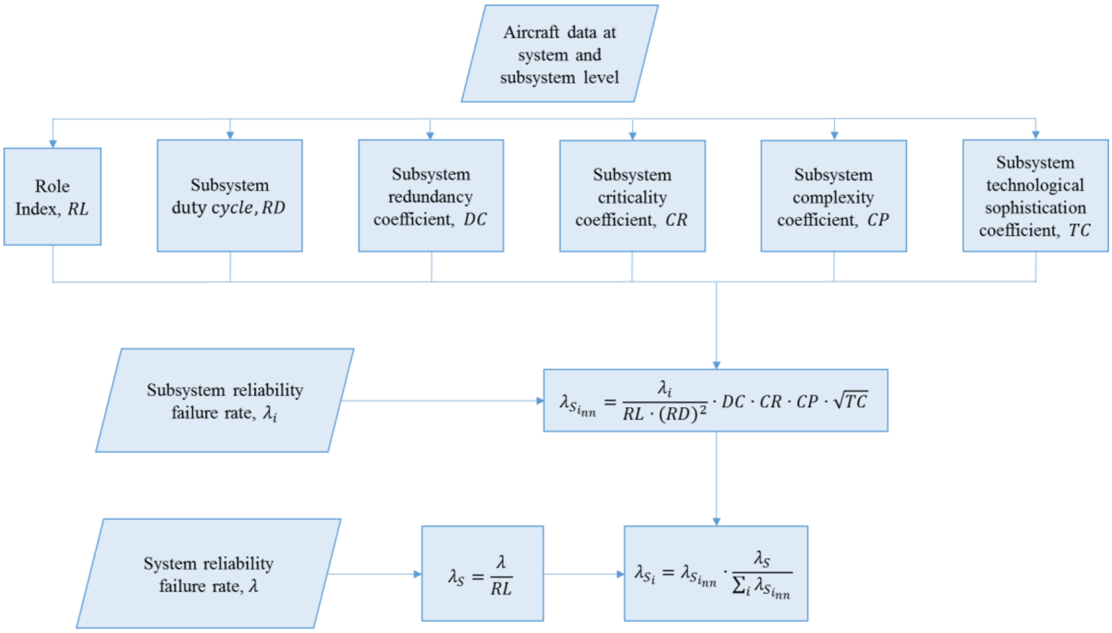



**Figure 7**: Estimation and allocation of the safety failure rate [8]

The first step of the allocation procedure is the calculation of the non-standardised safety failure rate $\lambda_{S_{inn}}$ of the $i_{th}$ subsystem, through the following expression:

$$\lambda_{S_{inn}} = \frac{\lambda_i}{RL \cdot (RD)^2} \cdot DC \cdot CR \cdot CP \cdot \sqrt{TC}$$

Where:

- RD: *subsystem redundancy coefficient*. It takes value equal to either 1.7 in case of redundancy (not 2 because redundancy is never perfect) or 1 in case the system has no redundancies;

- DC: *subsystem duty cycle coefficient***.** It expresses the ratio between the subsystem operating time and the aircraft life cycle, in terms of flight hours. The value of is between 0.1 and 1;
- CR: *subsystem criticality coefficient* for the safety of the entire aircraft. It takes values inferior to 1 in case of subsystems with strong influence on aircraft safety, vice versa it takes values major than 1 in case of subsystems resulting not critical for the aircraft safety;
- CP: *subsystem complexity coefficient*. Considering that a system that a very complex system can have an higher failure probability, CP coefficient takes value over 1 in case of complex subsystem in order to increase the safety failure rate, otherwise it takes value 1;
- TC: *subsystem technological sophistication coefficient*. It expresses the technological sophistication of each single subsystem (while IC expresses the same one of the entire aircraft).

In order to have that the summation of the subsystem values is equal to the safety failure rate of the aircraft, it is necessary to standardise the estimated values, as it follows:

$$\lambda_{S_i} = \lambda_{S_{inn}} \cdot \frac{\lambda_S}{\sum_i \lambda_{S_{inn}}} = \lambda_{S_{inn}} \cdot \frac{\frac{\lambda}{RL}}{\sum_i \lambda_{S_{inn}}}$$

## Maintenance hours per flight hour estimation

*System level*

For this estimation it is necessary to introduce a two new coefficients:

- *Maintenance Role Index*, IRM equal to 1.5, 3.0 and 4.4 for civil, military and hunting aircraft respectively;
- *Design to Maintain Coefficient*, CDTM ranging from over 2 to under 1 depending on the attention paid on maintenance and maintainability during design.

Through their utilisation it possible to define the expression of MMH/FH:

$$\frac{MMH}{FH} = IRM \cdot CDTM \cdot IC \cdot IA \cdot MEW^{0.25} = IRM \cdot CDTM \cdot \lambda/(1.8 \cdot IR \cdot MEW^{0.75})$$

| Maintenance Role Index, IRM | Hunter aircraft IRM=4.4 | Military transport aircraft IRM=3.0 | | Civil transport aircraft IRM=1.5 | |
|---|---|---|---|---|---|
| | | | | | |
| **Level of Maintenance influence on design** | Maintenance not considered in design | First attempts to consider maintenance in design | RAMS discipline considered in design requirements | Testability and Integrated Logistic Support(ILS) considered since the first design phases | RAMS and Logistic Support considered as guideline of the design |
| **Design to Maintain coefficient CDTM** | 2.1 | 1.5 | 1.2 | 1.0 | 0.8 |

**Table 5:** IRM and CDTM values [8]

The expression appears logical because it establishes a linear relation with the FR, while with $MEW^{0.75}$ a logical escalation effect is created: when the weight increases it does not play a linear role because, the more is the weight, the more facilitation is introduced into the maintenance process.

| **Aircraft** | **IRM** | **CDTM** | **IA** | **IC** | **MEW, [t]** | $\frac{MMH}{FH}$ **(estimated)** | $\frac{MMH}{FH}$ **(known)** | **Data source** $\frac{MMH}{FH}$ |
|---|---|---|---|---|---|---|---|---|
| TORNADO | 4.5 | 1.1 | 2.0 | 1.4 | 13.8 | 26.71 | 24.3 | - |
| AMX | 4.5 | 1.0 | 1.5 | 1.0 | 6.0 | 10.56 | 11.02 | - |
| EF2000 | 4.5 | 0.9 | 1.0 | 1.4 | 9.6 | 9.98 | 9.67 | - |
| SCALT | 4.5 | 0.8 | 0.9 | 1.2 | 4.2 | 5.57 | - | DIASp[1] |
| F104 | 4.5 | 1.5 | 2.5 | 1.0 | 8.0 | 28.38 | 27.7 | - |
| FIAT G91 | 4.5 | 2.1 | 3.0 | 0.6 | 3.5 | 23.27 | 25.5 | - |
| C130 | 3.0 | 1.1 | 2.5 | 1.0 | 35.0 | 20.07 | 19.6 | - |
| G222 | 3.0 | 1.1 | 2.0 | 1.0 | 15.0 | 12.99 | - | - |

[1] 'Dipartimento di Ingegneria Aeronautica e Spaziale', it was the Aerospace Engineering department of Politecnico di Torino

| Aircraft | IRM | CDTM | IA | IC | MEW, [t] | $\frac{\text{MMH}}{\text{FH}}$ (estimated) | $\frac{\text{MMH}}{\text{FH}}$ (known) | Data source $\frac{\text{MMH}}{\text{FH}}$ |
|---|---|---|---|---|---|---|---|---|
| ATR42 | 1.5 | 1.0 | 1.5 | 1.0 | 10.0 | 4.0 | 3.64 | ATR |
| A320 | 1.5 | 1.0 | 1.0 | 1.5 | 42.0 | 5.73 | - | - |
| B747 | 1.5 | 1.0 | 2.0 | 1.4 | 170.0 | 15.17 | 14.5 | Roskam |

**Table 6**: Examples of MMH/FH estimation at subsystem level [8]

*Subsystem level*

Once estimated the correspondent value at system level, it is possible to proceed with its allocation at subsystem level. Professor Chiesa, suggests a more empirical method: he provides reference ranges values basing on which it is possible to assume a plausible value of the $i_{th}$ subsystem $(\text{MMH/FH})_{\text{i}_{\text{nn}}}$ %. After the choice of these values for each subsystem, it is possible to proceed with a standardisation of itself, as it follows:

$$\left(\frac{\text{MMH}}{\text{FH}}\right)_{\text{i}} \% = \left(\frac{\text{MMH}}{\text{FH}}\right)_{\text{i}_{\text{nn}}} \% \cdot \frac{100}{\sum_{\text{i}} \left(\frac{\text{MMH}}{\text{FH}}\right)_{\text{i}_{\text{nn}}} \%}$$

Finally, the standardised value $(\text{MMH/FH})_{\text{i}}$ of the $\text{i}_{\text{th}}$ subsystem can be obtained:

$$\left(\frac{\text{MMH}}{\text{FH}}\right)_{\text{i}} = \left(\frac{\text{MMH}}{\text{FH}}\right) \cdot \frac{\left(\frac{\text{MMH}}{\text{FH}}\right)_{\text{i}} \%}{100}$$

where MMH/FH is the value at system level.

## 2.2 Maintenance, Repair and Overhaul in civil aviation

### 2.2.1 Objectives and prescriptions

After the initial approval of airworthiness, aircraft maintenance has to continuously sustain the airworthiness status by performing required maintenance tasks.

Traditionally, the maintenance tasks are divided into categories – 'line'/'transit','A','B','C' and 'D' (from lightest to heaviest) – enabling aircraft operators to plan regular inspections.

Although the required maintenance tasks and the number of engineers assigned will vary between aircraft type and maintenance, repair and overhaul (MRO) company, Table summarises typical checks. Additional or revised tasks are notified by regular Advisory Circulars (AC) and Airworthiness Directives (AD) issued by civil aviation regulatory authorities, such as the European Aviation Safety Agency (EASA) and the FAA.

For modern aircraft types, Maintenance Steering Group (MSG) 3 task-oriented maintenance programmes. MSG-3 (replacing the earlier MSG-1 and MSG-2 philosophies) allows maintenance tasks to be grouped into packages in a way that is more efficient for the operator – matching work against operational requirement – rather than carrying out checks that are pre-defined by the Maintenance Planning Document. Although MSG-3 based checks arrange tasks into multiples of phase intervals (e.g. 48 times the 'Phase 1' interval) the industry generally still refers to maintenance checks 'A','C', and so on.

In the competitive airline industry, low operating cost is a key element to airline profitability. Maintenance cost is a vital part of it. Depending on the aircraft age, type and range, maintenance costs typically represent 10-20 percent of operating costs. As a portion of the airplane Life Cycle Cost (LCC), maintenance plays also a relevant role in its breakdown:

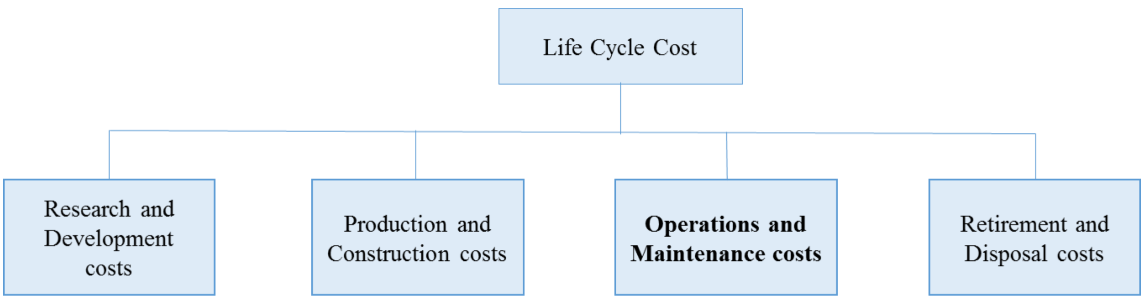



**Figure 8**: LCC breakdown [3]

It includes all processes assuring that the aircraft meets all requirements concerning the airworthiness and that it can be operated safely.

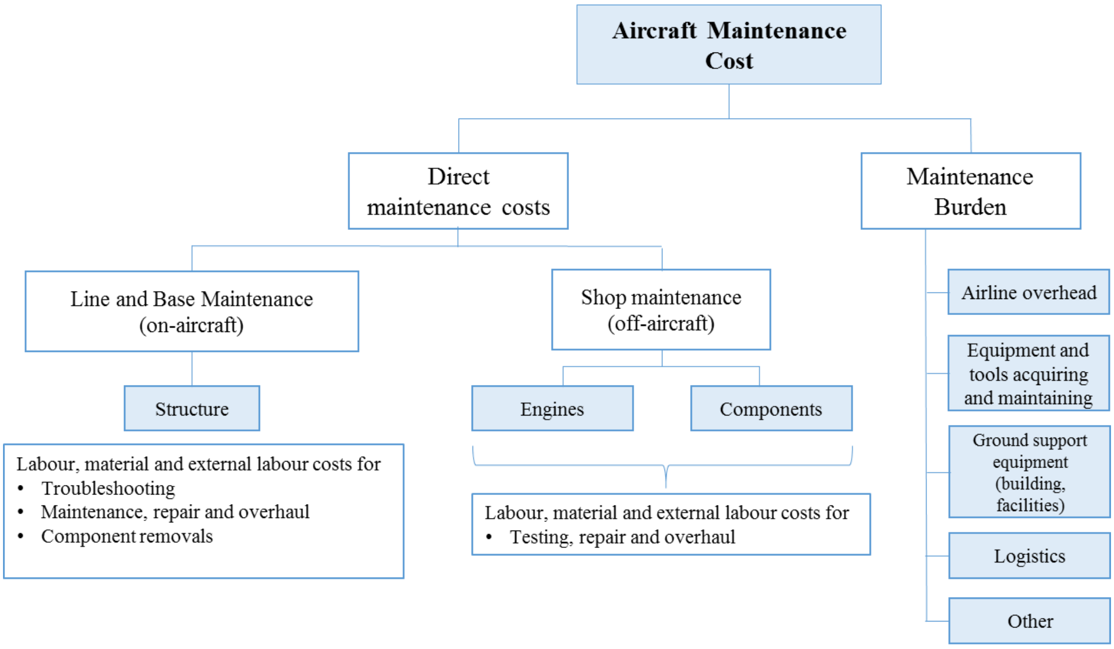



**Figure 9**: Classification of maintenance costs (modified from [9])

### 2.2.2 State of the art

Among the available research studies attention has been paid on *The Maintenance costs of aging aircraft* [29]. It examines how commercial aircraft maintenance costs change as aircraft grow older. It has a panel dating from 1965 to 2003. The model is based on observations based on three variables: categorical variables describing the fleet, continuous variables recording maintenance costs, and continuous variables recording usage. The categorical variables describing a fleet are airline, aircraft type, model, division, and year. The variables recording maintenance costs are separated down to the level of labor or material costs and then to the level of airframe, engine, contracted work, or overhead costs. Finally, the four usage variables are gallons of fuel, flight hours, days assigned to an airline, and block hours. The model, separately acquires the average fleet age (no more than 25 years). It is interesting but from the perspective of the aim of this thesis it only calculates total maintenance cost per flight hour and does not calculate the cost at subsystem level.

Overall, a key limitation of the state-of-the art methodologies lies in the approach adopted for the estimation of maintenance cost which is subdivided into direct maintenance costs (DMCs) and maintenance burden. The available methods calculate the contribution to maintenance costs given by the airframe and the engines without considering the influence of aircraft subsystems. Furthermore, there are no methods in literature estimating the aircraft maintenance cost for new generation aircraft.

### *Maintenance cost estimation model*

As proceeded for RAMS basis model, now it is necessary to give a closer look to the base model chosen for aircraft maintenance cost estimation [9].

It provides an evaluation of maintenance costs at subsystem level, according to the ATA Specification 100 code (Air Transport Association of America, "ATA Specification 100-Specification for manufacturers" Technical data) in order to assess the effective impact of each aircraft subsystem on the total maintenance cost. This model updates a cost-estimating method proposed in 1966. It is constituted by equations at subsystem level, based on cost drivers accurately specified. The outputs are *Direct Maintenance cost* breakdown and *Maintenance Burden* total cost. DMCs comprise the direct cost of labour and materials required for the maintenance activity for both airframe and engine. Maintenance burden includes airline overhead, the cost of acquiring, maintaining equipment and tools, building, facilities, and other indirect costs.

It is useful because, thanks to the estimation that it provides at subsystem level it allows to evaluate not only the impact of the specific on-board system architectures but also the technologies implemented on the aircraft. Combined with RAMS estimation model, it leads a more flexible (able to adapt to different systems) configuration. It will be sensitive to the adoption of innovative technologies.

#### Direct Maintenance cost estimation

The equations constituting the model have been built as update of the work of Pearlman and Simpson, using current aircraft data. They are applicable at conceptual design level. In order to generate new equations CERs (Cost-Estimating Relationships) able to estimate more reliable results, a new database has been built. Furthermore the model provides a set of cost drivers that will be multiplied for the relative coefficients of the equations present in **Table 7**. It is important to notice that the maintenance cost of each ATA component is influenced by different cost drivers, so the number of coefficients in each CER may vary.

The cost drivers are:

1) *Fleet size*;
2) *Aircraft utilisation*;
3) *Flight hours per flight cycle*;
4) *Fuselage length*;
5) *Aircraft cost*;
6) *Age of the type of aircraft*;
7) *Number of seats*;
8) *Average age*;
9) *Number of tires of the landing gear*;
10) *Number of engines*;
11) *Engine thrust*.

The coefficients provided in the table give an output cost for FY[2] 2013. To obtain a cost estimation for the year 2017 (in which the model has been developed), the result of each CER should be multiplied by a cost escalation factor (CEF) of 1.05.

### Maintenance Burden

The total cost of the maintenance burden can be expressed as a percentage of the direct maintenance cost, since it is difficult to find or to build a CER with well-defined cost drivers as for direct maintenance cost. Direct maintenance cost represents 60 percent of the total maintenance cost. The DMC is given by the sum of all costs calculated using the CERs in the table. Once the total DMC is known, the total maintenance cost is given by:

$$C_{tot,MAINT} = \frac{DMC}{0.6}$$

Consequently the maintenance burden can be calculated as the 40% of the total maintenance cost.

[2] FY: Financial Year

| | Constant | Fleet size | Utilization, h/day | FH/FC, h | Fuselage length, ft | Aircraft cost, $ $\times 10^6$ | Age of type of aircraft, months | Number of seats | Average age, years | Number of tires | Number of engines | Thrust, lbf |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Line maintenance** | 193.1600 | 0.0107 | -18.6940 | 14.537 | -- | 0.8842 | 0.1193 | -- | −1.9720 | -- | -- | -- |
| **Base Maintenance** | 144.8700 | 0.0080 | −14.0200 | 10.903 | -- | 0.6632 | 0.0894 | -- | −1.4790 | -- | -- | -- |
| **Engine overhaul** | 135.1600 | -- | −19.7540 | -- | -- | -- | −0.0189 | -- | -- | -- | 110.72 | 0.0055 |
| **Autopilot** | 2.7564 | -- | -- | 0.1178 | -- | 0.0175 | −0.0007 | -- | −0.0065 | -- | -- | -- |
| **Communications** | 5.1822 | 0.0013 | −0.1459 | 1.020 | -- | -- | −0.0060 | 0.0177 | -- | -- | -- | -- |
| **Electrical** | 7.0216 | -- | −0.3866 | -- | -- | 0.0423 | -- | 0.0003 | -- | -- | -- | -- |
| **Equipment/furnishings** | 5.6303 | -- | -0.0389 | 1.363 | -- | -- | -- | 0.232 | -- | -- | -- | -- |
| **Flight controls** | 9.7101 | -- | -0.7535 | 0.499 | -- | 0.0503 | 0.0017 | -- | -0.0004 | -- | -- | -- |
| **Fuel system** | 4.8767 | -- | 1.5254 | -- | -- | -- | -0.0189 | 0.0484 | -0.0111 | -- | -- | -- |
| **Hydraulic power** | 3.4695 | -- | -- | 0.638 | -- | -- | -0.0042 | 0.0127 | -- | -- | -- | -- |
| **Instruments** | 1.9568 | 0.0005 | -0.0551 | 0.385 | -- | -- | -0.0022 | 0.0067 | -- | -- | -- | -- |
| **Wheels and brakes** | 53.1630 | -- | -3.8567 | 2.668 | -- | 0.2730 | 0.0034 | -- | -- | 0.5725 | -- | -- |
| **Landing gear** | 12.4050 | -- | -0.8999 | 0.622 | -- | 0.0637 | 0.0008 | -- | -- | 0.1336 | -- | -- |
| **Navigation** | 11.4910 | -0.0039 | -- | 0.484 | -- | 0.0630 | 0.097 | 0.0108 | -0.2987 | -- | -- | -- |
| **APU** | 8.0316 | -- | 0.7763 | 3.984 | -- | -- | -- | -- | -- | -- | -- | -- |
| **Thrust reversers** | 5.1810 | -- | -0,7572 | -- | -- | -- | -0.0007 | -- | -- | -- | 4.2443 | 0.0002 |

**Table 7**: Table containing the coefficients of the DMC equations (CERs) (modified from [9])

# 3. Research methodology

## 3.1 Overview

The methodology, presented for new generation aircraft, is the aspect constituting the heart of this research work. It can be used by aircraft design engineers to assess maintainability through maintenance costs at the design stage. It is intended to facilitate design trade-offs early in the design process when changes can be done at lower cost.

The diagram below (**Figure 10**) shows the steps in which the methodology is articulated.

The models reported in the previous chapter have been chosen because they estimate their output at subsystem level. They need to be updated and adapted to the need of this research. After the updating activities the new models must be modified in order to estimate new technologies.

Two directions have been followed: *maintenance process modelling* and *data research*.

The former aims to model maintenance processes of new technologies through SysML usage. It is necessary to get some information like how maintenance tasks are structured, which people are involved in, which tools are used and how much time is needed to perform the repair.

The latter way is a thorough qualitative research that intervenes to support the modelling, making possible to identify which output trends are expected from the equations depending on whether one technology is evaluated, rather than another. From many different reliable references and from some interviews, numerical data have been collected where possible. The qualitative investigation, combined with the available numerical data provide a basis on which the modification of the equations can be accomplished.

Successive step is the implementation of the models together with validation process. Since for new technologies there is lack of data, the methodology constituted by the union of two tools (RAMS and Maintenance cost) has been validated only for conventional aircraft.

The last step is the models' testing and the evaluation of results.

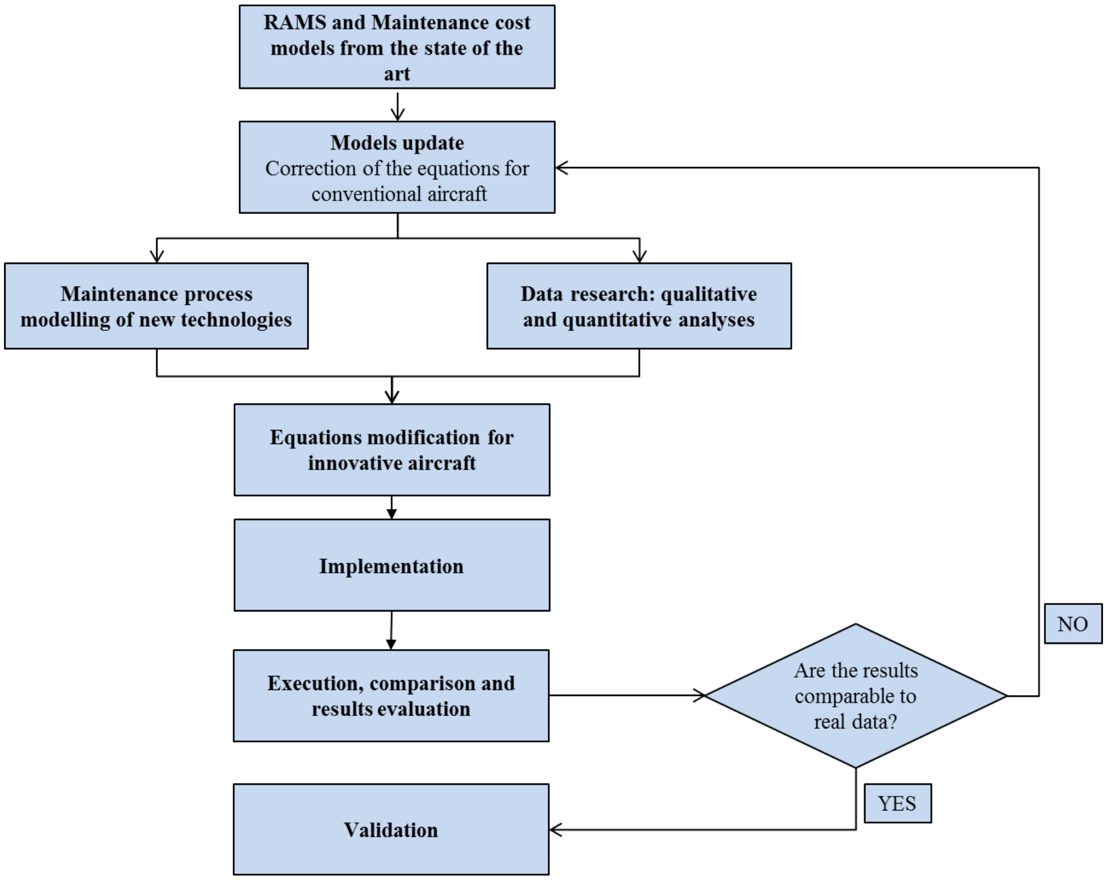



**Figure 10**: Flow chart of the whole methodology

## 3.2 Theoretical modification of the models for conventional aircraft

The models presented in the previous chapter constitute the starting point for the methodology to be determined to estimate the reliability and maintenance costs of civil transport aircraft. Since the first step is to obtain an up-to-date methodology in case of conventional aircraft, appropriate modifications to the two models are needed.

### 3.2.1 RAMS model update

#### *K vector modification*

In the previous chapter (Par. 2.1.2), the procedure for allocating the reliability failure rate has been presented. The model derives a vector K which expresses the ratio between an average percentage failure rate value of subsystem i, $\lambda_{i_{avg}}$% and a mean percentage weight value of each subsystem $W_{i_{avg}}$%. When the model, as it is in the state of the art, has been tested for conventional civil aircraft, the FR values of some systems were slightly inadequate. This is the reason why it has been opportune to remedy the problem by deciding not to calculate $K_i$ as the ratio between the average values, but as a ratio coming from the single civil twin-engine jet transport category.

| Subsystems | Four-engine turboprop military transport aircraft | | Two-engine turboprop military transport | | Two-engine turbojet civil transport | | Regional turboprop | | Average value | | $K_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\lambda_i$[%] | $W_i$[%] | $\lambda_i$[%] | $W_i$[%] | $\lambda_i$[%] | $W_i$[%] | $\lambda_i$[%] | $W_i$[%] | $\lambda_{i_{avg}}$[%] | $W_{i_{avg}}$[%] | |
| Flight controls | 1.10 | 8.20 | 5.20 | 3.80 | 2.30 | 6.40 | 1.00 | 6.10 | 2.40 | 6.13 | 0.39 |
| Hydraulic | 0.20 | 3.30 | 1.40 | 1.40 | 3.90 | 2.40 | 2.80 | 2.90 | 2.08 | 2.50 | 0.83 |
| Auxiliary Power Unit | 0.00 | 0.00 | 1.60 | 1.20 | 0.70 | 0.60 | 0.80 | 0.90 | 0.78 | 0.68 | 1.15 |
| Landing gear | 6.60 | 4.40 | 10.60 | 7.60 | 12.10 | 8.30 | 7.30 | 8.20 | 9.15 | 7.13 | 1.28 |
| Pneumatic and Anti-ice | 14.50 | 4.40 | 10.20 | 3.10 | 4.50 | 3.20 | 6.80 | 3.80 | 9.00 | 3.63 | 2.48 |
| Fuel system | 1.40 | 2.40 | 2.00 | 0.90 | 6.20 | 2.20 | 8.10 | 1.60 | 4.43 | 1.78 | 2.49 |
| Electrical | 12.60 | 3.10 | 9.50 | 3.30 | 3.60 | 2.20 | 8.70 | 2.70 | 8.60 | 2.83 | 3.04 |
| Avionics | 35.60 | 4.40 | 28.20 | 4.50 | 24.80 | 4.10 | 38.50 | 4.80 | 31.78 | 4.45 | 7.14 |
| Furnishings | 2.10 | 13.90 | 19.30 | 19.20 | 6.30 | 2.80 | 5.00 | 3.90 | 8.18 | 9.95 | 0.82 |
| Engines | 22.10 | 6.70 | 3.40 | 8.30 | 27.90 | 15.50 | 14.40 | 12.10 | 16.95 | 10.65 | 1.59 |
| Structure | 1.40 | 48.50 | 3.70 | 46.50 | 4.60 | 51.60 | 3.70 | 52.10 | 3.35 | 49.68 | 0.07 |
| Other | 2.40 | 0.70 | 4.90 | 0.20 | 3.10 | 0.70 | 2.90 | 0.90 | 3.33 | 0.63 | 5.32 |

**Table 8**: Estimation $K_i$ provided by [8] from a statistical database

### *Subsystem updated classification*

In view of the subsequent connection with the maintenance cost estimation model, it has been necessary to create a correspondence in the classification of the subsystems in order to have consistency. In this regard, among the subsystem entries the following have been added:

- Wheel and Brakes (W&B);
- Thrust reversers (T/R).

In order to make a consistent choice, the same proportion of distribution established in the maintenance cost model was followed (**Table 9**), assuming that the distribution of DMC and MMH/FH can be comparable. Regarding the former (W&B), the landing gear reliability failure rate has been split into two contributions: a percentage equal to 80 has been assigned to Wheel and Brakes, and the remaining part to landing gear. W&B subsystem requires regular inspections to ensure continuing integrity. Following the same philosophy, to the latter, Thrust Reversers, has been attributed a small fraction of the engines equal to 5 percent of both reliability failure rate and maintenance man-hour per flight hour.

| **RAMS [%]** | |
|---|---|
| **W&B** | **Landing gear** |
| 80 | 20 |
| **T/R** | **Engines** |
| 5 | 95 |

**Table 9**: Fractions assigned for improved consistency

### *Maintenance man-hours per flight hour update*

Finally, one last problem has been fixed. It is related to the magnitude order of the maintenance man hours. The model suggests estimating these outputs on the basis of a more empirical approach, based on reference ranges that come from statistical database. In the last 10-year period, the way of doing maintenance has radically changed, since every single improvement has been made in order to decrease labour hours and consequently the relative costs. On the basis of current data of some aircraft samples, an actualisation coefficient has been introduced:

$$\frac{\mathrm{MMH}}{\mathrm{FH}} = \mathrm{IRM} \cdot \mathrm{CDTM} \cdot \mathrm{IC} \cdot \mathrm{IA} \cdot \mathrm{MEW}^{0.25} \cdot \mathbf{\frac{1}{6}}$$

Thanks to this simple modification, the model is now able to estimate a more realistic maintenance man-hour value.

| $\left(\frac{MMH}{FH}\right)_{i_{nn\%}}$ | | | | | | |
|---|---|---|---|---|---|---|
| | **Range values** | | **Twin-engine, No APU** | **Twin-engine, APU** | **Twin-engine, APU** $^{+}$ [3] | **Four-engine, APU** |
| Flight controls | 5.00-9.00 | Sophistication level | 6.43 | 7 | 8 | 9 |
| Hydraulic system | 2.70-3.50 | Actuators number | 3 | 3.25 | 3.35 | 3.5 |
| APU | 0.00-6.00 | Presence or absence | 0.00 | 2.00 | 4.00 | 6.00 |
| Landing gear | 6.60-9.00 | Number of legs, number of tires | 7.29 | 7.86 | 8.43 | 9 |
| ECS & Anti-ice | 1.50-4.50 | Number of passengers | 2.57 | 3.21 | 3.85 | 4.49 |
| Pneumatic system | 2.00-2.30 | - | 2.25 | 2.3 | 2.35 | 2.4 |
| Fuel | 3.00-8.00 | 2 engines, no APU, more engines with APU | 3.22 | 4.81 | 6.4 | 7.99 |
| Electrical system | 1.7 | - | 1.82 | 1.7 | 1.7 | 1.7 |
| Avionic system | 6.00-18.00 | Sophistication level | 8.57 | 11.38 | 14.19 | 17 |
| Furnishings | 2.00-12.00 | Cargo/Passengers, "In flight entertainment" | 10.72 | 11.36 | 12.00 | 12.64 |
| Engines | 16.00-22.00 | Number of engines, eventual plus for propeller | 28.94 | 16.00 | 19.00 | 21.00 |
| Structure | 24.00-36.00 | Sophistication level | 21.44 | 24 | 30 | 35 |
| Other | 2.00-5.00 | - | 96.25 | 94.87 | 113.27 | 129.72 |

**Table 10**: Identification of $\left(\frac{MMH}{FH}\right)_{nn\%}$ vectors for different civil aircraft categories

### 3.2.2 Maintenance cost model update

The maintenance cost estimation model presented in the previous chapter (Par. 2.2.2) required an expansion in order to have a deeper view of the new technologies' impact on

[3] Twin-engine, APU $^{+}$ means larger than a twin-engine with APU. It stands for an aircraft similar to Airbus A320 in dimensions.

maintenance costs. Thanks to its manageability, the Airbus method has been applied, allowing the breakdown of direct maintenance costs (DMC) in:

- *Direct Labour Cost, $DLC$*: the amount of money that can range from the cost of labour related a specific maintenance event to the cost of the entire technical division [30]. It is the labour performed by the employees that specifically and consistently work on aircraft and its parts;

- *Material cost*, $MC$: amount of money spent for spares parts.

The equation governing the Airbus method is as follows:

$$\mathrm{DMC} = \underbrace{\frac{\mathrm{MMH}}{\mathrm{FH}} \cdot \mathrm{LR}}_{\mathrm{DLC}} + \mathrm{MC} \qquad [\$/\mathrm{FH}]$$

Where:

LR: *Labour Rate*, it is a unit cost (e.g. an amount of money per hour) [30]

Through the above equation it is possible to unpack DMC in two contributions. DMC is one of the output of the maintenance cost model from the state of the art, now new output will also be the cost of the spare parts at the subsystem level. This integration allows a more in-depth analysis of the effects of the implementation of a certain technology through maintenance man-hours on the direct maintenance costs. As a consequence a better analysis can be carried out and a direct link between the two models has been established through maintenance man-hours.

Again, in order to have a better consistency, the following correspondence has been set:

<table>
<tr><th colspan="2">RAMS state of the art</th><th>Maintenance cost state of the art</th></tr>
<tr><td colspan="2"></td><td>Engines</td></tr>
<tr><td colspan="2"></td><td>Electrical system</td></tr>
<tr><td colspan="2"></td><td>Hydraulic system</td></tr>
<tr><td colspan="2"></td><td>Flight controls</td></tr>
<tr><td colspan="2"></td><td>Fuel system</td></tr>
<tr><td colspan="2" rowspan="5">Avionics</td><td>Instrument panel</td></tr>
<tr><td>Automatic Flight System</td></tr>
<tr><td>Communication</td></tr>
<tr><td>Integrated Modular Avionics</td></tr>
<tr><td>Navigation</td></tr>
<tr><td colspan="2"></td><td>Landing gear</td></tr>
<tr><td rowspan="2">Pneumatic_Anti-ice</td><td>Air conditioning</td><td rowspan="3">Furnishings</td></tr>
<tr><td>De-icing</td></tr>
<tr><td colspan="2">Furnishings</td></tr>
<tr><td colspan="2"></td><td>APU</td></tr>
<tr><td colspan="2"></td><td>Wheel and Brakes</td></tr>
<tr><td colspan="2"></td><td>Thrust reversers</td></tr>
<tr><td colspan="2" rowspan="2">Structure</td><td>Line Maintenance</td></tr>
<tr><td>Base Maintenance</td></tr>
</table>

**Table 11**: Comparison between RAMS and Maintenance cost PBS

The subsystems indicated at the left of the equal sign are from RAMS model, while the others to the right are subsystems from Maintenance cost model. In addition Maintenance cost model included *Pneumatic* system in *Furnishings*.

## 3.3 Modification of the models for innovative aircraft

### 3.3.1 Maintenance process modelling

Considering the lack of data in the literature regarding reliability failure rate, maintenance man-hours per flight hour, and maintenance costs in case of new technologies assessment, the first part of the second stage of the methodology is to get as much information as possible through maintenance process modelling.

To analyse a maintenance process in its structure (tasks, tools, time, technicians) is very helpful in order to obtain useful data for the modification of the models.

The choice of the way in which representing maintenance processes fell on a very useful representation tool: the Systems Modeling Language (SysML).

The SysML is a modelling language that supports the specification, design, analysis, and verification of systems that may include hardware, software, data, personnel, procedures, and facilities [31]. It has a specific semantic for representing requirements, behaviour, structures, properties of the system and its components. SysML is intended to facilitate the application of an MBSE approach to create a cohesive and consistent model of the system.

It can represent the following aspects of systems, components, and other entities:

- Structural composition, interconnection, and classification;
- Function-based, message-based, and state-based behaviour;
- Constraints on the physical and performance properties;
- Allocations between behaviour, structure and constraints;
- Requirements and their relationship to other requirements, design elements, and test cases.

SysML includes nine diagram types.

Among these different types the most suitable to a maintenance process development are two:

- *Activity diagram*: it is structured as a flow of inputs and outputs representing the actions to be performed. The activity diagram defines the actions to be performed and has control between them.
- *Use case diagram*: it describes the goals of a system of or a process from the perspective of the users. The goals are described in terms of functionality that the system must support. An actor is used to represent the role of a human, an organization, or any external system that participates in the use of the system or in the process. Actors may interact directly with the system or indirectly through other actors.

### *Composites*

Among the three considered technologies, as a relative new technology, composites development and practice continues to evolve. For instance in the A350-900, the parts in composites are:

- wings;
- center wing box and keel beam;
- empennage and tail cone;
- fuselage skin panels;
- frames, stringers and doublers;
- doors (passenger and cargo).

Hence, most of the external structures of the airframe are made with composite materials [32].

#### Standards for composite repair

The flow information has been evidently restricted because of the deep competition among airframe manufacturers, like Airbus and Boeing. Composite technology is evolving in real time, with new-generation design and manufacturing technologies for large composite structures being researched and developed. Manufacturing techniques are also changing, combined with property developments. Evolving composite technologies are oftentimes considered proprietary and are not available in the public domain. As a consequence, composite property standards are requiring special skills and awareness of safety implications of composite maintenance and repair. Reason why they are in the early stages of development.

The report [33] has been very useful to develop a repair process model for a typical composites structure. It provides an industry standard, taking into evidence the need of development of a standard awareness of composite technology and its safety implications in industry.

The term *continued airworthiness* is often used to monitor the safety of the aircraft when it enters service. There are a number of factors affecting the continued airworthiness of composite structure. Accidental damage (e.g., foreign object impact), unlike metal structures where fatigue cracking can be a primary threat to structural integrity, is a critical threat for composites. In fact to protect from hidden deficiencies incurred in manufacturing also accidental damage needs to be considered. For example, surface contamination may cause weak bonds that may not be detected by initial inspection methods. As a result, quality control procedures (QCs) and redundant design features are needed in order to ensure the continued airworthiness of bonded structures.

The different levels of degradation and damage that can occur during service must be considered for structural in order to refine the composite repair standards needed. Since compressive strength, and other matrix-dominated composite properties, is the most sensitive to moisture absorption over time and high temperatures, a first evaluation of environmental consequences and fluid compatibility is needed. Static strength validation includes the smaller damages that will not be detected in production or maintenance inspection, while damage tolerance addresses larger damages that need to be repaired once discovered.

Repairs and continued airworthiness procedures must be provided in service documents, including approved sections of the maintenance and instruction manuals for continued airworthiness. In the discipline of composite materials, it is important to realize that the material structural properties are set during the fabrication processes of parts or repairs. This differs from metals where in most part and repair fabrication processes do not alter the base material properties of the raw material form (exceptions include heat treatments, welding, and some forming processes). Special skills are needed for composite engineers, inspectors, and technicians involved in production and maintenance. These skills depend on the specific details of a given structural design, processing specification, QC procedure, tooling, inspection method, and repair. If any of these details are not followed properly, the database and analyses used for structural substantiation may not be representative of the fabricated part or repair.

The complexity is increased because special care is required to perform bonded repairs while the fabrication facilities are not enough prepared in terms of control. Reliable procedures are needed to ensure sufficient cleanliness and environmental controls for proper bonding.

Furthermore, it is necessary to consider limits on the size of bonded repairs performed, in order to keep structural redundancy as fixed in the design of bonded structure. All repairs should have supporting data references based on tests or analyses.

Many of the field damages are due to foreign object impact, which is one of the primary safety issues for composite structures. Repeated loads, by themselves, typically do not lead to service damage because of relatively flat composite fatigue curves and a need to account for accidental damage in design criteria, which reduces the working strain levels. The few cases where fatigue has been a problem usually are due to bad design detail, where secondary out-plane loads occur in service, damaging the weak direction of the composite. Other field damages are due to environmental conditions, including hail, ultraviolet (UV) radiation, rain erosion, moisture ingression, and ground-air-ground cycles (temperature, pressure, and moisture excursions).

All critical inspection items should be kept in documentation in order to support maintenance. Maintenance instructions should include material and process controls, fabrication steps, cured-part tolerances, non-destructive inspection (NDI), and other QC checks for bonded repair.

There are other elements that have an impact on composite product certification and continued airworthiness management. Lack of engineering standards for composites can affect the associated costs and timelines. This effect can be minimized, depending on skills of the engineering team. The mentoring and training of new engineers and technicians is also essential to a successful aircraft service use while the techniques are changing.

A good balance of team members with engineering experience in composite design, analysis, manufacturing, and maintenance practice is needed to coordinate a product development and certification program. The tasks performed by each discipline must be coordinated to avoid adding costs and risks in meeting schedule milestones.

Good communication must exist between the engineering disciplines involved in the continued airworthiness management of composite products in service. Maintenance and operations personnel should have knowledge of factors affecting the performance of a composite structure. This is important when working with structures engineers on the disposition of anomalous events (e.g., structural overloads and ground vehicle collisions) and damage found in service.

### Technical issues

Technical issues associated with the maintenance (repair) of composite materials used in aircraft products start with a realization of how to gain knowledge and acquire skills for safe industry practices. Since the technology has not been standardized, textbooks and reports documenting the working knowledge needed to be proficient in the field do not exist. Experience must be gained from working in the industry and using methods and procedures that are often proprietary for a given product. Some references help to clarify the critical technical issues, to put the lack of standard industry practices into context, and to illustrate the additional training necessary for the maintenance (repair) of composite structures on a given aircraft.

There are many source documents that contain maintenance, modification, rework, and repair information. The SRM (Structure Repair Manual), or equivalent, is often the most complete maintenance document in terms of instructions for damage disposition, inspection, and repair. A SRM typically contains previously approved data but this should always be confirmed. Service Bulletins (SB) issued by an OEM are the means for sharing modifications to previous maintenance instructions. These include supplemental inspection, rework, and repair instructions for a given composite part.

## DAMAGE DETECTION AND CHARACTERIZATION

Despite stringent controls, some defects and damage are likely to occur from manufacturing or service exposure. Defects and handling damages that occur during manufacturing are controlled by in-process and post-process QCs., requiring factory disposition. Most processing anomalies that are allowed to enter the field are much smaller than damage considered from service. This relates to advanced NDI procedures used in the factory. Factory NDI methods are more stringent than those that can be practically applied in the field. Hence, design criteria must account for larger field damage to accommodate practical maintenance practices.

Weak bonds are a type of manufacturing defect that has posed field problems, where bond surface contamination, tooling, or curing problems lead to insufficient bond strength. This manufacturing defect is best controlled in-process because factory NDI performed after cure typically will not detect the problem. Composite design criteria have protected against this problem by making sure there is redundant design detail and damage tolerance to ensure the associated debonding can be found in service.

There are different damage types that significantly reduce the residual strength of composites. The drops in residual strength are related to damage type and size. In the case of impact damage, compression, shear and tensile strength can all be reduced. There are also some damage types that have very little effect on residual strength but, depending on the design detail, some of these may combine with environmental effects and ground-air-ground cycling to cause further damage. The following subsections will present the different composite damage types and their sources.

### *Delamination and Debonds*

This form of composite damage occurs at the interface between the layers in the laminate, along the bondline between two elements, and between facesheets and the core of sandwich structures.

Delaminations can occur due to stress concentrations at laminate-free edges, matrix cracks, or structural details (e.g., radii and ply drops). They may also form from poor processing or from low-energy impact. Debonds may also form similarly. Delaminations and debonds break the laminate into multiple sublaminates and reduce the effective stiffness of bonded structural assemblies. For this reason they decrease structural stability and strength, threating safety structure.

### *Fibre Breakage*

The main strength given by composite structures is due to the presence of the fibers. Broken fibers can be critical because fibers carry most of the load. Luckily, fibre failure is typically limited to the zone of impact contact and depends on the impact-object size and energy. The resulting loss in residual strength is controlled by a relatively small damage size.

### *Dents*

Dents are typically caused by an impact event. The dent is usually an evidence of latent damage. Damage can consist of one or more of the following: sandwich core damage, facesheet delaminations, matrix cracks, fibre breakage, and debonds between facesheets and core.

### *Erosion*

Erosion can occur at the edge of a laminate panel or at a sandwich edge band as a result of airflow over the structure or the impingement of debris, rain, etc. Erosion can expose surface fibers to reduce local strength and lead to moisture ingression. In most cases, erosion is not a safety threat because damage is found before becoming serious.

### *Heat Damage*

This type of damage is possible near sources of high temperature (e.g., engines, air-conditioning units, or other systems). There are usually visual indications of heat damage caused by exhaust or charring of the part surface, but it may be difficult to determine the extent of heat damage.

### *Damage from Fluid Ingression into Sandwich Panels*

This type of damage usually requires another damage to be present, allowing a leak path into the sandwich core. Some design details (e.g., porous fabric weave styles used for facesheets, square edge sandwich close-outs) may also allow fluids to enter the core through leaks. Once the fluid gets into the sandwich part, it can degrade the core or its bond with the facesheets.

After having reviewed the main types of damage of the composite structures, it is possible to move on the damage detection and characterization phase. The steps constituting this phase are:

- cleaning intervention;
- visual inspection;
- NDIs control inspections

Methods used in the field for composite part damage detection, damage characterization, and post-repair inspection are typically less sophisticated than those employed by the OEM for their post-processing inspection. Operators and maintenance organizations use visual inspection as their main technique for initial detection of field damages, unless NDI techniques are specified by the specific maintenance planning manual or aircraft maintenance manual.

Inspect the damage carefully, which may require careful cleaning of the part before a detailed inspection can be made.

The full extent of the damage to a composite part must be mapped using visual and NDI techniques. Despite the use of visual inspection to first detect damage, NDI methods are essential to map the full extent of the damage in orther to establish the subsequent damage proper disposition and repair processes. Since a disposition of repair size limits also depends on accurate mapping, decisions on whether the repair substantiation database is sufficient also relies on a complete inspection with the proper NDI. Visual detection methods are possible, assuming a composite structure was designed to carry loads with nonvisible damages occurring in service. Many of the damage types described have both visual and hidden damages. Hidden damage in composites usually covers a larger area than visual indications of damage and dominates the lost residual strength. Typical NDI methods used for composites are tap testing, ultrasonic inspection, x-radiography. If the damaged part is a honeycomb sandwich panel, a coin tap test may be used to map the damage. If the damage is to a solid laminate area of a sandwich panel (e.g., the edge band) or a stiffened laminate part, the coin tap test will only detect disbond in the first few layers and an ultrasonic method will be required to establish the boundary of the damage.

It is essential that the proper NDI methods are applied to damage found on composite structure to map the full extent of the damage, which is needed to determine whether damage is below the ADL or whether repairs are required:

- If a small damage exists in a honeycomb panel that is within the specific allowable damage limit (ADL) for that component, it should be dried to specified repair documentation requirements, and then filled with potting compound and taped over. This prevents the damage from deteriorating, and the part must be scheduled for permanent repair within the time limits given in the source documentation.
  However, if the temporary repair is inspected and no further damage is detected, the temporary repair (i.e., speed tape) may be reinstalled without permanent repair. If the damage exceeds tolerance limits, the OEM should be consulted. If the above procedures are not satisfactory, the part must be removed and replaced, if appropriate; rebuilt by the OEM or a qualified maintenance and repair organization (MRO); or be scrapped. In the event that the damaged part is not removable (e.g., a wing skin), the aircraft is grounded, commonly referred to as aircraft on ground (AOG) and an AOG team is sent out to complete a permanent repair. Typically, the AOG team is sent out from the OEM. The term "allowable damage" allows the aircraft to return to service without being permanently repaired, but does not exclude the requirement for a permanent repair.

- If a part is determined to be damaged beyond the specific ADL for that part, it must be repaired before the next flight. The part must be replaced either while the original part is removed for repair or the original part must be repaired before the next flight per the instructions in the authorized repair documentation.

The description from the cleaning intervention of the part to the full map extent of the damage is represented in **Figure 11** below. It is an extract of the SysML activity diagram modelled for a composite repair process.

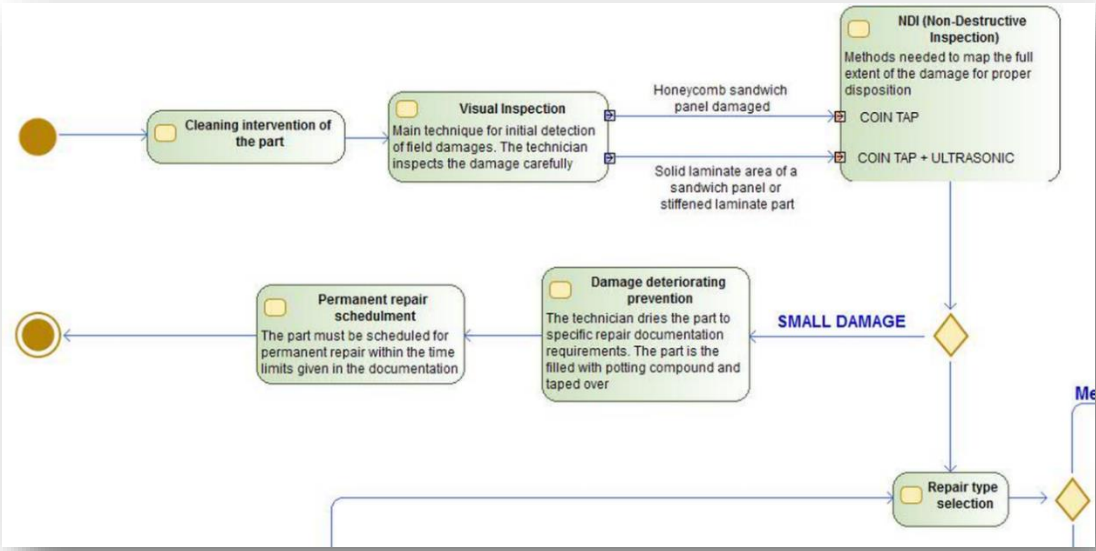



**Figure 11**: From the cleaning intervention to the full extent characterisation of the damage

## REPAIR PROCESS SELECTION

### *Repair process types*

The two basic types of composite repair processes are bonded and bolted. The latter has processing steps that are similar to bolted metal repairs. However, there are several differences that need to be understood to successfully perform a composite bolted repair. The important technical issues for bonded repairs are similar to those for composite part fabrication.

$$Bolted \rightarrow Bolted\ metal\ repairs$$

$$Bonded \rightarrow Composit\ part\ fabrication$$

However, the issues become more difficult when addressed for bonded repairs made in the field, sometimes performed on-airplane. Sometimes bolted repairs may start with laminate fabrication of repair patches, reason why some of the topics that need to be addressed are common with the following discussions on bonded repairs.

Approved repairs for control surfaces must evaluate the effects on overall part stiffness, weight and balance, and flutter characteristics. Many composite control surfaces use a sandwich panel design.

Damaged sandwich panels typically require local core removal and a bonded repair to the facesheet. After the repair, the mass balance of a control surface must be checked against operational limits before returning the part to service. One possible issue when using composite curing for bonded repairs is that the part distorts or warps due to uneven cure or tooling problems. This issue can further cause problems with control surface clearances and deployment mechanisms. As a result, the clearances with adjacent fixed and movable structure should also be checked using the full range of deployment, including possible deflections when under load.

Other considerations for the repair of composite parts include the restoration of coatings and exterior protective layers.

The primer and paint used to protect composite parts from UV degradation must also be restored. To protect against corrosion, fibreglass isolation plies are often used to separate carbon composite from aluminium parts.

***Bonded Composite Repair***

Basic laminate fabrication involves creating fibre-reinforced composite parts from uncured material. The most common fabrication techniques use epoxy pre-impregnated tape and fabric materials (pre-preg).

Heat and pressure are used during the cure process in order to form it into a final shape. When including adhesive bonding in part fabrication (i.e., bonding used to attach pre-cured elements), special care is needed to prepare the procured surfaces for bonding. Since much of the composite part has already been cured, bonded repair requires adhesive bonding on at least one of the repair surfaces. As is the case for a laminated part fabrication that includes bonded elements, bonded repair surface preparation is one of the most critical processing steps.

Some OEMs use autoclaves for curing large epoxy pre-preg laminate components. This method provides vacuum, heat, and pressure to the bagged composite part. The addition of autoclave pressure provides ply consolidation that helps minimize internal defects, such as porosity. Autoclaves are generally not available for bonded composite repairs in the field.

There are generally two types of bonded composite repairs. The first is called a pre-preg repair, and the second is called a wet lay-up repair. Pre-preg repairs can be made using either the original part pre-preg material or a substitute pre-preg material that has been approved for a specific pre-preg repair. Shipping, handling, and storage of the pre-preg must be controlled because it is perishable. To maximize life, pre-preg must be stored at low temperatures in sealed bags until use and then allowed to reach room temperature before being removed from the bags and applied to laminate lay-up. Pre-preg repairs can be performed using an autoclave if the damaged part can be easily removed from the aircraft.

The correct processing of bonded composite repairs is critical to the elimination of defects.

This includes all processing steps, such as damage removal, surface preparation, material handling and storage, patch material lay-up, part bagging and cure, and post-process inspection. In the case of a wet lay-up repair, resin mixing and dry fabric impregnation are added steps. In the case of a pre-preg repair, the material must be removed from the freezer and allowed to thaw before opening the bag and starting the lay-up process. It is essential to realize that in-process inspections are at least as important as post-process NDI for bonded composite repairs.

Before a bonded repair, all fluids must be removed from the damaged component using vacuum and heat. Failure to remove all moisture and fluids from the repair region of the component may cause a patch bondline failure. This may be particularly troublesome for sandwich construction where fluid ingression into damaged core (e.g., honeycomb) may cause internal vapour pressures when heated during cure, blowing facesheets off the core. It is also essential that the protective coating (e.g., conductive coating, if present, paint enamel, and primer) should be completely removed from an area larger than the bonded repair using a prescribed method such as abrading or sanding.

Damage removal and surface preparation must be performed prior to a bonded repair.

Good surface preparation requires (1) an approved process shown to reliably work for the specific adhesive and composites included in the bonded repair, and (2) a technician with the skills needed to properly execute the process. Deviations may cause a poorly bonded repair that appears acceptable when inspected using a post-bond NDI method.

This highlights the importance of stringent in-process controls for the bond surface preparation steps.
Most post-repair NDI methods are unable to determine individual repair ply orientations, again highlighting the importance of in-process QCs.

A repair cure cycle must be controlled on-airplane or in an autoclave. Substructure heat sinks for on-airplane bonded repairs can cause the cure temperatures to vary by drawing heat away from the repair zone. For this reason, it is important to be cognizant of the substructure when placing the thermo-couples. If underlying structure or equipment will be adversely affected by adjacent heating, the equipment must be either removed prior to the repair, or protected from excessive heat. During the cure cycle, any loss of vacuum, autoclave pressure, or temperature can result in anomalies such as voids, porosity, and delamination. These problems can be detected by post-repair NDI. An improperly cured part may also have lower than required thermal stability in addition to lower mechanical properties. If such problems occur without indications of porosity or delamination, the NDI may not detect an issue. Instead, in-process control measurements of temperature and vacuum are needed to identify a possible problem associated with under- or over-cure.

Post-process NDI of a bonded repair is performed after specified cooldown and removal of bag and cure materials. Approved repair documents should specify NDI procedures to be used. Qualified inspectors are typically needed for most post-process NDI methods. The NDI can find processing anomalies, such as voids, delaminations, and porosity, which occur during the cure process, and may be the result of poor tooling, insufficient ply consolidation, low autoclave pressure, or loss of vacuum during the cure cycle. The NDI can also detect handling damage on laminate edges, impact damage and delaminations from poorly machined parts (i.e., drilled holes or edge trim), or improper assembly. The NDI measurements combine with in-process quality checks to indicate that the repair is satisfactory. Once such a determination is made, protective coatings can be restored over the repaired area, per approved documents, and the component can be returned to service.

Many OEMs have a factory process called the Material Review Board (MRB). The MRB is a process that is intended to make team dispositions concerning reported defects or unsatisfactory raw material and take corrective actions as necessary. A similar process should be established whenever questions arise in composite field repair.

### ***Bolted Composite Repair***

The use of bonded composite parts in aircraft structures enables the elimination of thousands of mechanical fasteners that exist in similar metal components. However, mechanical fasteners are still used for joining the more highly loaded composite elements and components. Benefits from the use of composite bolted joints include the higher joint reliability of discrete fasteners, the improved inspection capability, and the ability for possible disassembly during maintenance. It is important to understand the effect that holes and loaded fasteners can have on the strength of the composite laminates being joined. An open hole in a composite laminate produces stress concentrations that can significantly increase the stresses at the edges of the hole compared to the stresses in the unnotched section of the laminate. The bearing stress of the fastener, which transfers load from one part to the other, must be added to the stresses at the edge of the hole. All of these stresses cause significant reductions in strength of the laminate in the joint area.
The use of mechanical fasteners to assemble airframe structural components or elements is a mature technology. Composite part joining is no exception to this. Failure modes for composite-fastened joints are similar to those for metallic-fastened joints. Despite their similarities, the behaviour of composite-fastened joints differs significantly from that of a metal.

Bolted repairs can be smaller than bonded repairs, and thus are often used for the repair of composite parts when the thickness of the part requires a very large scarfed out area for bonding. The main consideration for any aircraft component repair is that, in general, aircraft components, such as wings, stabilizers, and fuselage skins, are loaded in multiple directions. A bolted composite repair has to be carefully designed, and knowledge of the component design loads is essential. The quality of holes drilled in a component that is loaded in multiple directions can have significant effects on the capability of that component.

The surface of damaged composite parts must be prepared for bolted repairs. The surfaces should be clean and it is essential that there is no protruding damage (e.g., fibers) that may prevent the repair doubler and base composite part from mating properly. If a repair doubler is not in proper contact with the part being repaired, fastener installation may be affected (e.g., effectively changing the pull-up forces or fastener grip length).

As with bonded repairs, bolted repairs benefit from in-process QCs. The use of two technicians to share in the bolted repair tasks can provide the in-process checks needed to avoid defects. On any given step, one technician can serve as the inspector for proper use of tools, equipment, and procedures, while the other performs processing tasks.

### *Repair process selection*

Authorized documentation must be consulted for permitted sizes of repairable damage. The repair size that is allowed depends on the type of repair.

- ❖ Repairs using room temperature-curing adhesives or resins are usually limited in size.

- ❖ If a hot 65°-93°C (150°- 200°F) curing adhesive or resin is used, the permitted repair size becomes larger. However, hot-cured repairs may require tooling to maintain the shape of the part, and this tooling may not be available.

- ❖ If repairs are made at the original cure temperature, then large repairs and sometimes unlimited size repairs are allowed. Repairs at the original cure temperature also require pressures higher than can be attained using a vacuum bag, thus requiring an autoclave or press.

- ❖ If a large repair is necessary, the part may be sent to an approved repair station that has the required equipment. If the damage is to a stiffened laminate part, the skin should be carefully trimmed to avoid damaging the substructure (e.g., a stringer or rib). Special fasteners and drilling equipment may be needed. Damage to flight critical structure will usually involve consultation with the OEM.

The part drawing or authorized repair documentation, commonly known as an SRM, is typically available at large airlines and MROs that provide the exact lay-up details, the type of fibre used, and the weight and orientation of each tape and fabric layer. The SRM will list the type of sandwich core, if used, as well as the resins and adhesives that may be used for the part in question. Repairs using the original part materials can be more difficult than manufacturing since availability of the materials in small batches may be difficult. The correct part and revision number must be used to verify the required repair materials and lay-ups.

It is essential to select the correct fibre type and weight of fabric or tape with the correct surface finish to make a strong, durable repair. It is very easy to use a fabric with the wrong weight, and great care must be taken to ensure that this does not happen. Correct identification, location, and orientation of each ply within the lay-up is important. Since the transverse strength of a specific composite layer (ply) is low compared to the fibre direction of the ply, the orientation of each ply is critical to ensure adequate repair strength and stiffness. When preparing the repair surface, it is important to ensure that it is clean, it has been dried to SRM requirements, and the repair fabric has the required finish. Only the surface resin layer should be abraded without damaging the first layer of fibre, using the grit size recommended in the SRM. For repair work, the first ply should be oriented in the same direction as the ply to which it is to be bonded.

## REPAIR MATERIALS SELECTION

- If the required materials are not in stock, the manufacturer may have to be contacted for alternatives;

- If the materials are in stock, it is necessary to check that they are within their permitted shelf life;

- If all the materials are within their shelf-life limits, the materials can be ordered from
stock and the work can be planned.

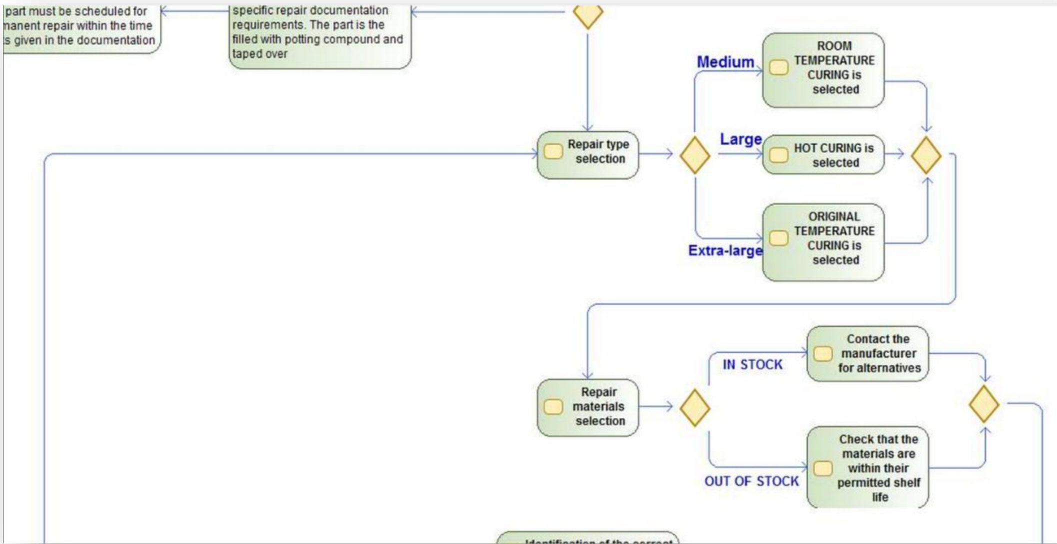



**Figure 12**: From the repair process selection to the repair materials selection

## PAINT AND SURFACE PROTECTION SYSTEMS REMOVAL

Other considerations for the repair of composite parts include the restoration of coatings and exterior protective layers.

The primer and paint used to protect composite parts from UV degradation must also be restored. To protect against corrosion, fibreglass isolation plies are often used to separate carbon composite from aluminium parts.

The original paint and primer, and any other surface protection system (such as aluminium flame spray for lightning protection), must be removed very carefully to avoid damaging the first layer of fibre. For repairs, careful sanding is probably the best method.

## DAMAGE REMOVAL and REPLACEMENT

Depending on the type of repair, a two-part paste adhesive may be applied to the bottom skin or a layer of film adhesive may be put in place. This may require a fairly heavy layer of film adhesive to bond the honeycomb core. The new piece of honeycomb must be cut to size so the ribbon direction of the honeycomb matches the original, and the adhesive must be spread on the bottom cells (if a paste is used). If a hot cure is to be performed, the edges of the core must be joined either with an approved potting compound or a layer of foaming film adhesive must be placed around the edge. Heat and pressure will need to be applied to both the bottom and top skin if the honeycomb on the bottom skin is to be cured at the right temperature and at the same time as the top skin. For this process, the honeycomb must be exactly flush with the top skin. For this reason, it is often better to cure the honeycomb to the bottom skin joint and the edge potting compound in one operation, and then sand the core flush with the top skin and bond the new top skin as a second operation. Room temperature repairs are much easier than hot-cured repairs because the honeycomb can be potted in place without any pressure and left to cure while the top skin layers are cut to shape. Often, room temperature repairs can be made without tooling, which is another advantage over hot cure. However, the SRM usually permits only small repairs of at-room temperature cure.

## PREPARATION FOR FINAL CURE

Before final room temperature or hot curing starts, the repair area for the skin patch, the honeycomb core, and the new honeycomb insert must be dried to SRM requirements.

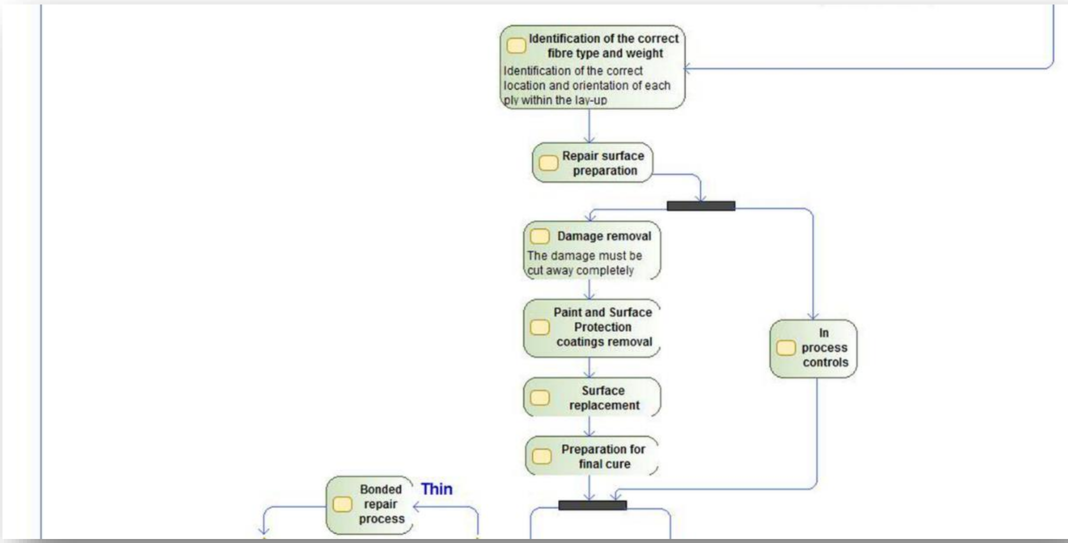



**Figure 13**: From the identification of the correct fibre type and weight to the preparation for final cure

## REPAIR PROCESSING

- Apply a vacuum bag to the repair. A vacuum bag is also used with an autoclave repair to ensure that the autoclave pressure will hold the plies together. If the autoclave pressure leaks into the vacuum bag, the actual pressure to clamp the parts together will be reduced. The lay-up of the vacuum bag and all the release films, both perforated and non-perforated in their correct positions is given in the SRM. If hot curing is used, then thermocouples must also be located as specified in the SRM. The specified temperature and vacuum or autoclave pressure must be maintained throughout the cure cycle, and the pressure must be maintained until the temperature has fallen below 50°C (122°F).

- Post-repair vacuum bag removal. Care must be taken when removing the vacuum bag and release films to ensure that no damage is done to the repair area or the rest of the part.

## POST-REPAIR INSPECTION

Visual inspections and NDIs should be carried out at this stage to confirm that there are no disbonded areas in the repair. The in-process quality control (QC) records (e.g., strip charts printed from the hot bonder or autoclave) must be inspected to make sure that the correct vacuum, autoclave pressure (if used), and temperature were used for the specified period of time.

## PROTECTION COATINGS RESTORATION

If the repair is considered satisfactory, any protective coatings, such as erosion-resistant coatings or lightning protection systems, need to be restored before painting. Lightning protection systems must be tested and meet the SRM electrical conductivity requirements.

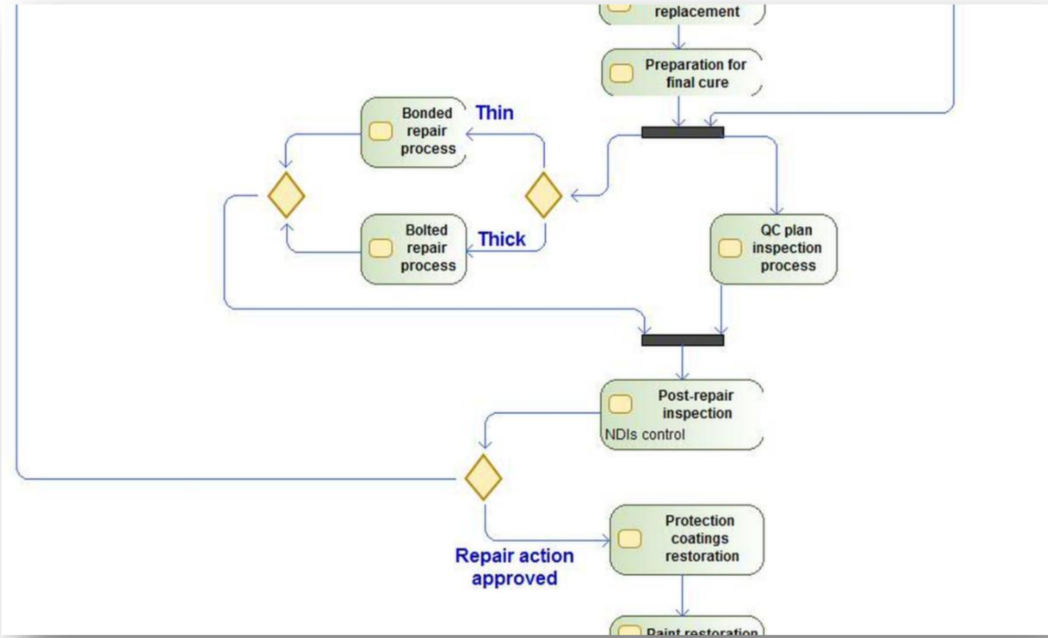



**Figure 14**: From the repair process action to the protective coatings restoration

## PAINT RESTORATION

The part should be painted in accordance with the company logo using SRM-approved materials. Some paints, such as polyurethanes, require special masks be worn and safety precautions be taken when being applied.

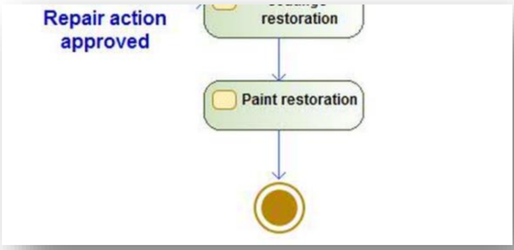
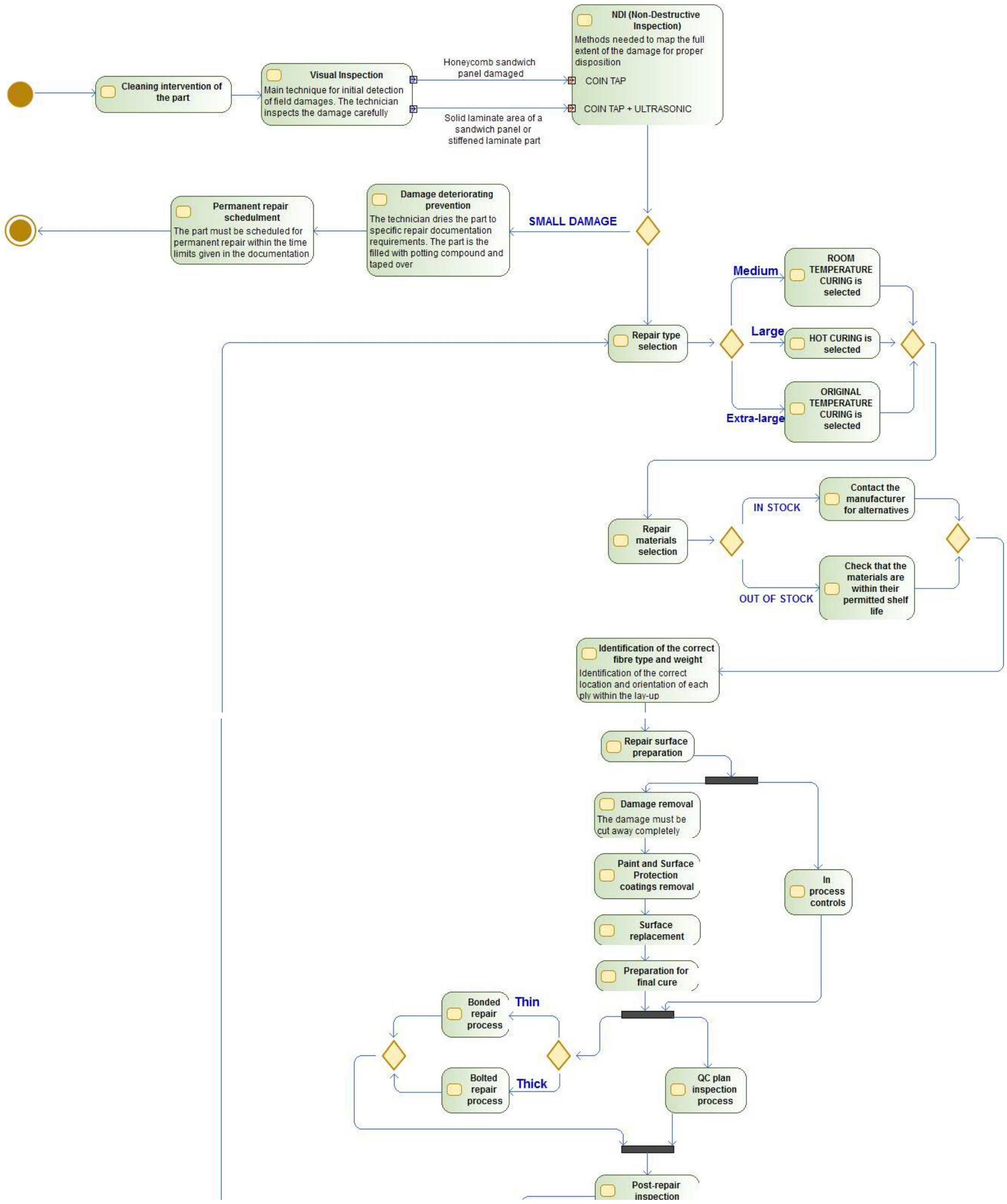



**Figure 15**: From the paint restoration to end of the repair process



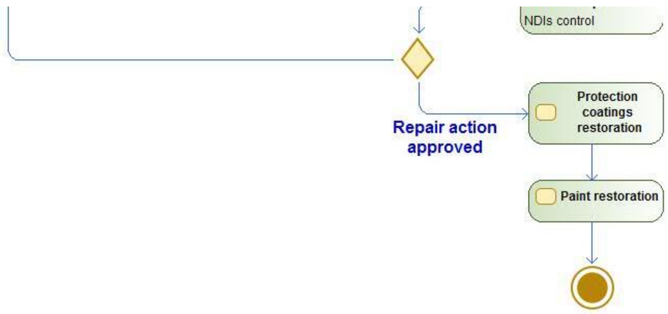



**Figure 16**: Overview of the composite maintenance repair process activity diagram

## *EHAs*

Regarding the maintenance process modelling such as the removal and replacement of electro-hydrostatic actuators, the lack of sources has been predominant. Although it is a mature technology, the competition between manufacturers makes that the procedures are not in public domain. In this case, the modelling took place on the basis of some reasonable assumptions that can be subject to future improvements and modifications. The main purpose of the activity diagram below is to highlight the power of representation of this instrument: by representing in the same diagram the comparison between an HA actuator replacement activity and EHA compliance, it is possible to evidence which maintenance tasks are in common and other that are different. This allows making comparisons in order to get more information about time, tools, tasks and technicians needed to perform the operations in case of EHAs.

**Figure 17**: Aileron EHA and electro-hydraulic actuator [23]

In the **Figure 17** above it is possible to appreciate the differences between the two different kinds of actuators. The relevant diversity is in the weight: with EHA the weight doubled.

### Activity diagram for removal and reinstallation process of flight control actuator (EHA or HA)

**Figure 18**: Flight control actuator removal simulation

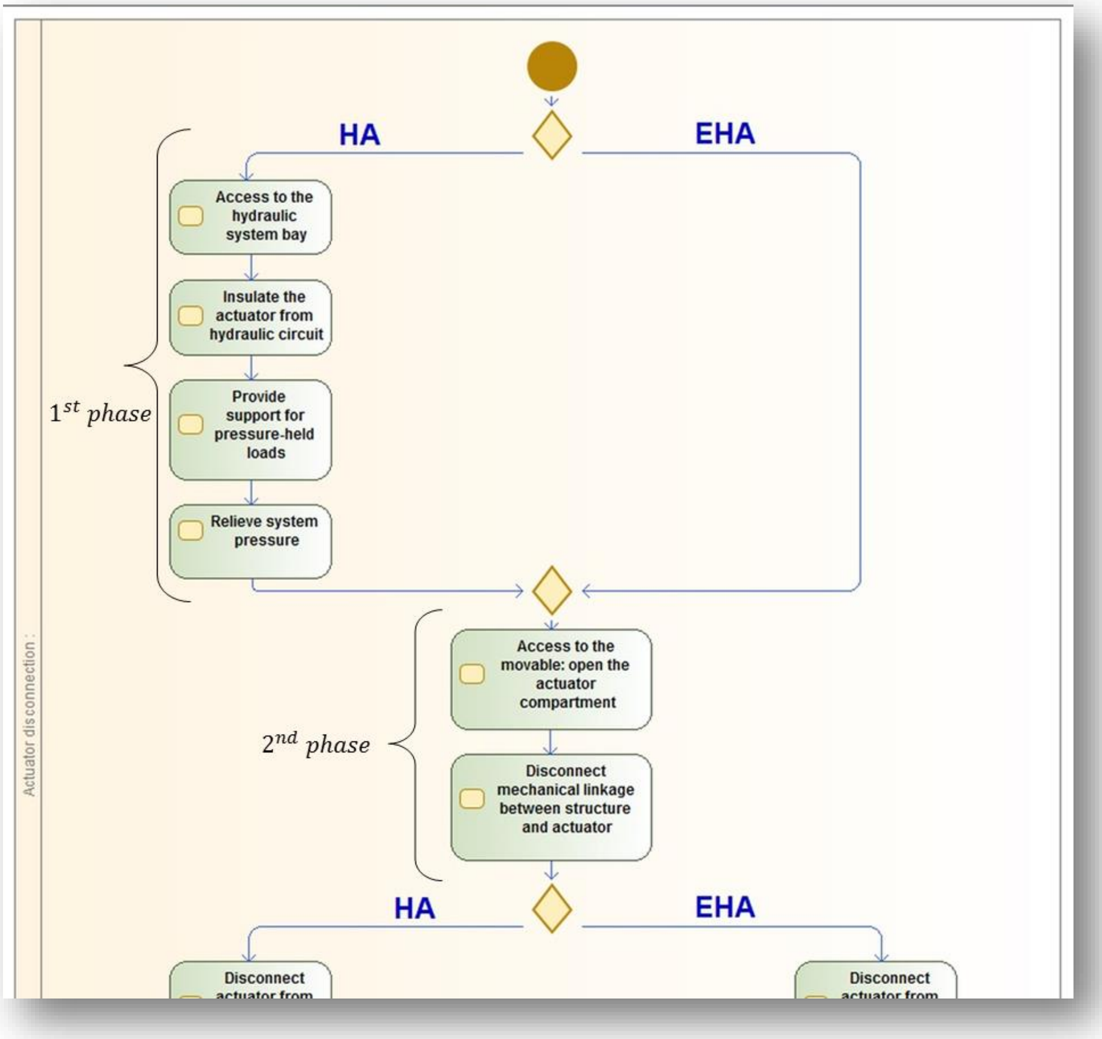



**Figure 19**: Activity diagram EHA and HA, first and second phase

### $1^{st}$ phase

The first phase of the diagram consists in the beginning of the actuator removal activity. In particular, even before accessing the movable, the hydraulic actuator requires some precautions. Firstly, the mechanic must access the hydraulic system bay in order to isolate the actuator from the hydraulic circuit. Furthermore, it is necessary to make sure that the pressure has been set to 0 psi. It is possible to highlight that this time is not spent in the case of an electro-hydrostatic actuator.

### $2^{nd}$ phase

The actions of accessing the actuator compartment and disconnecting it from mechanical connections to the structure are in common to both cases. They constitute the second phase: a single central branch meaning that the actions must be performed independently of the type of actuator.

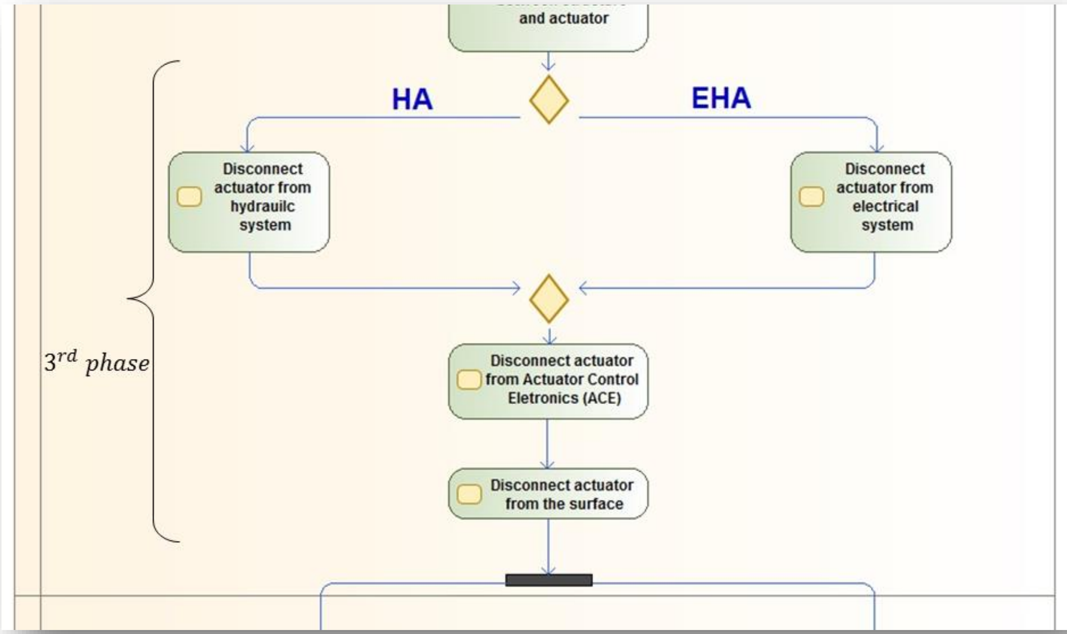



**Figure 20**: Activity diagram EHA and HA, third phase

### $3^{rd}$ *phase*

Depending on the type of the actuator the aircraft mechanic has either to disconnect the actuator from the hydraulic system or from the electrical system. Following disconnection actions are from the Actuator Control Electronics (ACE) and from the flight control surface. The removal actions have been concluded.

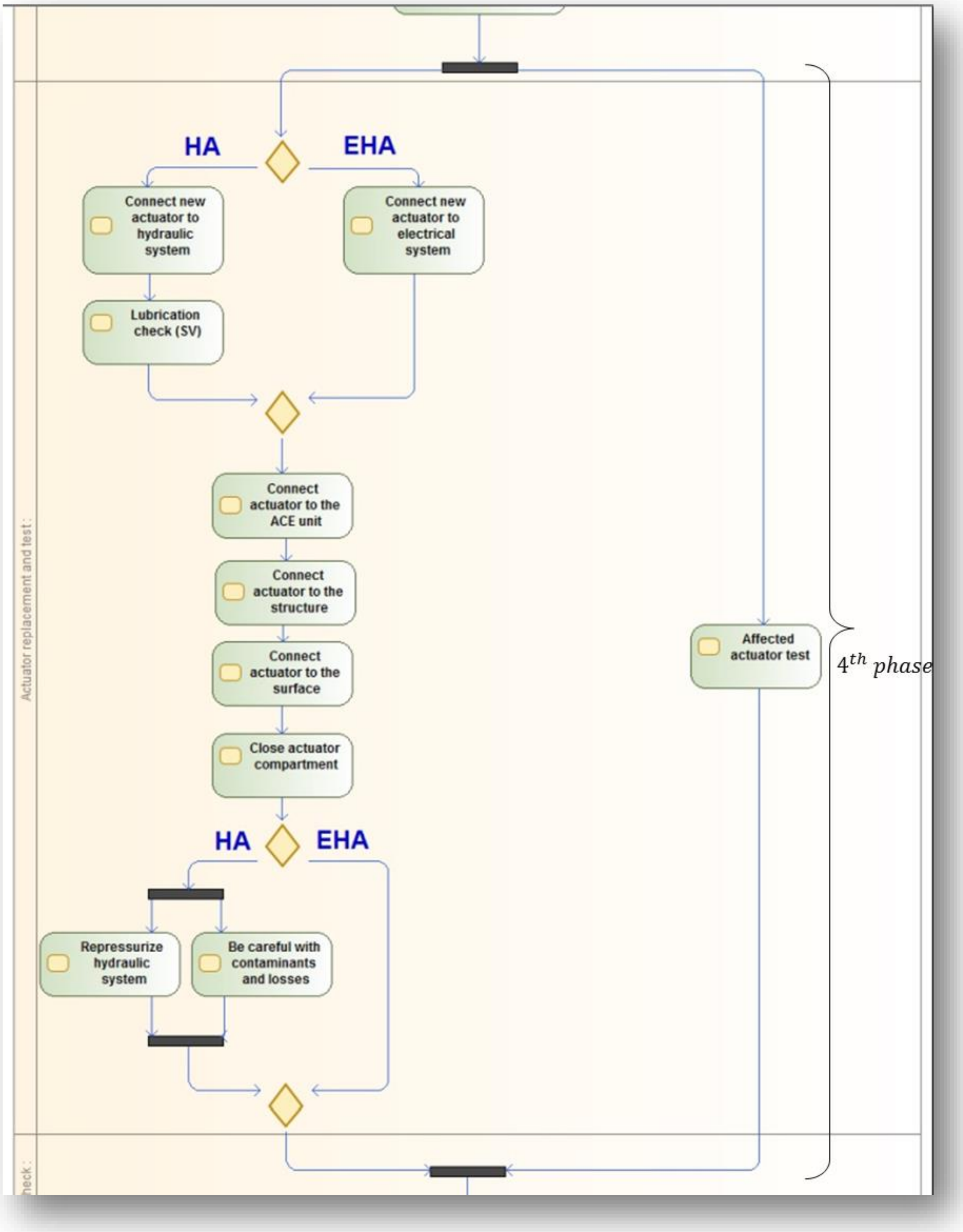



**Figure 21**: Activity diagram EHA and HA, fourth phase

## $4^{th}$ *phase*

In this phase two activities are usually carried out in parallel:

- Tests of the affected actuator that has been removed (right side);
- Installation of the new actuator (left side). The actions are quite reflecting the same done during the removal activity. A more detailed look on the diagram

shows that the hydraulic requires paying more attention. After the connection of itself with the hydraulic system, a lubrication check of the servo-valve is needed. Moreover, at the end the hydraulic actuator requires to be repressurised; more care to eventual contaminants and losses.

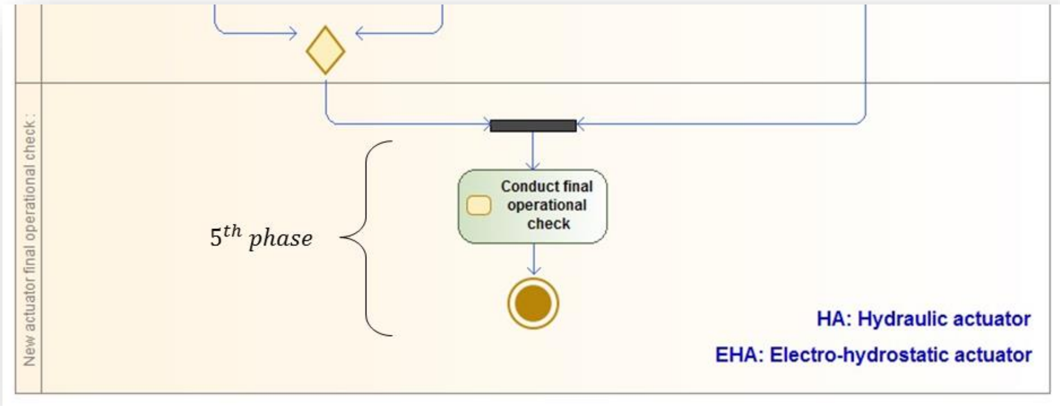



**Figure 22**: Activity diagram EHA and HA, fifth phase

### $5^{th}$ *phase*

This part is common to both actuators: after the installation of the new actuator the technicians have to conduct final operational checks before the item enters service.

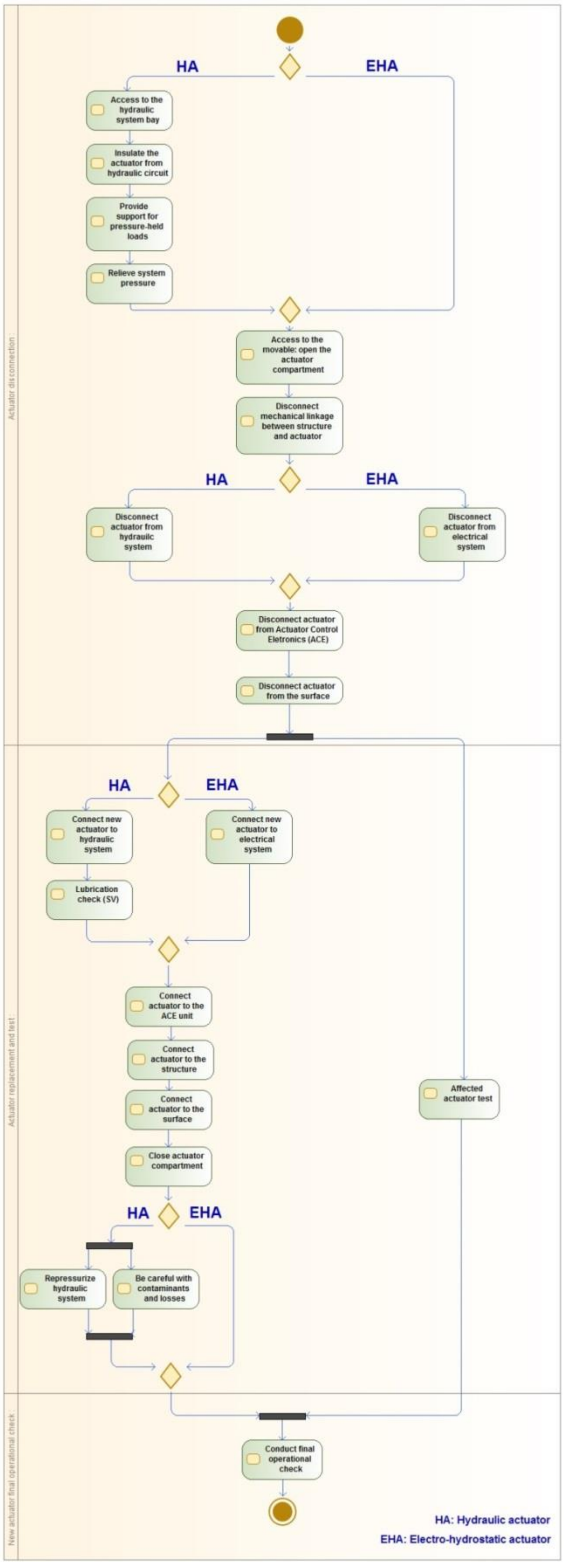



**Figure 23**: Overview of the activity diagram for removal/installation of flight control actuator

### 3.3.1 Qualitative and quantitative analyses

As stated in the Par.3.1, the qualitative research intervenes to support this modelling, which makes possible to identify which output trends are expected depending on whether one technology is implemented, rather than another.

The goal is to modify the equations of the subsystems on which the implementation of new technologies has impact. In order to achieve this purpose, the unpacking of maintenance tasks, through the SysML activity diagram, is not sufficient on its own to provide precise details.

| NEW TECHNOLOGIES | PROs | CONs | Impact on RAMS | Impact on Maintenance cost |
|---|---|---|---|---|
| Composites | • Fatigue and corrosion resistance<br>• Low structure weight<br>• Reduced number of parts<br>• Quicker reparation (?) | • Need to employ new tools and new technologies<br>• Special material storage is required<br>• Delaminations and debonds can occur<br>• Low superficial resistance (e.g. hail impact)<br>• Low high temperature resistance | • $(FR)_{structure}$ ↓<br>• $\left(\frac{MMH}{FH}\right)_{structure}$ ↓ | • Base Maintenance ↓<br>• Maintenance Burden ↑ |
| Natural Laminar Flow Wing | • Drag is reduced (→ fuel consumption → weight and cost of the aircraft is reduced) | • Sensitive to dirt and insects<br>• Sensitive to a possible crack (superficial roughness damaged)<br>• More development and production accuracy | • $(FR)_{structure}$ ↑<br>• $\left(\frac{MMH}{FH}\right)_{structure}$ ↑ | • Base Maintenance ↑<br>• Line Maintenance ↑ |
| EHA | • Hydraulic system with lower number of components → lower weight → less complex | • Electrical system weight and complexity are increased<br>• Local cooling could be needed | • $(FR)_{hydraulic}$ ↓<br>• $(FR)_{electrical}$ ↑<br>• $\left(\frac{MMH}{FH}\right)_{structure}$ ↓<br>• $\left(\frac{MMH}{FH}\right)_{structure}$ ↑ | • $(DMC)_{hydraulic}$ ↓<br>• $(DMC)_{electrical}$ ↑<br>• $(DMC)_{landing\ gear}$ ↓<br>• $(DMC)_{flight\ control}$ ↓ |

**Table 12**: Qualitative investigation for RAMS and Maintenance cost

A more detailed look has been given on the following three factors:

- *weight*: fundamental driver in aircraft design. The most effective way to reduce fuel consumption is reducing the mass of aircraft, as a lower mass requires less lift force and thrust during the flight;
- *fuel consumption:* in spite of the majority of the times a weight increase or reduction is accompanied by the same trend of the fuel, to take fuel consumption in consideration is not redundant. Some technologies do not change the weight but act directly by improving fuel efficiency. For this reason it is advisable to analyse fuel efficiency to have a complete view of the disadvantages and advantages given by the new technologies considered;

- *maintenance costs:* in terms of maintenance man-hours and costs. As the main figure of merit for trade-offs between different configurations in aircraft design, it is an indispensable driver during this investigation.

In particular the first two factors have been studied in order to have an overall perspective of the impact taken by the introduction of new technologies. The data and trends needed to be collected in order to modify not only the equations of the two estimation models but also other disciplines like Masses, Aerodynamics and Mission with the goal of assessing the overall advantages and disadvantages brought by a certain new technology.

### Composite investigation

The qualitative investigation made led to the following characterization.

Let first analyse qualitative behavioural characteristics. The main benefit is the opportunity to have lightweight structures through their usage with consequently improved aircraft performance compared to the conventional aluminium counterparts. As already stated at the beginning, the composites, unlike aluminium, have a good resistance to fatigue (lower inspection and maintenance costs) and to corrosion. Moreover, unlike the metal material, the number of parts to be made can be reduced [5].

More than one source states that one of the reasons why composites is one of the favourite choices among innovations is for the benefits it offers through durable products [5], [34]. The major durability means a lower failure rate and fewer maintenance events. By contrast newer composite materials are more expensive to be stored since they require stringent environmental controls and have limited shelf lives [35]. Materials costs are higher ( [10], [35]) because the storage is more expensive. In fact, when comparing with aluminium, the metal is easier to repair, while instead in case of composite structures new tools, new repair procedures should be developed by the MRO organizations to ensure they are adequately prepared for handling the new generation aircraft.

Furthermore one of the main issues for composite structures is the low resistance to impact damage [36]. To tackle this problem basic tools are needed in order to characterise blunt impact events to improve prediction of damage formation and its effect on structural performance.

Together with impact damage, delamination is another critical damage for composites.

About the comparison between the repairs time, on composites, more time is spent preparing the aircraft, performing the NDI, and so sometimes it is quicker to do a metallic repair [37].

Quantitatively, in the weight perspective Airbus estimates 10 percent of weight saving in the A350 thanks to the 50 percent composites adoption. Boeing declares 20 percent of weight saving in the Boeing 787 with respect to other aluminum conventional structures.

From the fuel point of view, as a consequence, the weight reduction due to composite materials takes to an increase of the fuel capacity, from one side, and a decrease of fuel consumption on the other side [38]. In the case of the Boeing 787, the 20 percent weight saving results in 10-12 percent of fuel efficiency improvement [10].

Finally from the maintenance cost changes perspective the scheduled maintenance burden is reduced [5] thanks to the behavioural advantages of these materials.

The maintenance material cost is increased and the maintenance intervals are reduced taking to a reduction of the scheduled labour hours. In particular interesting is the comparison reported by Boeing (**Figure 24**)Figure 24: Maintenance Man Hours improvement for composite vertical tail among three different vertical tails [5]:

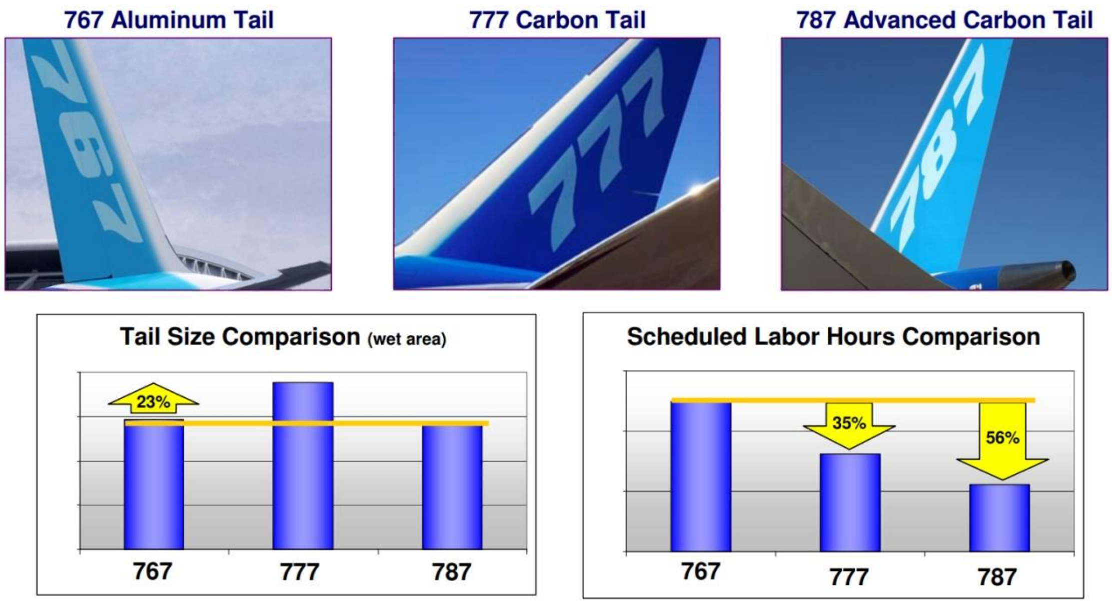



**Figure 24**: Maintenance Man Hours improvement for composite vertical tail [5]

The usage of a higher percentage of composites led to a lower maintenance cost: B787-8 has 20 percent less maintenance cost than B777-200ER, and 30 percent less than B767-300ER [5].

### *Natural Laminar Flow Wing investigation*

The NLFW is a more complex technology because it is very sensitive to multiple factors, but its advantages can be very powerful.

When the flow around the laminar wing is effectively established, the drag is reduced. Consequently, fuel consumption is estimated to be 10 percent lower and therefore weight and cost of the aircraft are consequently reduced.

For the implementation of new coefficients that take into account all the factors involved when using this technology, all the issues connected to NLFW are now presented [19].

It is very sensitive to dirt and insects that degrade the laminarity condition on the wing. To overcome this problem additional cleaning events need to be scheduled. A rough guess can be done by supposing to establish one additional cleaning intervention per month with a hypothetical price of 2000 dollars. Moreover it is sensitive to cloud encounters that jeopardize the laminar flow designed around the wing taking to a worse fuel efficiency. It is clear how important the surface finish of the wing is, since it is also sensitive to a possible crack. It follows that line maintenance and base maintenance are expected to be increased. The estimations are one additional line intervention per week (70 dollars) in order to add visual inspections, while one base maintenance intervention (30000 dollars) every 1.5 year should be dedicated only to the wing doing more detailed inspections and repairs. This means that additional maintenance man hours have to be taken into account both for line and base maintenance.

The weight of the wing is not supposed to be changed. Instead from the fuel efficiency perspective, it is needed to estimate the factors playing against the laminar flow. Cloud encounter in high altitudes and insect contamination make the fuel efficiency fall down by 1 percent each one. The operative fuel consumption becomes 8 percent lower instead of 10.

From a cost view the production of NLFW aircraft has a cost higher than the conventional counterpart, since more development and production accuracy is required.

*Electro-hydrostatic actuators investigation*

The implementation of EHAs allows to have a less complex hydraulic system, with lower number of components, consequently with a lower weight. By contrast, electrical weight and complexity are increased, and local cooling could be needed.

Weight has been permanently challenged during the design phase and is believed to be minimum. Although the weight of the EHA is twice the weight of the adjacent hydraulic actuator, the elimination of one hydraulic system results in a very significant overall saving [23].
The resulting reduction in weight makes the EHA ideal for aerospace, especially since the performance and fuel efficiency are becoming increasingly important [39].

In reality for much of the flight, actuator demands are minimal and this represents a wasteful approach as lost energy ultimately results in higher energy off-take from the engine and hence higher fuel consumption. The EHA seeks to provide a more efficient form of actuation where the actuator only draws significant power when a control demand is sought; for the remainder of the flight the actuator is quiescent [22].

Maintenance is a bit reduced, but requires hydraulic pipes to the hydrostatic transmissions since the oil degrades [40]. With EHAs a modular design is possible, which lends itself to simple maintenance [39].

As a result, since EHAs can improve the viability and reliability of aircraft, this brings down the cost of maintenance [41].

### 3.3.2 Equations modification

Based on what described in paragraph 3.3.1 above, the data collected were used to move from the estimates of conventional aircraft to those of innovative aircraft. Subsequent subparagraphs present the equations (and therefore the subsystems) on which a modification has been made.

### *New equations in RAMS estimation model*

#### Composites

| Subsystem | FR | MMH/FH |
|---|---|---|
| **Structure** | 1 | 0.95 |

**Table 13**: Coefficients for Composites in RAMS

The FR coefficient is set equal to 1 because there is the effect of lightweight taken into account by the weight and balance experts. In order to not take into account this effect twice, it is equal to 1. The better behaviour that composites have make maintenance man hours per flight hour reduce. Roughly a 0.5 percent of the maintenance man hours per flight hour spent on structure can be saved.

#### Laminar Flow Wing

| Subsystem | FR | MMH/FH |
|---|---|---|
| **Structure** | 1.02 | 1.30 |

**Table 14**: Coefficients for NLFW in RAMS

The numbers estimated and reported in the Paragraph 3.3.1 are imposed and the corresponding rates have add to the unit coefficient.

#### EHAs

| Subsystem | FR | MMH/FH |
|---|---|---|
| **Flight controls** | 1 | 1 |
| **Hydraulic** | 1 | 1 |
| **Electrical** | 1 | 1 |

**Table 15**: Coefficients for EHAs in RAMS

Since this technology, quantitatively, brought not enough data, it has been preferable not to guess some rates. These unit coefficients are also to not taken into account twice the effect of weight changes.

### *New equations in Maintenance Cost estimation model*

#### Composites

| Subsystem | DMC |
|---|---|
| **Structure** | 0.95 |

**Table 16**: Coefficients for Composites in Maintenance cost

#### Laminar Flow Wing

| Subsystem | | DMC |
|---|---|---|
| **Structure** | **Line Maintenance** | 1.01 |
| | **Base Maintenance** | 1.05 |

**Table 17**: Coefficients for NLFW in Maintenance cost

#### EHAs

| Subsystem | DMC |
|---|---|
| **Flight controls** | 0.95 |
| **Hydraulic** | 0.60 |
| **Electrical** | 1.1 |

**Table 18**. Coefficients for EHAs in Maintenance cost

Notice that the coefficient value assumed for the hydraulic system is in the case in which only one hydraulic line has been removed.

# 4. Implementation and execution

In the previous chapters the methodology developed during this research work has been presented in order to estimate the impact of the implementation of new technologies on aircraft in terms of RAMS and maintenance costs.
This chapter aim to present:

- simulation environment;
- tool set-up and MDO tools;
- execution of different solutions for a test case;
- evaluation of results;

## 4.1 Simulation environment

The assessment of the effects of new technologies on reliability and maintenance costs becomes valuable and emphasized when these two disciplines are integrated into the design work environment. The environment in which the tools developed can be integrated has to be modular through a correspondence in which each module is associated with a discipline. In this way all the disciplines involved can be collected in the same multidisciplinary environment. As a consequence, it allows to do a work of optimization of a selected parameter. In addition it has to give the possibility to change the baseline of the aircraft object of study.

The main elements need to satisfy these requirements in order to do have an innovative MDO environment are three [42]. All the three elements chosen are from a new aircraft design methodology developed through the MDO approach:

- ❖ The first one is an engineering framework software for the management of the development process and the optimization. This type of tool is named Process Integration and Design Optimization (PIDO) environment. The one used for the thesis purpose is called “Remote Component Environment” (RCE) [43] developed by the German Aerospace Center DLR.

- ❖ The second main element is the data model. It has to be a common namespace for the exchange of information between the disciplinary experts, in order to support the collaboration among many different experts. It is called CPACS (Common Parametric Aircraft Configuration Schema). It allows the exchange of information between the disciplinary codes, facilitating the integration of the analysis tools and hence the assembly of the workflow, and managing all the generated data [42].
- ❖ The last element is represented by the disciplinary tools. This modules should be able to extract the required information from the CPACS, to calculate some specific quantities of interest and then to upload CPACS file with the results.

## 4.2 Models set-up in RCE

### 4.2.1 RAMS set-up

Let consider the work environment just described: RCE, CPACS file and disciplinary tools. Both modified and updated models have been first coded in Python and implemented in RCE where they have become disciplinary tools.

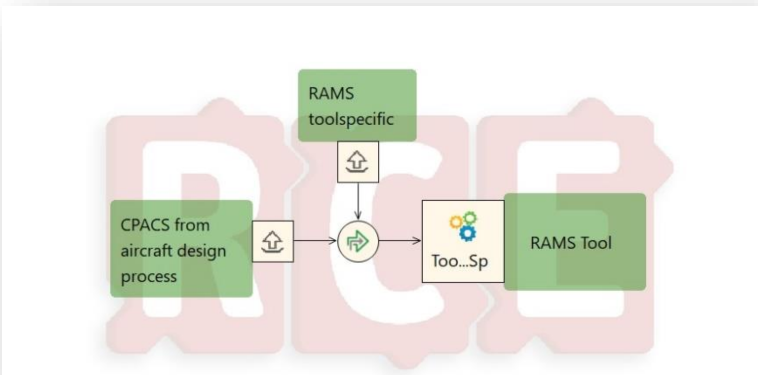



**Figure 25**: RAMS tool set-up in RCE

The RAMS tool takes in input a CPACS file coming from the merge of the baseline (or CPACS output xml file from the tool that precedes it) and of the CPACS xml toolspecific file. The latter is a file containing the specific parameters needed as peculiar inputs of the RAMS discipline (**Figure 26**), often required to set manually.

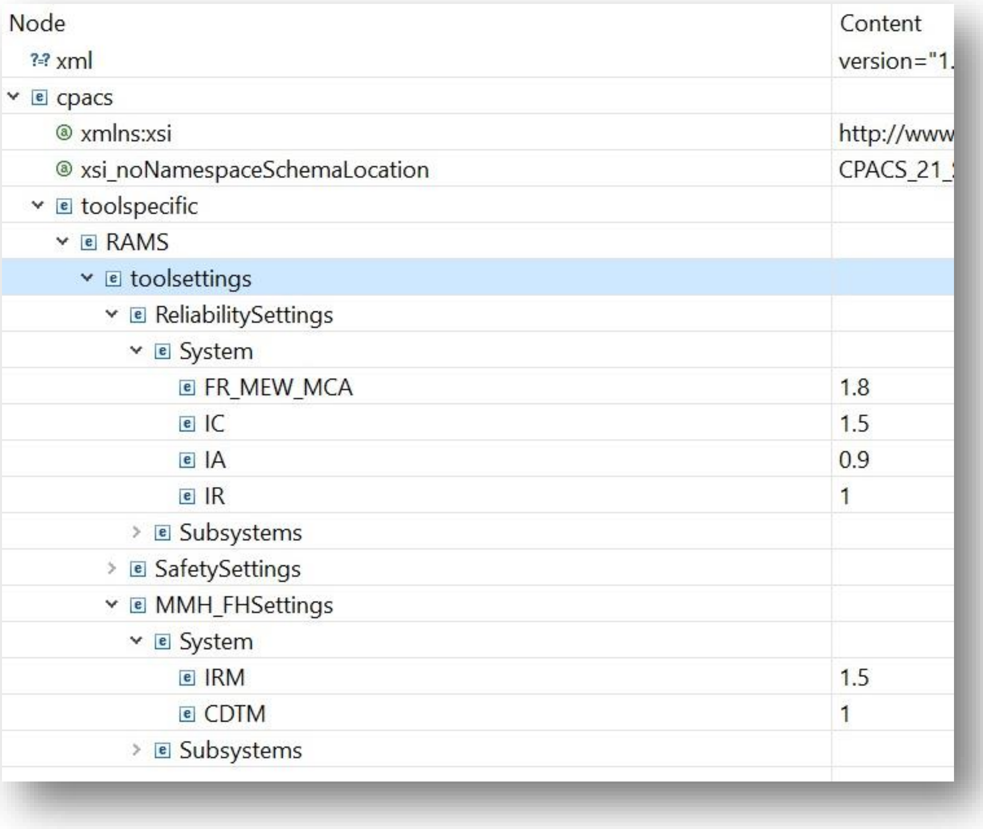



**Figure 26**: Example of RAMS toolspecific

In particular the data input that RAMS tool needs from other disciplinary tools, preceding it in the workflow, are the *subsystems weights* and the *MEW*.
When the execution is completed, the analysis derives the results that will be added (or updated) on the CPACS file as new outputs and then passed to the successive disciplinary tools present in the workflow.

### 4.2.2 Maintenance cost set-up

In the **Figure 27** below it is possible to see the Maintenance Cost tool, first coded in Python, set-up in RCE.

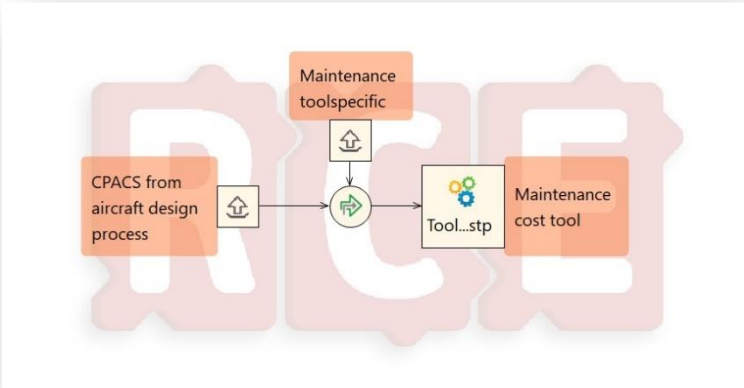



**Figure 27**: Maintenance cost tool set-up in RCE

The Maintenance Cost tool takes in input a CPACS xml file coming from the merge of the baseline (or CPACS output xml file from the RAMS tool that precedes it) and of the CPACS xml toolspecific. As stated for RAMS, the latter is a file containing the specific data needed as inputs of the Maintenance Cost tool, **Figure 28**.

| Node | Content |
|---|---|
| xml | version="1. |
| cpacs | |
| xmlns:xsi | http://www |
| xsi_noNamespaceSchemaLocation | CPACS_21_ |
| toolspecific | |
| Maintenance_cost | |
| toolsettings | |
| drivers | |
| Constant | 1 |
| Fleet_size | 890 |
| Day_utilization_h_per_day | 10 |
| FH_per_FC | 0 |
| Fuselage_length_ft | 0 |
| Aircraft_cost_dollarsx10e6 | 95.12 |
| Age_type_aircraft_months | 300 |
| Seats | 0 |
| Average_aircraft_age_years | 8.2 |
| Tires_number | 6 |
| Engines_number | 2 |
| Thrust_lbf | 0 |
| Technology_factor | 1 |
| coefficients | |
| LR_dollars_MMH | 40 |

**Figure 28**: Example of Maintenance cost toolspecific

It is responsibility of the discipline expert to define or to eventually modify the values in the CPACS xml toolspecific.

In this case, the inputs of the CPACS xml toolspecific file requiring to be checked or inserted are:

- *Fleet size;*
- *Day utilization per day, in hours;*
- *FH/FC (eventually);*
- *Aircraft cost, in dollars* $10^6$
- *Age of the type of the aircraft, in months;*
- *Number of tires;*
- *Number of engines.*

In particular the data input, that MC tool needs from the tools of other disciplines preceding it in the workflow, are:

- *Mission duration*, output from Mission tool;
- *Fuselage length,* from the CPACS Baseline;
- *Passengers number*, from the CPACS Baseline;
- MMH/FH, output from RAMS tool.

### 4.2.3 Operating costs tool: definition and set-up

As stated in Par. 3.3.1 the objective of the impact analysis of new technologies is to maintain a complete perspective of the effects being involved. For this reason it is necessary to take into account other influences on weight, aerodynamics, fuel and operating costs in general. The impacts on weight and aerodynamics have been developed by the experts owning the relative tools, basing on data investigation. As regards the impact on fuel, an equation has been implemented that estimates the fuel burnt cost per flight hour in order to carry out the flight mission.

The equation implemented is:

$$\text{Fuel cost}\left[\frac{\$}{\text{FH}}\right] = \text{Fuel price}\left[\frac{\$}{\text{kg}}\right] \cdot \text{Fuel burnt}\left[\frac{\text{kg}}{\text{FH}}\right]$$

Moreover, in order to compare the results in terms of operating costs, also crew cost is needed:

$$crew\ cost = 85 * crew\ number \quad \left[\frac{\$}{FH}\right]$$

In this thesis operating costs will be considered to be constituted only by total maintenance cost, fuel and crew cost. Other dependencies are considered not variable with the technologies considered and with different on-board system architectures.

### 4.2.4 Overview of the workflow

The design process starts with the definition of top level requirements, for instance number of passengers and additional payload, range or endurance, runway length for take-off and landing and a typical mission profile, especially in terms of speeds and altitudes.

Starting from these requirements, an initial aircraft layout is sketched. In particular, a rough sizing of the fuselage is made, the relative wing-fuselage position is established, and the type, number and position of the engines are set-up. Soon after the initial layout definition, the aircraft multidisciplinary design begins. This Multidisciplinary Design Analysis (MDA) encompasses the following design disciplines: aerodynamics, structures, performance, on-board subsystems, engines, mission, weight estimation, RAMS, maintenance cost and operating costs estimation.

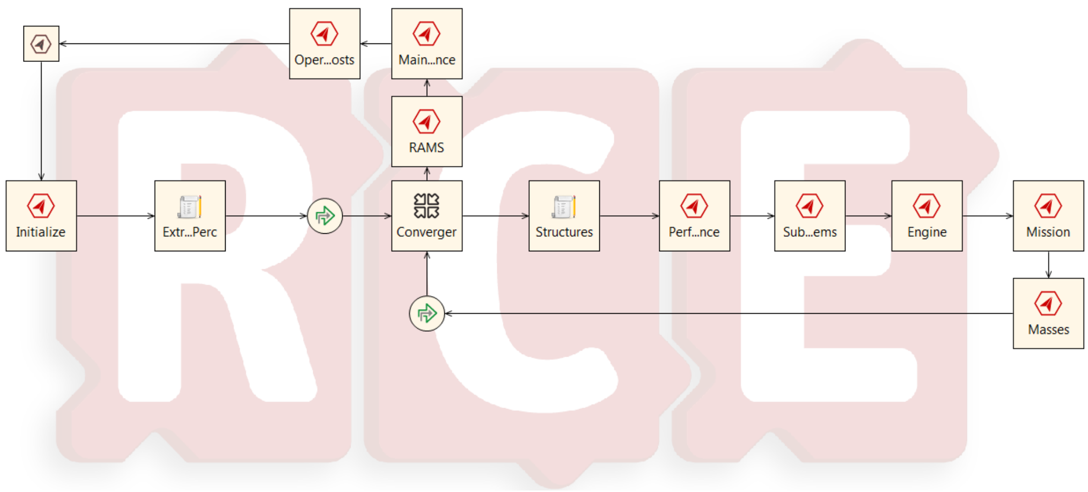



**Figure 29**: Workflow used for the MDA

During this work, in order to simplify the complexity of the workflow, the initialiser contains the baseline with already the Aircraft synthesis outputs, a module including aerodynamic and structural (structural loads, $FEM$) analyses.
Since structural design is done before entering the converger, depending on the chosen new technology there might be a difference. For instance, if composites structure is selected, the baseline file is modified by a script that recalculates the structural results, reducing the weight of the structures by 20 percent and updates MEW and MTOW. In addition, in this case new fuel mass will be calculated within the converger loop. In the event in which no innovative technology is selected, the structure remains unchanged.

The used MDA workflow is composed by two parts: an internal part, *Inner Loop* (converger) and an external one, called *External Loop*.
The internal loop aims to design the entire aircraft. At the end of this iterative process, a design solution is returned to RAMS tool. The estimation of the Operating costs is the aim of the external loop.
In the converger loop, there are the following disciplinary tools:

1) <u>Performance</u>: it calculates aircraft total thrust required for each mission phase (take-off, climb, cruise, descent, landing). In order to do it, it takes the aerodynamic polar from the initialiser and the wing surface. Basing on the cruise flight altitude it calculates air density. From MTOW and aircraft speed it gets the coefficients $C_L$ (lift coefficient) and $C_D$ (drag coefficient) need to calculate the outputs.
2) <u>On-board systems</u>: calculates masses and power off-takes (both pneumatic and mechanical, converted in electrical and hydraulic).
3) <u>Engine</u>: calculates a new engine SFC, basing on the power off-takes calculated in On-Board systems tool. Furthermore, it calculates mass and diameter of the engine.
4) <u>Mission</u>: depending on the duration of the mission phases of the mission profile it calculates the amount of fuel required for each phase taking into account the typology of propulsion system and relative SFC calculated in the Engine module. The maximum quantity of boarded fuel is finally calculated by adding the fuel reserves, generally expressed as a percentage of the total fuel required during the mission. This tool requires input from the aerodynamics airplane, the engine performance, the aircraft weights to estimate the block and reserve fuel required during a predefined mission.

5) Masses: it does a preliminary mass estimation. Takes as inputs the masses of systems, structures, engine, fuel and estimates a new MTOW. Hence, the aircraft maximum empty weight is calculated from the sum of these weights. Taking into account also the fuel weight and the payload, the new value of MTOW will be different from the prior tentative guest at the beginning of the design process.

The MTOW given as result by Masses will be the new tentative value of MTOW for the second iteration. This iterative loop will proceed until the design will reach a convergence, i.e. until the difference among the values of MTOW of two sequential loops will be lower than a predetermined threshold (for instance, 1 kg).

So fare a new baseline has been obtained constituting the CPACS xml file input of RAMS tool, and successively of maintenance cost and operating costs tools.

Finally it is possible to observe that in order to manage the different disciplinary tools owned from different experts, BRICS has been used. It is a component that allows distributed design, facilitating smooth execution of the collaborative engineering workflow [44].

For each tool, both the input and the output files are exchanged with the other disciplines by means of BRICS software. The CPACS files are stored inside a server hosted at the DLR of Hamburg, in Germany. Two BRICS interfaces are integrated in order to download and upload to the server the two i/o CPACS files.

In order to evaluate multiple configurations of the same baseline in a more efficient way, a workflow has been developed, in order to call the MDA workflow, using DOE. This workflow (**Figure 30**) starts with the baseline, after which the new technologies toolspecific is added. Then the DOE intervenes by automatically modifying the input combinations of new technologies. For each combination selected by the DOE an MDA runs through BRICS and the output file is stored in a folder. At the end of the process it is possible to get a folder with as many output files as the number of combinations dictated by the DOE. Each output file contains the results from the MDA analysis.

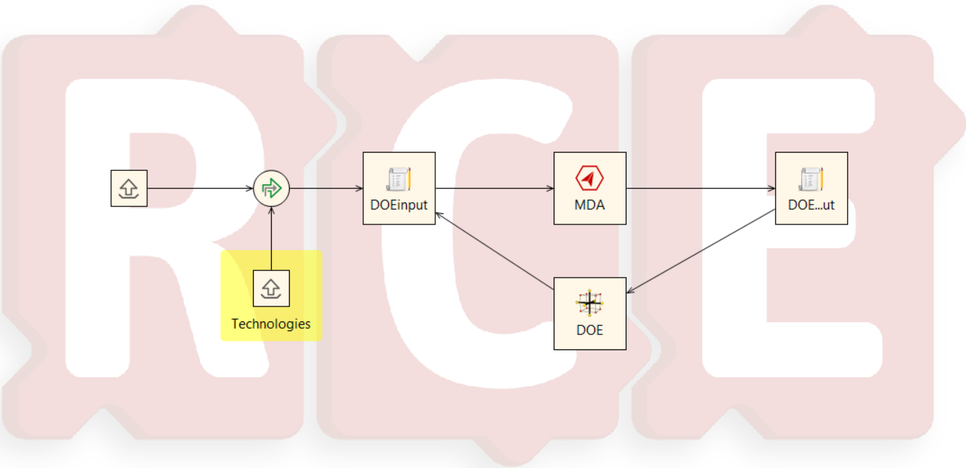



**Figure 30**: Workflow for the DOE launch to evaluate different design configurations in a single run

Through the toolspecific for new technologies the DOE establishes the combination regarding the implementation of new technologies (0 = no; 1 = yes):

- Composite structure;
- EHAs;
- Natural Laminar Flow wing.

For example, choosing 0; 0; 0 (**Figure 31**) the analysis will be performed for a case study of the baseline with conventional technologies (aluminium structures, electrohydraulic actuators, conventional wing design).

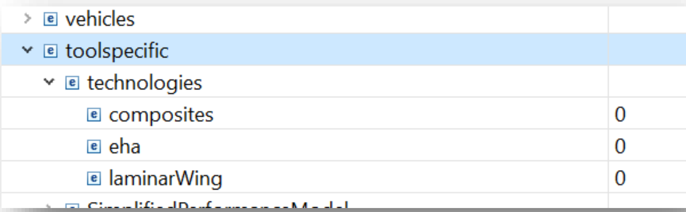



**Figure 31**: Example of set-up values for conventional aircraft in technologies CPACS xml toolspecific

It is possible to carry out studies of the solutions with combined innovative technologies available. Once the combination has been selected, the baseline is integrated with the choice of new technologies.

## 4.3 Reference aircraft

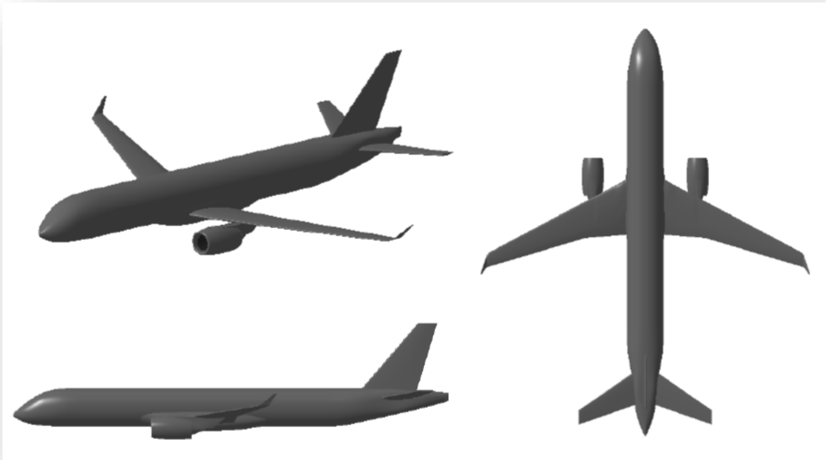


**Figure 32**: Visualization of baseline aircraft [42]

The test case selected as reference aircraft in order to analyse the new technologies impact on RAMS and maintenance costs is represented in **Figure 32**.

| **Civil regional jet** | | |
|---|---|---|
| **Parameter** | **Unit** | **Baseline** |
| Design range | km | 3500 |
| Passenger capacity | pax | 90 @ 102 kg |
| Cruise Mach No. | - | 0.78 |
| Maxi Take-Off Weight (MTOW) | tons | 45.0 |
| Max Landing Weight (MLW) | % MTOW | 90 |
| Maximum Empty Weight (MEW) | tons | 23.3 |
| Max Operating Altitude | m | 12500 |
| Fuselage diameter | m | 3 |
| Fuselage length | m | 34 |
| Fuel reserve | % | 5 |

**Table 19**: Key aircraft design characteristics

It is a 90-passenger regional jet and several levels of subsystem technology are considered, in order to identify some different possible on-board system architectures. From the set of requirements, a first conceptual design of the entire aircraft was performed within the AGILE project [42].
The main features of different on-board system architectures are estimated by the tool previously described that designs by means of ASTRID (Aircraft On Board Systems Sizing and Trade-Off Analysis in Initial Design). It is an in-house (Politecnico di Torino) L1 fidelity tool. ASTRID has been conceived to enable the design of both conventional and innovative subsystems, as More and All Electric architectures and the hybrid propulsion system. Other than the definition of the global architecture of each on-board system and the preliminary estimation of subsystem masses, the main results of ASTRID include the subsystems shaft power and bleed air off-takes estimated during every segment of the mission profile [42].

The study carried out for this test case proceeds in stages:

- *Conventional test case*. It has aluminium structure, electro-hydraulic actuators and conventional wing design. The on-board system architecture is from the state of the art: presence of electric, hydraulic and pneumatic systems. The objective is to understand in detail RAMS and maintenance costs outputs at subsystem level.
- *Study of innovative solutions (only one technology for each configuration)*. The objective is to compare the effects of each new technology compared to the conventional case in RAMS, maintenance cost and operating costs perspectives.
- *Study of innovative solutions with combinations made of multiple technologies in each configuration*.

## 4.4 Conventional execution

In this paragraph the conventional configuration of the test case will be presented and analysed. The main goal is to understand in detail the outputs in order to be able to compare the future changes with the innovative configurations that will be tested.

### 4.4.1 Inputs

The choice of the inputs has often been made on the basis of the similarity consideration between the test case under consideration and the Embraer 175.

The main inputs of interest, typical of the test case are shown below.

*RAMS estimations*

| RAMS, system level | |
|---|---|
| IC | 1.5 |
| IA | 0.9 |
| IR | 1 |

**Table 20**: Specific inputs in RAMS toolspecific file for Reliability failure rate estimation at A/C level

The complexity coefficient established corresponds to high complexity aircraft. The age coefficient corresponds to 2010 year estimated because a similar E175 are both from 2005 and from 2017 year. Role coefficient set corresponds to civil transport aircraft.[4]

| MMH/FH, system level | |
|---|---|
| IRM | 1.5 |
| CDTM | 1 |

**Table 21**: Specific inputs in RAMS toolspecific file for Maintenance manhour per flight hour estimation at A/C level

Since the research is at the early design phase CDTM is set equal to 1.[5]

In addition, with regard to the vector percentage, the "Twin-engine, APU" column from **Table 10** was chosen.

*Maintenance cost*

| **Cost driver** | **Value** |
|---|---|
| *Constant* | 1 |
| *Fleet size* | 511 |
| *Day utilisation* $[h/day]$ | 10 |

[4] See Section 'Reliability Failure Rate estimation' in Par. 2.1.2.

[5] See Section 'Maintenance hours per flight hour estimation' in Par. 2.1.2

| Cost driver | Value |
| --- | --- |
| *FH/FC* | - |
| *Fuselage length* [ft] | - |
| *Aircraft cost* $(\$ \cdot 10^6)$ | 45.7[6] |
| *Age of the type of aircraft* [months] | 199.2[7] |
| *Number of seats* | - |
| *Average age of the aircraft* [years] | 8.3[8] |
| *Number of tires of the landing gear* | 6 |
| *Number of engines* | 2 |
| *Engine thrust* [lbf] | - |

**Table 22**: Manual inputs provided in Maintenance toolspecific for maintenance cost assessment

FH/FC is calculated from the mission time estimated by Mission tool. The plane is assumed to perform two 5-hour cycles (maximum missione time), for a total of 10 hours. All values omitted are autonomously calculated by the tool through inputs coming from other tools present in the workflow.

Another input inserted is the labour rate, a fixed amount per FH representing how much a mechanic will cost to the organization [30]:

$$LR = 40\ \$/FH$$

It is a value provided by IATA [30] for adjusted labour cost after overhead allocation.

### *Operating costs*

The only input that can be inserted in its relative tool specific is the crew number. For the test case the input inserted is:

$$Crew\ number = 4$$

[6] From [47]
[7] From 16.6 years as reported in [45]
[8] As reported in [46]

### 4.4.2 Outputs

*RAMS estimations*

In **Figure 33** the breakdown of reliability failure rate of the aircraft is reported. The value at system level results to be equal to 54.3 failures/1000FH.

| | **$\lambda_i$, Reliability failure rate [failures/1000FH]** |
|---|---|
| Engines | 15.5 |
| Electrical system | 2.1 |
| Hydraulic system | 2.3 |
| Pneumatic & Anti-ice | 2.6 |
| Flight controls | 1.3 |
| Fuel system | 3.6 |
| Avionics | 14.5 |
| Landing gear | 1.4 |
| Furnishings | 3.7 |
| APU | 0.4 |
| Wheel and brakes | 5.7 |
| Thrust reversers | 0.8 |
| Structure | 2.7 |
| **Total** | **54.3** |

**Table 23**: Reliability failure rate results at subsystem level

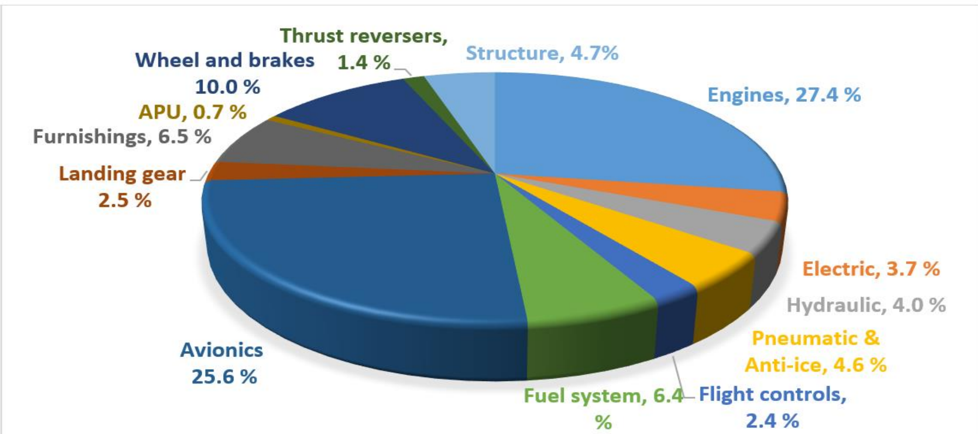



**Figure 33**: Reliability failure rate breakdown

Systems that have less MTBFs are more complex systems like avionics and engines. Together they occupy about half of the failures that could occur in the range of 1000 FH. They are followed by furnishings and fuel system, the former because it includes the cabin that is subject to a high number of failures due to continuous usage, the latter because since it is equipped with pumps has a certain complexity. Another important system subject to failures is W&B: they play an important role, any signs of suspected damage that may require removal of the wheel assembly from the aircraft should be investigated. After these, particular importance have hydraulic, electrical and pneumatic power generation systems. The electrical system is the most reliable among those because it does not have so bulky mechanical elements.

Different is the distribution of the maintenance man hours per flight hour (**Figure 34**). For example the even if the failure rate of the structure is not high, when it needs to be repaired the maintenance man hours per flight hour rate is greatly higher. By contrast, the avionics system, even if with more frequent failures, requires quick maintenance interventions that lead to a fewer maintenance effort. Electrical system shows to require quick interventions, as opposed to hydraulic and pneumatic system. Overall it results that, roughly, one hour and a quarter is required to maintain on-board systems, engines and structure for each flight hour. APU even if with high MTBF, reveals to be complex to repair because requires more time.

| | $(\mathbf{MMH/FH})_\mathbf{i}$ **Maintenance manhours per flight hour** |
|---|---|
| Engines | 0.1188 |
| Electrical system | 0.0133 |
| Pneumatic & Anti-ice | 0.0254 |
| Flight controls | 0.0431 |
| Fuel system | 0.0547 |
| Avionics | 0.0376 |
| Landing gear | 0.0889 |
| Furnishings | 0.0307 |
| APU | 0.0888 |
| Wheel and brakes | 0.0156 |

| | $(MMH/FH)_i$ **Maintenance manhours per flight hour** |
|---|---|
| Thrust reversers | 0.0307 |
| Structure | 0.0063 |
| Total | 0.74 |

**Table 24**: Maintenance man hours per flight hour results at subsystem level

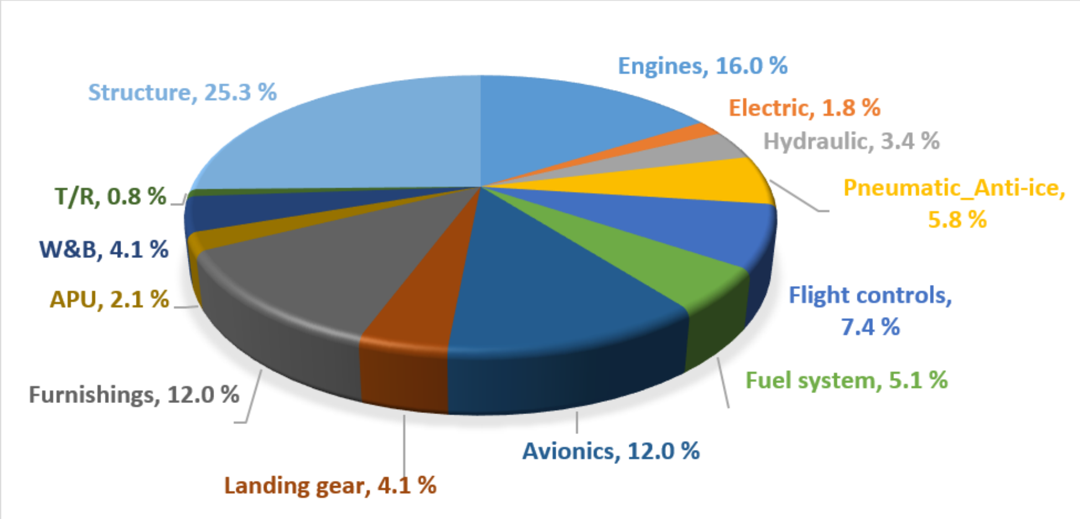



**Figure 34**: Maintenance manhours rate breakdown

### *Maintenance cost*

| | **Direct Maintenance cost, $(DMC)_i$ [$/FH]** |
|---|---|
| Engines | 268.4 |
| Electrical | 5.4 |
| Hydraulic | 5.3 |
| Flight controls | 6.1 |
| Fuel system | 21.7 |
| Avionics | 28.5 |
| Landing gear | 8.9 |
| Pneumatic & Furnishings | 8.0 |

| | Direct Maintenance cost, $(DMC)_i$ [$/FH] |
|---|---|
| APU | 25.0 |
| W&B | 38.4 |
| T/R | 10.1 |
| Line maintenance | 95.1 |
| Base maintenance | 71.3 |
| **Total** | **592.0** |

**Table 25**: Direct maintenance cost at subsystem level

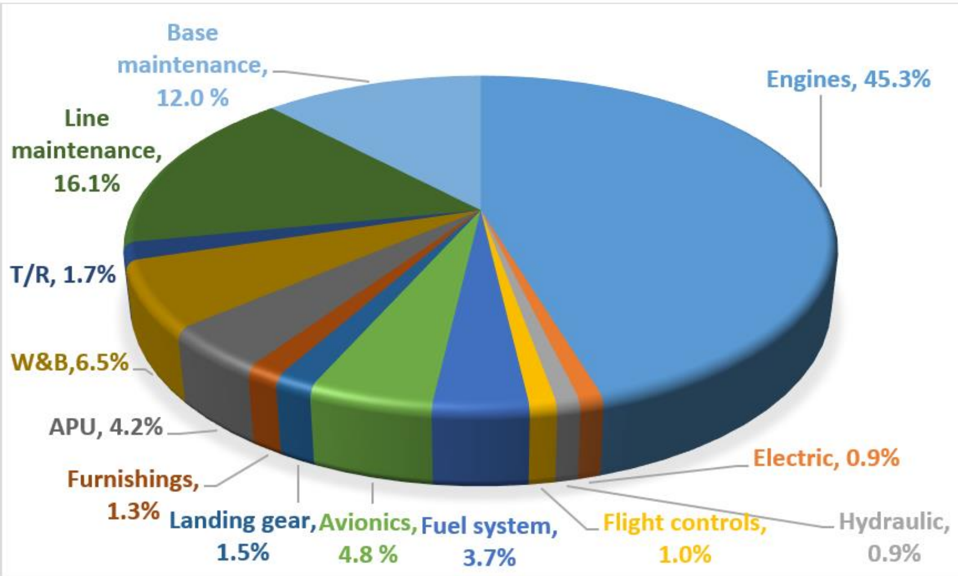



**Figure 35**: Direct maintenance cost breakdown at subsystem level

The engines are the most expensive to maintain. Following, line and base maintenance, which we roughly approximate to the amount spent to maintain the structure, since the majority of the time is spent for structural repairs. Since they are very expensive in terms of spare, W&B occupies a big part of the breakdown equal to almost 7 percent. In addition, avionics is also quite relevant in the cost heading.

The tool provides also the output given by the introduction of Airbus method. In total it results that the majority of the total direct maintenance cost amount is spent for spare acquirements (**Table 26**).

| DMC, [$/FH] | | |
|---|---|---|
| Direct Labour cost, DLC, [$/FH] | 29.7 | 5.0 % |
| Material cost, MC, [$/FH] | 562.4 | 95.0 % |

**Table 26**: Total labour and material cost breakdown at A/C level

| | DLC | | MC | |
|---|---|---|---|---|
| | [$/FH] | [%] | [$/FH] | [%] |
| Engines | 4.8 | 16.0 | 263.7 | 46.9 |
| Electrical | 0.5 | 1.8 | 4.8 | 0.9 |
| Hydraulic | 1.0 | 3.4 | 4.3 | 0.8 |
| Flight controls | 2.2 | 7.4 | 3.9 | 0.7 |
| Fuel system | 1.5 | 5.1 | 20.2 | 3.6 |
| Avionics | 3.6 | 12.0 | 24.9 | 4.4 |
| Landing gear | 0.5 | 1.7 | 8.5 | 1.5 |
| Pneumatic & Furnishings | 5.3 | 17.8 | 2.7 | 0.5 |
| APU | 0.6 | 2.1 | 24.3 | 4.3 |
| W&B | 2.0 | 6.6 | 36.4 | 6.5 |
| T/R | 0.3 | 0.8 | 9.8 | 1.7 |
| Structure | 7.5 | 25.3 | 158.9 | 28.3 |

**Table 27**: Labour and material costs results at subsystem level

| | |
|---|---|
| Direct Maintenance cost, DMC, [$/FH] | 592.0 |
| Maintenance Burden, MB, [$/FH] | 394.7 |
| **Total Maintenance cost, [$/FH]** | **986.7** |

**Table 28**: Total maintenance cost breakdown at A/C level

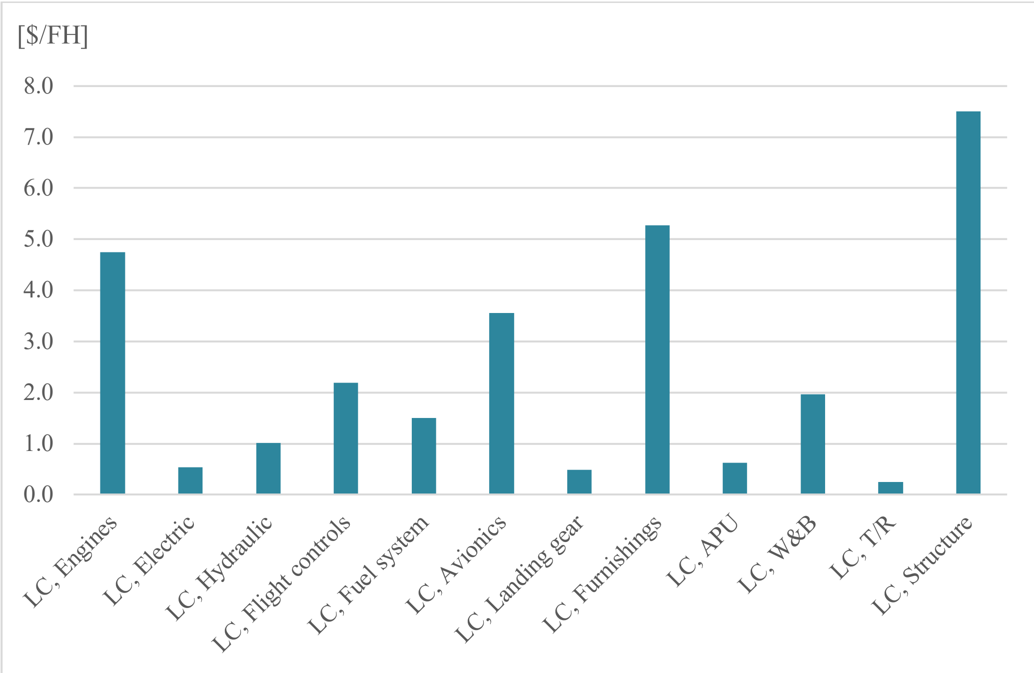



**Figure 36**: Distribution of direct labour costs among subsystems

The items that require higher labour costs are engines, avionics, structure, pneumatic and anti-ice systems (included in furnishings) and W&B. In fact, these are the most complex and most stressed subsystems in many different aspects during the various mission phases.

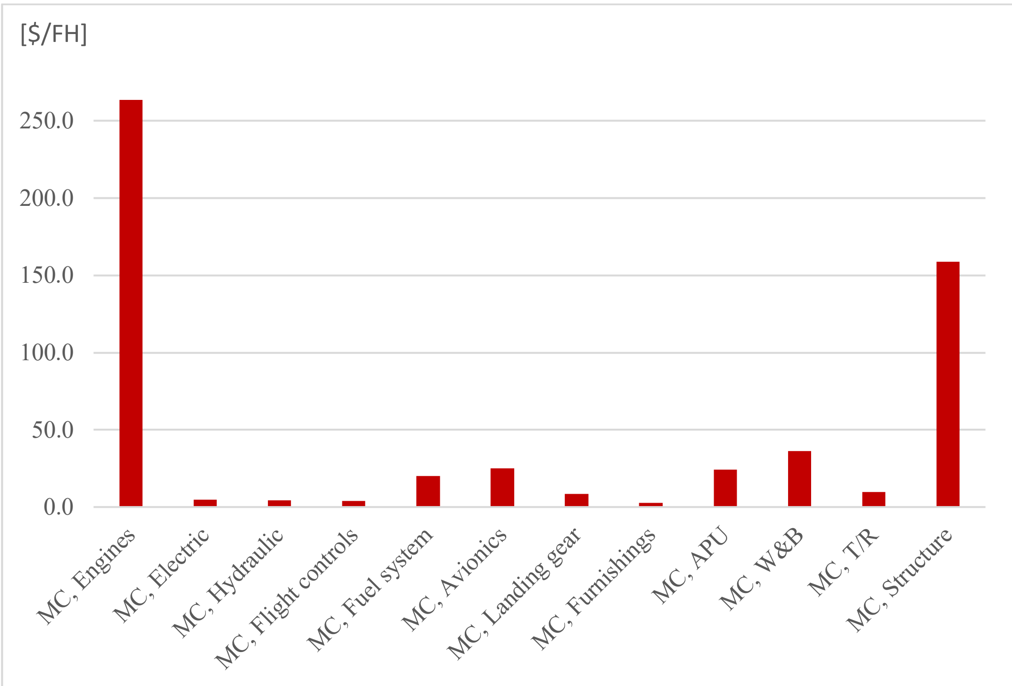



**Figure 37**: Distribution of maintenance material costs among subsystems

Structure and engines are the most expensive from both perspectives.

### Operating costs

| | |
|---|---|
| Total Maintenance cost [$/FH] | 987 |
| Fuel cost [$/FH] | 1577 |
| Crew cost [$/FH] | 320 |
| **Operating Costs [$/FH]** | **2903** |

**Table 29**: Operating costs breakdown per flight hour

## 4.5 Innovative test

### 4.5.1 Impact of singular solutions

The analysis carried out to look at the forefront of the innovative technologies also concerns the adoption of innovative on-board system architectures.
In particular, the architectures that have been considered are:

a) Conventional (CONV). Three typologies of non-propulsive power are possible [42]: electric, hydraulic and pneumatic power. Part of the power generated by the propulsion system (i.e. the engines) is converted in non-propulsive or secondary power to supply on-board systems. Mechanical shaft power off-takes are extracted from the engines and the APU. This mechanical power is then converted by Integrated Drive Generators (IDGs) in electric 115 V AC power at constant frequency (400 Hz). Analogously, part of the mechanical power is employed for the alimentation of engine-driven hydraulic pumps, which pressurize the hydraulic oil up to nearly 20.7 MPa (3000 psi). The hydraulic power is demanded by the actuators of moveable surfaces and landing gears, and by the braking system. Pneumatic users and the ECS are supplied by hot and high pressure air bled from the engine compressors and from the APU. The weakest point of the conventional architecture is represented by the bleed air off-take, consisting in penalties affecting the performance of the engine.

b) More electric 1 (MEA1). It is similar to the system architecture of the Airbus A380. This solution is characterized by the removal of the hydraulic system. Therefore, all the FCS and landing gear actuation systems are supplied by an augmented high voltage electric system. The innovative feature of this aircraft is represented by the FCS. For the first time in aviation history, Electro-Hydrostatic (EHAs) and Electro-Mechanical Actuators (EMAs) were installed aboard a civil passenger transport aircraft. In more detail, one of the three hydraulic circuits is replaced by two electrical lines. This solution is identified as “2H/2E” arrangement. Thus, almost every primary mobile surface is moved by a traditional hydraulic actuator and potentially by an EHA[9], which is set in stand-by mode. In MEA1, instead also the traditional actuators present in A380 are substituted by EHAs and EMAs. This architecture is on the military aircraft F22. Furthermore, part of the total power generated by the propulsion system is in the form of pneumatic high pressure airflow, as the conventional case.

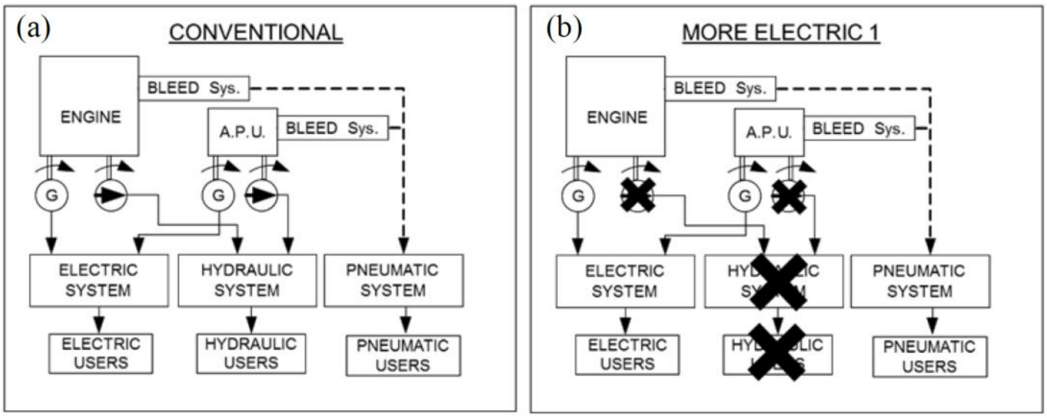



**Figure 38**: CONV and MEA1 on-board system architectures

[9] On the Airbus A380, for safety reasons, two spoilers and the rudder are powered by Electrical Backup Hydraulic Actuators (EBHAs), which combine the features of EHAs and conventional hydraulic actuators.

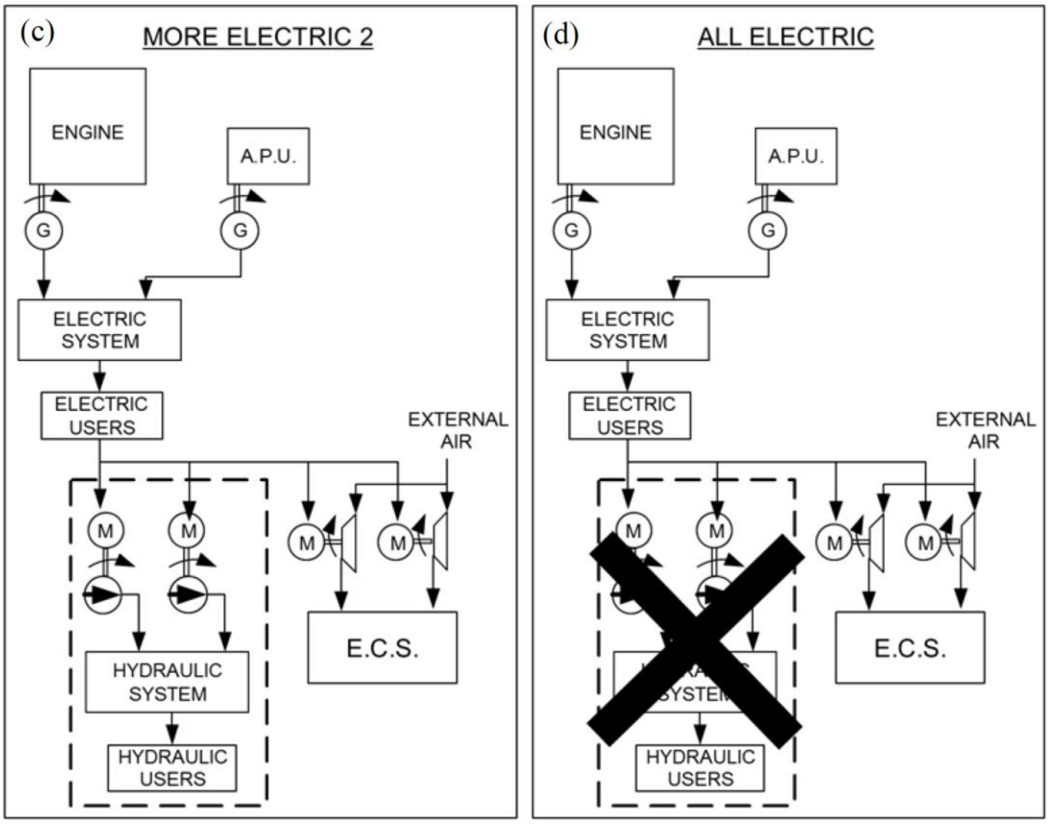



**Figure 39**: MEA1 and MEA2 on-board system architectures

c) More electric 2 (MEA2). It is peculiar of the Boeing 787. It adopts a so-called "bleedless" configuration: only a small portion of airflow is bled to protect the engine nacelles from the ice formation. The air-conditioning and pressurization systems and the Wing Ice Protection System (WIPS) are supplied by the electrical system. However, the "bleedless" configuration entails an increased electrical power generation. According to Boeing Company, this efficient solution entails a 3 percent of fuel saving per mission, against a significant increment of the subsystems weight. The peculiarity of the second more electric architecture (MEA2) is the generation of only electric secondary power, as depicted in (**Figure 39** (c)). This solution is a "bleedless" configuration, as the bleed air system is removed. Thus, the wing de-icing system and the air conditioning system are supplied by the electric power. Concerning the ECS, electrically driven air compressors are designed. The removal of the pneumatic system entails two consequences. First, the total demand of electric power increases considerably. Therefore, high voltage electric current shall be generated, as the previous case. This fact entails also an increment of the size of the generators.

Furthermore, the jet engine cannot be started pneumatically, but electrically. Hence, electric starter-generators are installed.
Finally, the hydraulic system is still present, but the hydraulic oil pressure is raised up to about 34.5 MPa (5000 psi). Furthermore, this solution is characterized by more efficient electric driven hydraulic pumps, instead of engine driven pumps [42].

d) All electric architecture (AEA). All the users are electric. Consequently the electric generation becomes heavier and more complex. It is the most innovative all electric architecture here considered (**Figure 39** (d)). It combines the peculiarities of the two more electric architectures. The electric power is the only one generated with this innovative configuration. All the actuators, the braking system and the air conditioning system are supplied by a high voltage electric system [42].

Hence, each solution will be identified through:

$$\mathrm{TECH/OBSA}^{10}$$

For instance:
$\mathrm{CONV/CONV} \rightarrow$ Aircraft with conventional technologies (e.g. aluminium structures, conventional wing, hydraulic actuators) and with conventional on-board systems architecture.

Not all the combinations are possible, because theoretically they are not practicable and also for how ASTRID is set-up.

Moreover in the following paragraphs, results for solutions with the usage of MEA2 and AEA2 will not be presented, since the more-electric architecture required to be taken into account into the equations with other specific coefficient modifications. It could be a future proposal to continue developing the present work.

[10] $OBSA$: On-board Systems Architecture

| TECH / OBSA | Conventional | Composite | Laminar | EHA |
|---|---|---|---|---|
| Conventional | CONV/CONV | COMP/CONV | LAM/CONV | |
| MEA1 | | | | EHA/MEA1 |
| MEA2 | CONV/MEA2 | COMP/CONV | LAM/MEA2 | |
| AEA | | | | EHA/AEA |

**Table 30**: All possible aircraft solutions given by combination of TECH and OBSA

Now these combinations will be discussed with a particular focus on the comparison with the conventional aircraft study, CONV/CONV.

### *COMP/CONV*

This solution highlights the aspects analysed before related to the usage of composites for structure. The elements that are set-up to be in composite are fuselage and wing. Nacelles are not usually made of composites because they would require to be extremely reinforced.

| | **Weight [kg]** | | **Δ[%]** |
|---|---|---|---|
| | **CONV/CONV** | **COMP/CONV** | |
| **Wing** | 5590 | 4057 | -25.0 |
| **Fuselage** | 5937 | 4309 | |
| **MEW** | 23280 | 19456 | -16.0 |
| **MTOW** | 45017 | 40503 | -10.0 |

**Table 31**: Comparison of the structure weights due to introduction of composites in COMP/CONV

It is possible to notice that beginning with the weight saving due to the employment of composites instead of aluminium takes to an overall MTOW saving equal to 10 percent for the innovative solution COMP/CONV. Since the on-board system architecture has not changed, the on-board systems do not have radical changes in terms of weights and complexity. For this reason the failure rates are expected to be very close to the conventional counterpart analysed before.

#### RAMS estimations

| | **$\lambda_i$, Reliability failure rate** | | | |
|---|---|---|---|---|
| | **CONV/CONV** | | **COMP/CONV** | |
| | **[failures/1000FH]** | **[%]** | **[failures/1000FH]** | **[%]** |
| Engines | 15.5 | 27.4 | 12.9 | 27.4 |
| Electrical system | 2.1 | 3.7 | 1.8 | 3.7 |
| Hydraulic system | 2.3 | 4.0 | 1.9 | 4.0 |
| Pneumatic & Anti-ice | 2.6 | 4.6 | 2.2 | 4.6 |

| | $\lambda_i$, Reliability failure rate | | | |
|---|---|---|---|---|
| | CONV/CONV | | COMP/CONV | |
| | [failures/1000FH] | [%] | [failures/1000FH] | [%] |
| Flight controls | 1.3 | 2.4 | 1.1 | 2.4 |
| Fuel system | 3.6 | 6.4 | 3.0 | 6.4 |
| Avionics | 14.5 | 25.6 | 12.1 | 25.6 |
| Landing gear | 1.4 | 2.5 | 1.2 | 2.5 |
| Furnishings | 3.7 | 6.5 | 3.1 | 6.5 |
| APU | 0.4 | 0.7 | 0.3 | 0.7 |
| Wheel and brakes | 5.7 | 10.0 | 4.7 | 10.0 |
| Thrust reversers | 0.8 | 1.4 | 0.7 | 1.4 |
| Structure | 2.7 | 4.7 | 2.2 | 4.7 |
| **Total** | **56.6** | **100** | **47.3** | **100** |

**Table 32**: Comparison between reliability failure rate allocation of CONV/CONV and COMP/CONV

It is possible to observe the effect of the application of a top-down approach. The reliability failure rate at A/C level is estimated by a relationship depending on the MEW. Since the MEW of the aircraft is reduced, as a consequence the allocation at subsystem level will be singularly reduced as well. The absolute values of the reliability failure rates are changing, but the rates given by the percentages showed in **Table 32** are exactly the same. A future correction with bottom-up approach instead of top-down can fix this behaviour. The allocation of the failure rate at system level also takes the weights of the subsystems for which it takes into account the lightening. In order to not amplify this reduction effect brought by this type of approach, we consider the natural reduction of the structure through a reduction brought by a unitary coefficient in the corresponding equation. For this reason, the analysis of the result describes that the failure rate of the structure has been reduced by 16 percent (from 2.7 to 2.2). Made the composite has a better behaviour than aluminium, but its poor impact resistance should be considered which therefore limits a possible more advantageous reduction.

| | $(\mathbf{MMH/FH})_i$ Maintenance manhours per flight hour | | | |
|---|---|---|---|---|
| | **CONV/CONV** | | **COMP/CONV** | |
| | **[failures/1000FH]** | **[%]** | **[failures/1000FH]** | **[%]** |
| Engines | 0.12 | 16.0 | 0.11 | 16.2 |
| Electrical system | 0.01 | 1.8 | 0.01 | 1.8 |
| Hydraulic system | 0.03 | 3.4 | 0.02 | 3.5 |
| Pneumatic & Anti-ice | 0.04 | 5.8 | 0.04 | 5.9 |
| Flight controls | 0.05 | 7.4 | 0.05 | 7.5 |
| Fuel system | 0.04 | 5.1 | 0.04 | 5.1 |
| Avionics | 0.09 | 12.0 | 0.09 | 12.1 |
| Landing gear | 0.01 | 1.7 | 0.01 | 1.7 |
| Furnishings | 0.09 | 12.0 | 0.08 | 12.1 |
| APU | 0.02 | 2.1 | 0.01 | 2.1 |
| Wheel and brakes | 0.05 | 6.6 | 0.05 | 6.7 |
| Thrust reversers | 0.01 | 0.8 | 0.01 | 0.9 |
| Structure | 0.19 | 25.3 | 0.17 | 24.3 |
| **Total** | **0.74** | **100** | **0.70** | **100** |

**Table 33**: Comparison between maintenance man hours of CONV/CONV and COMP/CONV

There is a small fluctuation due to the snow ball effect and to the type of approach used. However the fluctuations are maximum equal to 0.2 h (in Engines) correspondent to an error of 1 percent, absolutely tolerable in this early design phase. The only consistent change in values is taken by the Structure: the introduction of composite materials, for wing and fuselage, takes to an advantage in maintenance man hours that is estimated to be reduced by 1 percent.

This result shows that the introduction of the composites has an effect only on the maintenance effort required to maintain the structure. This effect is manifested by a reduction due to the better resistance to fatigue and corrosion of these materials. The total reduction is reaches 6 percent of savings on the overall maintenance effort.

The composite structures reduce the number of parts compared to an aluminium structure. For this reason, maintenance is often more laborious. In fact it could happen that the reliability decrease because of the better behaviour of composites in fatigue and corrosion, but by contrast MMH/FH.

### Maintenance cost

| | **Direct Maintenance cost, $(DMC)_i$** | | |
|---|---|---|---|
| | **CONV/CONV** | **COMP/CONV** | |
| | **[$/FH]** | **[$/FH]** | **Δ[%]** |
| Engines | 268.4 | 249.8 | -7.0 |
| Electrical | 5.4 | 5.4 | -- |
| Hydraulic | 5.3 | 5.3 | -- |
| Flight controls | 6.1 | 6.1 | -- |
| Fuel system | 21.7 | 21.7 | -- |
| Avionics | 28.5 | 28.5 | -- |
| Landing gear | 8.9 | 8.9 | -- |
| Pneumatic & Furnishings | 8.0 | 8.0 | -- |
| T/R | 10.1 | 9.4 | -7.0 |
| Line maintenance | 95.1 | 95.1 | -- |
| Base maintenance | 71.3 | 67.7 | -5.0 |
| **Total** | **592** | **569** | **-4.0** |

**Table 34**: Direct maintenance costs savings due to composites in COMP/CONV compared to CONV/CONV

The dependence from the cost drivers is quite evident: Engines and T/R have the thrust among the cost drivers. As a result, they are sensitive to the weight reduction of the aircraft, and consequently to the thrust reduction. Furthermore the effect of the composites' introduction takes to assess a saving in the direct costs spent for base maintenance. In fact during base maintenance structure is evaluated together with complex and time consuming tasks for structural repair. Composites allow to reduce the number of the parts and together with the good behaviour in fatigue and corrosion involve an overall saving.

| | | CONV/CONV | COMP/CONV | |
|---|---|---|---|---|
| | | [$/FH] | | Δ[%] |
| Structure | DLC | 7.5 | 6.8 | -10.0 |
| | MC | 158.9 | 156.0 | -2.0 |

**Table 35**: Comparison of DLC and MC of the structure between CONV/CONV and COMP/CONV

The change that can appreciated in the table above is a decrease in both costs. This has not be interpreted as a complete advantage: composites are much more expensive and difficult to work with, but they should be repaired less often. Therefore, given the lower mean-time-between-failures, pound for flight hour, the cost of the materials is reduced. In fact it should be noticed the different savings between the two cost items. Se il componente spare potrebbe costare di piu ma lo si applica meno volte perche' ha FR inferiore

## Operating costs

| | CONV/CONV | COMP/CONV | |
|---|---|---|---|
| | [$/FH] | | Δ[%] |
| Total Maintenance cost | 987 | 949 | -4.0 |
| Fuel cost | 1577 | 1385 | -13.0 |
| Crew cost | 320 | 320 | -- |
| **Operating costs** | **2903** | **2674** | **-8.0** |

**Table 36**: Comparison of operating costs between CONV/CONV and COMP/CONV

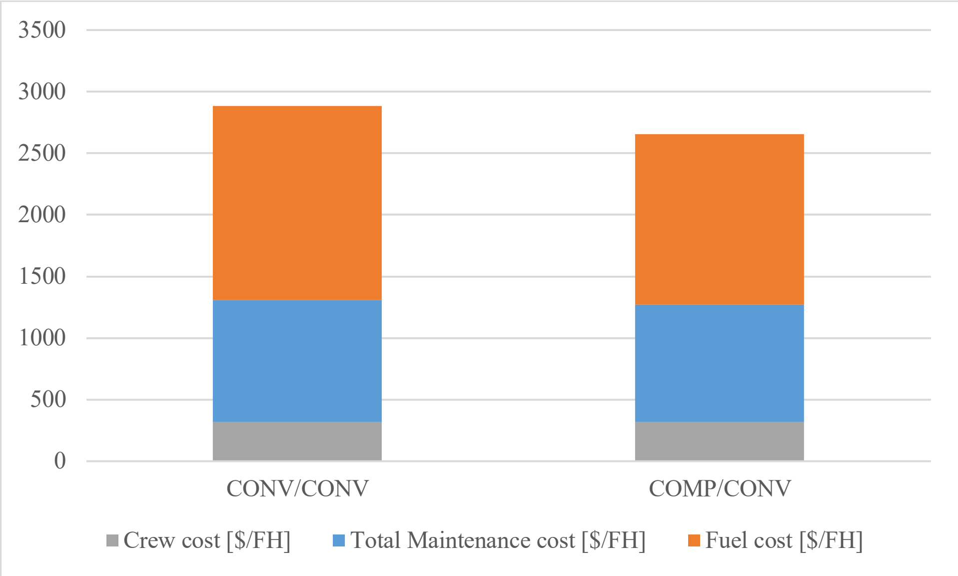



**Figure 40**: Comparison of operating costs per flight hour between CONV/CONV and COMP/CONV

Mainly the weight saving obtained through the composites utilisation leads to not only a maintenance cost reduction, but also to improved fuel efficiency. The lower fuel cost highlights a major cost saving that only through maintenance cost cannot be appreciated. Maintenance cost savings, in fact are 4 percent, while operating cost ones doubled in rate.

### *LAM/CONV*

The introduction of NLFW does not intend to modify the weights. However, weights are lighter because of the snow ball effect:

| | CONV/CONV | LAM/CONV | |
|---|---|---|---|
| | Weight [kg] | | Δ[%] |
| **Wing** | 5590 | 4057 | -2.5 |
| **Fuselage** | 5937 | 4309 | |
| **MEW** | 23280 | 19456 | -2.0 |
| **MTOW** | 45017 | 40503 | -3.0 |

**Table 37**: Comparison of the structure weights due to introduction of NLFW in LAM/CONV

Hence, like observed for composites introduction, also the introduction of NLFW experiences the snow ball effect: the demand of less amount of fuel reflects as a lighter aircraft (lower structure, lower MEW and MTOW).

### RAMS estimations

| | $\lambda_i$, Reliability failure rate | | | |
|---|---|---|---|---|
| | CONV/CONV | | LAM/CONV | |
| | [failures/1000FH] | [%] | [failures/1000FH] | [%] |
| Engines | 15.5 | 27.4 | 15.2 | 27.3 |
| Electrical system | 2.1 | 3.7 | 2.1 | 3.7 |
| Hydraulic system | 2.3 | 4.0 | 2.2 | 4.0 |
| Pneumatic & Anti-ice | 2.6 | 4.6 | 2.6 | 4.6 |
| Flight controls | 1.3 | 2.4 | 1.3 | 2.4 |
| Fuel system | 3.6 | 6.4 | 3.5 | 6.4 |
| Avionics | 14.5 | 25.6 | 14.2 | 25.6 |
| Landing gear | 1.4 | 2.5 | 1.4 | 2.5 |

| | $\lambda_i$, Reliability failure rate | | | |
|---|---|---|---|---|
| | **CONV/CONV** | | **LAM/CONV** | |
| | **[failures/1000FH]** | **[%]** | **[failures/1000FH]** | **[%]** |
| Furnishings | 3.7 | 6.5 | 3.6 | 6.5 |
| APU | 0.4 | 0.7 | 0.4 | 0.7 |
| Wheel and brakes | 5.7 | 10.0 | 5.5 | 10.0 |
| Thrust reversers | 0.8 | 1.4 | 0.8 | 1.4 |
| Structure | 2.7 | 4.7 | 2.7 | 4.8 |
| **Total** | **56.6** | **100** | **47.3** | **100** |

**Table 38**: Comparison between reliability failure rate allocation of CONV/CONV and LAM/CONV

The snow ball effect is reflected in the failure rate estimation and allocation. In facts RAMS tool reveals that $\lambda_{structure}$ switched from 2.63 (due to the lower weight of the innovative solution considered) to 2.68 due to more sensitivity of NLFW.

| | $(MMH/FH)_i$ **Maintenance manhours per flight hour** | | | |
|---|---|---|---|---|
| | **CONV/CONV** | | **LAM/CONV** | |
| | **[failures/1000FH]** | **[%]** | **[failures/1000FH]** | **[%]** |
| Engines | 0.12 | 16.0 | 0.12 | 14.9 |
| Electrical system | 0.01 | 1.8 | 0.01 | 1.7 |
| Hydraulic system | 0.03 | 3.4 | 0.03 | 3.2 |
| Pneumatic & Anti-ice | 0.04 | 5.8 | 0.04 | 5.4 |
| Flight controls | 0.05 | 7.4 | 0.05 | 6.9 |
| Fuel system | 0.04 | 5.1 | 0.04 | 4.7 |
| Avionics | 0.09 | 12.0 | 0.09 | 11.1 |
| Landing gear | 0.01 | 1.7 | 0.01 | 1.5 |

| | $(MMH/FH)_i$ Maintenance manhours per flight hour | | | |
|---|---|---|---|---|
| | **CONV/CONV** | | **LAM/CONV** | |
| | **[failures/1000FH]** | **[%]** | **[failures/1000FH]** | **[%]** |
| Furnishings | 0.09 | 12.0 | 0.09 | 11.1 |
| APU | 0.02 | 2.1 | 0.02 | 2.0 |
| Wheel and brakes | 0.05 | 6.6 | 0.05 | 6.2 |
| Thrust reversers | 0.01 | 0.8 | 0.01 | 0.8 |
| Structure | 0.19 | 25.3 | 0.24 | 30.6 |
| **Total** | **0.74** | **100** | **0.79** | **100** |

**Table 39**: Comparison between maintenance man hours of CONV/CONV and LAM/CONV

The percentage match is lost because the global value has increased (from 0.74 to 0.79) due to the increase of the Structure entry due to the introduction of NLFW. In fact, this technology takes to a consistent increase of more than 5 percent due to the additional visual inspections during line maintenance, to additional periodical cleaning interventions and to the more accuracy required during maintenance because of its sensitivity.

### Maintenance cost

| | Direct Maintenance cost, $(DMC)_i$ | | |
|---|---|---|---|
| | **CONV/CONV** | **LAM/CONV** | |
| | **[$/FH]** | **[$/FH]** | **Δ[%]** |
| Engines | 268.4 | 263.3 | -2.0 |
| Electrical | 5.4 | 5.4 | -- |
| Hydraulic | 5.3 | 5.3 | -- |
| Flight controls | 6.1 | 6.1 | -- |
| Fuel system | 21.7 | 21.7 | -- |
| Avionics | 28.5 | 28.5 | -- |
| Landing gear | 8.9 | 8.9 | -- |

| | Direct Maintenance cost, $(DMC)_i$ | | |
|---|---|---|---|
| | CONV/CONV | LAM/CONV | |
| | [$/FH] | [$/FH] | Δ[%] |
| Pneumatic & Furnishings | 8.0 | 8.0 | -- |
| APU | 25.0 | 25.0 | -- |
| W&B | 38.4 | 38.4 | -- |
| T/R | 10.1 | 9.9 | -2.0 |
| Line maintenance | 95.1 | 96.0 | +1.0 |
| Base maintenance | 71.3 | 72.7 | +2.0 |
| **Total** | **592** | **589.1** | **-1.5** |

**Table 40**: Direct maintenance costs savings due to composites in COMP/CONV compared to LAM/CONV

Although NLFW is more expensive from a maintenance point of view, maintenance costs globally have decreased slightly. This is another evidence of the snowball effect: NLFW would consume less fuel, so it can be loaded less and consequently the structure can be lighter; it follows that the necessary thrust is reduced and therefore also the maintenance costs of the engines and of the t / r. in reality this fluctuation should not be considered. It is too small to be tolerated, on the other hand, the increase due to NLFW based on maintenance and in line must be taken into account, because once accumulated after a certain number of FH would be greater and, together with the advantages obtained by a greater fuel efficiency, it is reason for evaluation and trade-off on the convenience of this technology.

| | | CONV/CONV | LAM/CONV | |
|---|---|---|---|---|
| | | [$/FH] | | Δ[%] |
| Structure | DLC | 7.5 | 9.7 | +29.0 |
| | MC | 158.9 | 159.0 | -- |

**Table 41**: Comparison of DLC and MC of the structure between CONV/CONV and LAM/CONV

It is possible to appreciate the usefulness of having introduced the airbus method in the model for estimating maintenance costs: the laminar wing requires more labour costs. This is in line with the information already obtained from MMH/FH.

### Operating costs

| | CONV/CONV | LAM/CONV | |
|---|---|---|---|
| | [$/FH] | | Δ[%] |
| Total Maintenance cost | 987 | 982 | -1.5 |
| Fuel cost | 1577 | 1494 | -5.0 |
| Crew cost | 320 | 320 | -- |
| **Operating costs** | **2903** | **2816** | **-3.0** |

**Table 42**: Comparison of operating costs between CONV/CONV and LAM/CONV

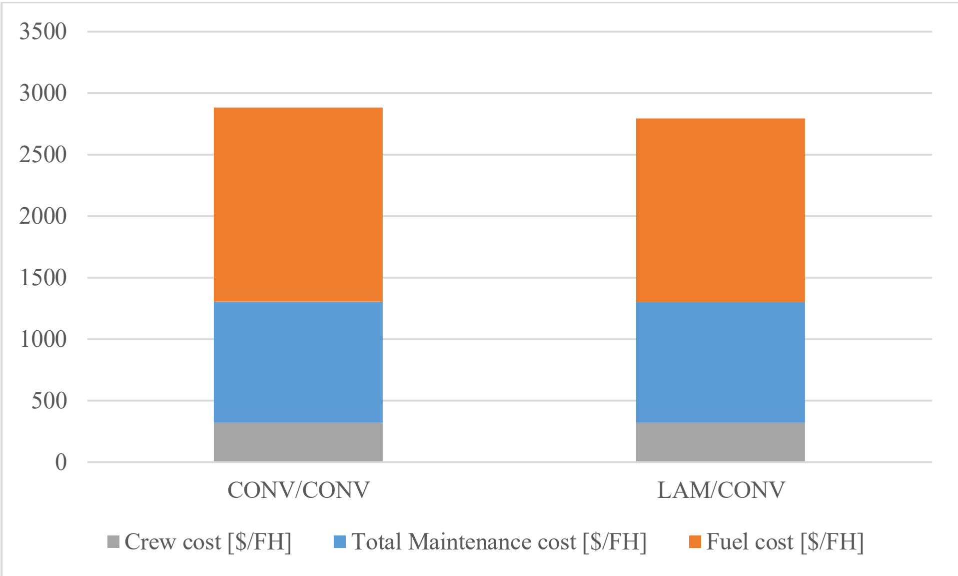



**Figure 41**: Comparison of operating costs per flight hour between CONV/CONV and LAM/CONV

Keeping the same crew cost[11], the 3 percent reduction is clear in **Figure 41**. The real advantage taken by NLFW technology is in the fuel efficiency. For this reason is important to assess the laminarity effectivity in order to not alter the fuel efficiency predicted during design.

[11] Crew number does not change, hence crew cost will remain steady

### EHA/MEA1

Since actuators are part of the on-board system architecture, EHA/CONV cannot exist. Hence, the most 'traditional' solution in which EHA could be considered is EHA/MEA1.

| | CONV/CONV | EHA/MEA1 | |
|---|---|---|---|
| | Weight [kg] | | Δ[%] |
| **Wing** | 5590 | 5494 | -2.0 |
| **Fuselage** | 5937 | 5835 | |
| **MEW** | 23280 | 22982 | -1.0 |
| **MTOW** | 45017 | 44164 | -2.0 |

**Table 43**: Comparison of the structure weights due to introduction of EHAs in EHA/MEA1

The removal of the hydraulic system brings the weight down and also from overall perspective because of the snow ball effect.

### RAMS estimations

| | $\lambda_i$, Reliability failure rate | | | |
|---|---|---|---|---|
| | CONV/CONV | | EHA/MEA1 | |
| | [failures/1000FH] | [%] | [failures/1000FH] | [%] |
| Engines | 15.5 | 27.4 | 15.6 | 27.9 |
| Electrical system | 2.1 | 3.7 | 3.3 | 6.0 |
| Hydraulic system | 2.3 | 4.0 | 0.0 | 0.0 |
| Pneumatic & Anti-ice | 2.6 | 4.6 | 2.6 | 4.7 |
| Flight controls | 1.3 | 2.4 | 1.4 | 2.4 |
| Fuel system | 3.6 | 6.4 | 3.6 | 6.5 |
| Avionics | 14.5 | 25.6 | 14.6 | 26.1 |
| Landing gear | 1.4 | 2.5 | 1.4 | 2.5 |
| Furnishings | 3.7 | 6.5 | 3.7 | 6.6 |

| | $\lambda_i$, Reliability failure rate | | | |
|---|---|---|---|---|
| | CONV/CONV | | EHA/MEA1 | |
| | [failures/1000FH] | [%] | [failures/1000FH] | [%] |
| APU | 0.4 | 0.7 | 0.4 | 0.7 |
| Wheel and brakes | 5.7 | 10.0 | 5.7 | 10.2 |
| Thrust reversers | 0.8 | 1.4 | 0.8 | 1.5 |
| Structure | 2.7 | 4.7 | 2.7 | 4.8 |
| **Total** | **56.6** | **100** | **55.9** | **100** |

**Table 44**: Comparison between reliability failure rate allocation of CONV/CONV and EHA/MEA1

Looking at the absolute values, the effect that brings EHA technology combined with MEA1 on-board system architecture, is an overall lightening of the aircraft (very small) which leads to a reduction in the reliability failure rate at system level. This is an effect of the approach used (already discussed in section 4.5.1) that is function of MEW.

More in detail, it is worth noting that the system on which this new technology has the greatest impact is the electrical: it must generate more power to be distributed to the electro-hydrostatic actuators, reason why the weight increases. In fact, the latter have no connection to the hydraulic system, but have a small hydraulic circuit inside. The removal of the hydraulic system is reflected in improved reliability and in a lightening of weight.

| | Weight [kg] | |
|---|---|---|
| | CONV/CONV | EHA/MEA1 |
| Electrical | 584 | 653 |
| Hydraulic | 354 | 0.0 |
| Flight controls | 554 | 637 |

**Table 45**: Impact of MEA1 on subsystems weight

It is possible to observe that also Flight controls subsystem weight increases. This is mainly due to the fact that EHAs weight is twice of conventional actuator weight.

| | $(\mathbf{MMH/FH})_\mathbf{i}$ **Maintenance manhours per flight hour** | | | |
|---|---|---|---|---|
| | **CONV/CONV** | | **EHA/MEA1** | |
| | **[failures/1000FH]** | **[%]** | **[failures/1000FH]** | **[%]** |
| Engines | 0.12 | 16.0 | 0.12 | 16.5 |
| Electrical system | 0.01 | 1.8 | 0.02 | 2.7 |
| Hydraulic system | 0.03 | 3.4 | 0.00 | 0.0 |
| Pneumatic & Anti-ice | 0.04 | 5.8 | 0.04 | 6.0 |
| Flight controls | 0.05 | 7.4 | 0.06 | 7.6 |
| Fuel system | 0.04 | 5.1 | 0.04 | 5.2 |
| Avionics | 0.09 | 12.0 | 0.09 | 12.3 |
| Landing gear | 0.01 | 1.7 | 0.03 | 4.3 |
| Furnishings | 0.09 | 12.0 | 0.09 | 12.3 |
| APU | 0.02 | 2.1 | 0.02 | 2.2 |
| Wheel and brakes | 0.05 | 6.6 | 0.03 | 4.3 |
| Thrust reversers | 0.01 | 0.8 | 0.01 | 0.9 |
| Structure | 0.19 | 25.3 | 0.19 | 26.0 |
| **Total** | **0.74** | **100** | **0.79** | **100** |

**Table 46**: Comparison between maintenance man hours of CONV/CONV and EHA/MEA1

### Maintenance cost

| | Direct Maintenance cost, $(DMC)_i$ | | |
|---|---|---|---|
| | **CONV/CONV** | **EHA/MEA1** | |
| | **[$/FH]** | **[$/FH]** | **Δ[%]** |
| Engines | 268.4 | 267.0 | -0.5 |
| Electrical | 5.4 | 5.9 | +10.0 |
| Hydraulic | 5.3 | 0.0 | -- |
| Flight controls | 6.1 | 5.8 | -0.5 |
| Fuel system | 21.7 | 21.7 | -- |
| Avionics | 28.5 | 28.5 | -- |
| Landing gear | 8.9 | 8.9 | -- |
| Pneumatic & Furnishings | 8.0 | 8.0 | -- |
| APU | 25.0 | 25.0 | -- |
| W&B | 38.4 | 38.4 | -- |
| T/R | 10.1 | 10.0 | -0.5 |
| Line maintenance | 95.1 | 95.1 | -- |
| Base maintenance | 71.3 | 71.3 | -- |
| **Total** | **592** | **585.5** | **-1.1** |

**Table 47**: Direct maintenance costs savings due to composites in COMP/CONV compared to EHA/MEA1

As already stated in the previous cases, a change in the weight of the aircraft entails a change in the required thrust and therefore also in the output provided by the model as regards the maintenance cost of the engines and thrust reversers. This effect must be ignored. What should be appreciated is the increase in the cost of the flight control system. This is due to the fact that material cost increases (**Table 48**) since electronic units are necessary into EHAs actuators, more expensive. Another reason why material cost is higher is that, although easier to maintain, the number of EHAs installed is superior to that of conventional actuators in CONV/CONV, for safety reasons. Overall, balancing with the elimination of hydraulic plumbing, auxiliary pumps, servovalves, and the relative maintenance of filters and valves, there is a good result in maintenance cost reduction.

| | | CONV/CONV | EHA/MEA1 | |
|---|---|---|---|---|
| | | [$/FH] | | Δ[%] |
| Electrical | DLC | 0.5 | 9.7 | +49.0 |
| | MC | 4.8 | 5.1 | +5.0 |
| Hydraulic | DLC | 1.0 | 0.0 | -- |
| | MC | 4.3 | 0.0 | -- |
| Flight controls | DLC | 2.2 | 2.2 | -- |
| | MC | 3.9 | 3.6 | -9.0 |

**Table 48**: Comparison of DLC and MC between CONV/CONV and EHA/MEA1

As expected, electrical system DLC increases because of the more complexity it reaches. Moreover, DLC of flight controls is steady because EHAs labour is mainly operated for removal and replacement operations, while maintenance is often operated by the EHAs manufacturer (spare cost).

### Operating costs

| | CONV/CONV | EHA/MEA1 | |
|---|---|---|---|
| | [$/FH] | | Δ[%] |
| Total Maintenance cost | 987 | 976 | -1.1 |
| Fuel cost | 1577 | 1563 | -0.9 |
| Crew cost | 320 | 320 | -- |
| **Operating costs** | **2903** | **2859** | **-1.5** |

**Table 49**: Comparison of operating costs between CONV/CONV and EHA/MEA1

Even if with reduced effect, EHAs show their efficiency. Although their weight is higher, it is balanced by a better efficiency: it allows almost 1 percent of fuel cost saving per flight hour. This saving, combined with the reduced total maintenance cost leads to more than 1 percent of operating cost saving.

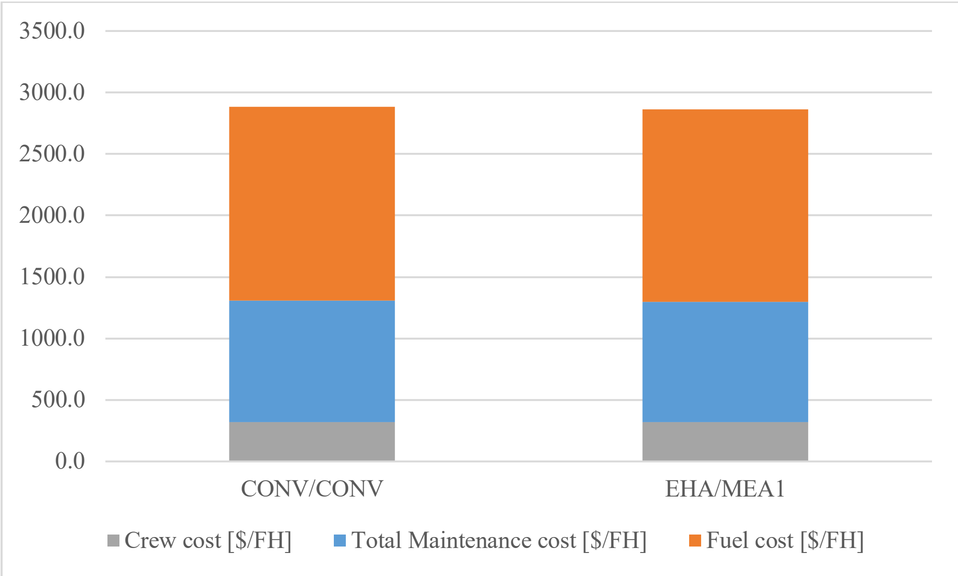



**Figure 42**: Comparison of operating costs per flight hour between CONV/CONV and EHA/MEA1

### 4.5.2 Impact of combined solutions

Interesting is the evaluation of combined solutions. It allows to appreciate the combination of the effects.

First let analyse the combination of NLFW and composites, keeping the conventional on-board system architecture.

| | **Direct Maintenance cost, $(DMC)_i$** | | |
|---|---|---|---|
| | **CONV/CONV** | **COMP+LAM/CONV** | |
| | **[$/FH]** | **[$/FH]** | **Δ[%]** |
| Engines | 268.4 | 245.7 | -8.5 |
| T/R | 10.1 | 9.3 | -8.5 |
| Line maintenance | 95.1 | 96.0 | +1.0 |
| Base maintenance | 71.3 | 69.1 | -3.1 |
| **Total** | **592** | **587.6** | **-4.2** |

**Table 50**: Changes of $(DMC)_i$ in COMP+LAM/CONV

To combine NLFW with composites brings to much more savings from the maintenance cost perspective. The solution is not only better than conventional CONV/CONV but also better than LAM/CONV, although NLFW takes some less economic efficiency in line and base maintenance.

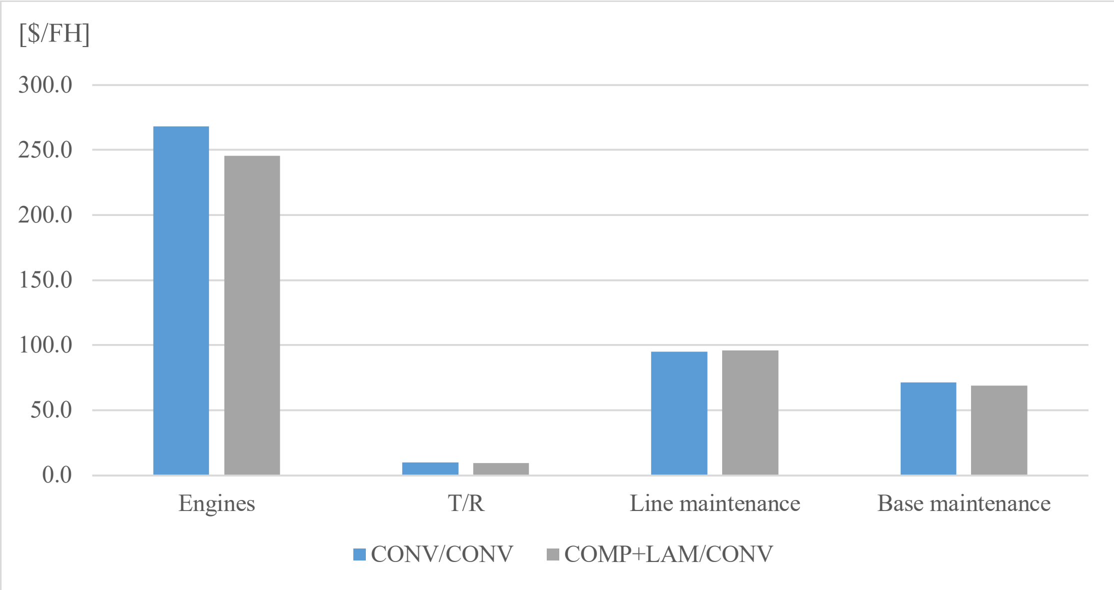



**Figure 43**: Comparison of $(DMC)_i$ between CONV/CONV and LAM+COMP/CONV

| | | Direct Maintenance cost, $(DMC)_i$ | | |
|---|---|---|---|---|
| | **CONV/CONV** | **COMP+EHA /MEA1** | **LAM+EHA /MEA1** | **COMP+LAM+E /MEA1** |
| | **[$/FH]** | **Δ[%]** | **Δ[%]** | **Δ[%]** |
| Engines | 268.4 | -7.4 | -2.4 | -8.9 |
| Electrical | 5.4 | +10.0 | +10.0 | +10.0 |
| Flight controls | 5.3 | -0.5 | -0.5 | -0.5 |
| T/R | 10.1 | -6.9 | -2.3 | -8.6 |
| Line Maintenance | 95.1 | -- | +1.0 | +1.0 |
| Base maintenance | 71.3 | -5.0 | +2.0 | -3.1 |
| **Total** | **592** | **-4.9** | **-1.6** | **-5.2** |

**Table 51**: Changes of $(DMC)_i$ rate in combined solutions

Overall, it appears that the previously analysed effects appear in the same way, but combined. The result is that, from the point of view of maintenance costs, the use of the composite certainly brings significant economic benefits. In particular, if combined with NLFW (COMP+LAM/CONV), it leads to very advantageous solutions: on the one hand a lower maintenance cost and on the other, a lower fuel consumption. If the solution switches to an on-board more-electric system architecture MEA1, the elimination of the hydraulic system further contributes to the cost reduction.

The most advantageous solution in terms of maintenance costs is COMP+LAM+EHA/MEA1 which sees the combination of the three technologies taken into consideration. But we also need to look at the aspects from an operational point of view.

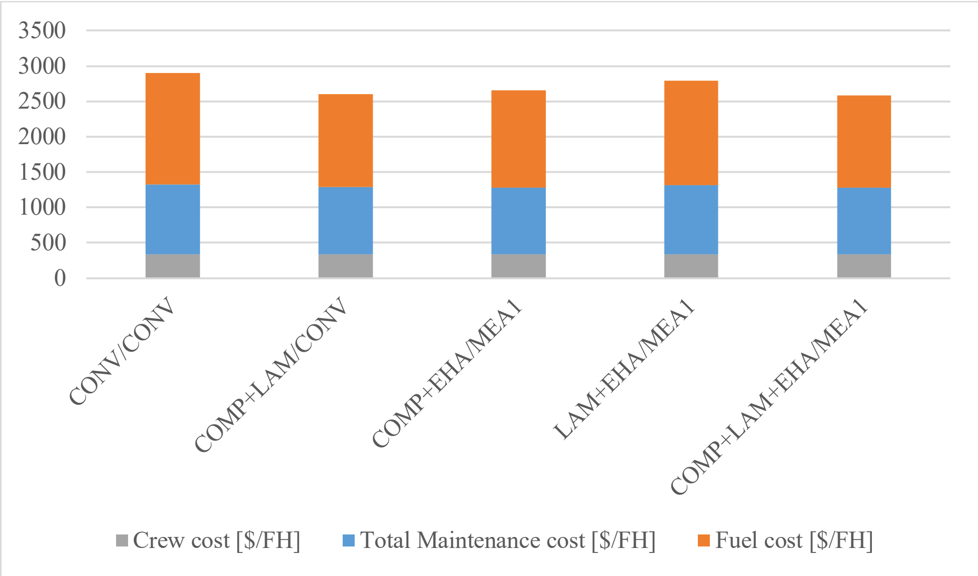



**Figure 44**: Comparison of operating costs per flight hour among combined solutions

| **[$/FH]** | **CONV /CONV** | **COMP+LAM /CONV** | **COMP+EHA /MEA1** | **LAM+EHA /MEA1** | **COMP+LAM+EH /MEA1** |
|---|---|---|---|---|---|
| Total Maintenance cost | 987 | 945 | 938 | 971 | 935 |
| Fuel cost | 1577 | 1317 | 1375 | 1482 | 1306 |
| Crew cost | 340 | 340 | 340 | 340 | 340 |
| **Operating costs** | **2903** | **2602** | **2653** | **2796** | **2585** |

**Table 52**: Comparison of operating costs per flight hour among combined solutions

It turns out that the solution that sees the use of the three technologies with MEA1 is the most favourable from the point of view of operating costs. COMP+LAM+EHA/MEA1 saves more than 10 percent of operating costs per flight hour.

## 4.6 RAMS and Maintenance influence in Aircraft Design

The execution and evaluation of results presented so far, showed that the methodology developed in this thesis work can facilitate design trade-offs during early design process when changes can be done at lower cost.

Apart every design choice, RAMS and Maintenance cost estimation, dictate the success of an aircraft design both in terms of safety and life cycle cost, reason why cost estimations have to be taken into account since the beginning of the design process. The methodology allows to understand the entries that have major influence on a particular cost parameter and to compare many different solutions.

Moreover the methodology adjusts problems also in case of conventional aircraft thanks to the comparison with available data output.

In this way it is possible to conduct numerous different studies, for example either to understand the influence of design parameters on maintenance costs or to identify the design configuration that minimizes maintenance costs.

# 5. Future work

Since this methodology is completely new and is not preceded by other work carried out before, numerous can be the ideas for improvement and development of this work. It is necessary to continue to work on this methodology in order to increase the level of reliability and to be able to expand the field of view, taking into account even more aspects that help to trade-off in terms of maintenance costs.
Below are the points on which further work could be carried out.

## 5.1 New approach for MMH/FH estimation

The estimate of the maintenance effort presented in Par.2.1.2 can be reset through a change of approach. Maintenance man hours per fligh hour assessments that take subsystem weight into account should be considered. The problem at the moment is that it is based on a top-down approach. A bottom-up approach could be better, in a way in which it takes into account the weight of each subsystem and not MEW. In addition, a vector of correction coefficients could be considered in such a way to change its components according to the aircraft class and to calibrate them according to each subsystem.

## 5.2 Improved allocation of Structure in Maintenance cost model

The fact that Structure subsystem that is present in RAMS is equivalent to Line Maintenance and Base Maintenance in the Maintenance cost tool is slightly rough approximated. Line maintenance and Base maintenance do not cover only Structure, even if definitely it covers a large percentage. For this reason a percentage division should be established.

## 5.3 Improved fidelity of DMCs estimation at subsystem level

DMCs are calculated with global aircraft cost drivers. They work well for estimating costs for different classes of aircraft but they work poorly when charateristics of a single ATA change. Also in this case it could be considered to use the tool that calculates values that should be scaled with subsystem weights.

## 5.4 Deepening of SysML diagrams

The application of SysML is very powerful but it can be wider. It can differ both in terms of diagrams to be used depending on the object of representation, and in terms of level of detail. The more data are available, the more it is possible to enrich the SysML diagram and therefore to obtain more information that help to improve the equations for innovative cases. For example, the activity diagram developed for composite repair can be further investigated. Tools, more cases and even more updated data can be included. It is possible to include all the repair process in detail and verification actions of the QC plans used for in-process inspection.

## 5.5 Modification for MEA2 and AEA system architectures

As already anticipated in Par. 4.5.1, as a possible future work, it would be necessary to go into detail in the models implementing the behavior of the outputs when the degree of electrification of the systems increases.

This development can lead the developed model to be more complete and more versatile, especially because great attention is nowadays paid to the electrification of future aircraft.

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