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ASSESSMENT OF NEW TECHNOLOGIES IN A MULTI-DISCIPLINARY DESIGN ANALYSIS AND OPTIMIZATION ENVIRONMENT INCLUDING RAMS AND COST DISCIPLINES

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Abstract

The aim of the present paper is to assess the effect of new technologies on the whole aircraft product including its costs, reliability and maintainability characteristics. Several studies have been conducted dealing with the preliminary evaluation of Reliability, Availability, Maintainability and Safety (RAMS) of conventional aircraft. They provide a very effective method to preliminary estimate RAMS characteristics but their employment is not completely suitable for the analysis of unconventional configurations adopting new technologies. This paper aims at evaluating how the aircraft costs and RAMS characteristics are affected by new structures material, natural laminar flow wing technology and unconventional actuator system (electro-hydrostatic actuators), hence an update of the state of the art models is needed. This evaluation is performed by means of a setup and execution of a Multidisciplinary Design Analysis and Optimization (MDAO) workflow. The MDAO environment includes the aircraft conceptual design, aircraft performance, structure design, engine design, on-board systems design, RAMS and maintenance cost modules. The RAMS module is used to obtain the failure rates and maintenance effort (in terms of maintenance man hour per flight hour) at subsystem level. The cost module is based on a new maintenance cost model able to estimate the operating cost of the different aircraft variants. The selected new technologies are applied to a regional jet developed within the framework of AGILE research project. For each technology, a different variant of this aircraft is analyzed. Results show that some important saves are reached both in terms of maintenance and fuel cost when new technologies are applied.

Keywords: RAMS, MDAO, Maintenance Cost, EHA, Composites

Nomenclature

DMC	Direct Maintenance Cost
EHA	Electro-Hydrostatic Actuator
FH	Flight Hour
FR	Failure Rate
LR	Labour Rate
MB	Maintenance Burden
MC	Material Cost
MDO	Multi-Disciplinary Design Optimization
$MDAO$	Multidisciplinary Design Analysis and Optimization
MEA	More-Electric Aircraft
MMH/FH	Maintenance Man Hour per Flight Hour
NDI	Non-Destructive Inspection
$NLFW$	Natural Laminar Flow Wing
OBS	On-Board Systems
$PIDO$	Process Integration and Design Optimization
$RAMS$	Reliability, Maintainability, Availability and Safety
$TLARs$	Top-Level Aircraft Requirements

1. Introduction

Aircraft design is a process that includes several disciplines (e.g. structures, aerodynamics, flight mechanics...) that have a strong interaction and influence among them. Finding a unique solution that satisfies the top-level aircraft requirements (TLARs) of each field becomes a difficult task. Multi-Disciplinary Design Optimization (MDO) is the methodology used in order to obtain the global optimal solutions. The main goals that are usually sought are high performance and low costs. Hence cost assessment and estimation should be taken into account at the design stages in order to be effective in terms of production costs and maintenance, since regular aircraft maintenance is essential to ensure aircraft airworthiness and therefore availability through its extended life-cycle [1].

For this reason, Reliability, Availability, Maintainability and Safety (RAMS) have recently become system design requirements with a big importance on the results. RAMS discipline dictates, for instance, the duration of the scheduled maintenance interventions. As a result, it constitutes one of the main trade-off factors of the maintenance program development and the maintenance cost predictions. During the aircraft design process RAMS assessment helps to make decisions regarding risk, efficiency, repair and maintenance [2]. Maintenance cost is the price associated to the whole process, which includes the time required to perform regular inspections and to bring the aircraft into serviceable condition according to airworthiness regulations [3]. The current tendency in aviation is to design the new aircraft aiming to improved maintainability and reliability. Some examples of this tendency are the A380 [4] and the B787 [5].

Several research studies have carried out reliability and maintenance analysis of the aircraft but detailed estimations on a subsystem level are still to be performed. The purpose of this paper is to provide a methodology of RAMS and maintenance cost estimation of a civil aircraft, at system and subsystem level. The analysis is designed for early design stages and a comparison between conventional aircraft and new generation ones is shown in the results.

Regarding the RAMS analysis, the main parameters that are taken into account for this analysis are the components' failure rate (FR) and the maintenance man hour per flight hour (MMH/FH), as suggested in some previous analysis [6]. Concerning the aircraft maintenance cost estimation, the methodology suggested is based on earlier studies such as the one in [7]. Both methods are updated so that the new generation aircraft could also be studied. Hence the methodology is done by combining two models after being updated.

1.1 New Technologies

The scope of this paper is to make a comparison, in terms of RAMS and maintenance cost, between conventional aircraft and new technologies. This allows to know which applications can also have potential improvements from a maintenance perspective. Three different technologies are chosen:

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

Composites and EHAs are already in use. NLFW has not been implemented in industry yet but it might have promising results in terms of fuel efficiency. These technologies ideally allow optimizing aircraft performance and reducing fuel consumption. A trade-off between efficiency and maintainability is present on these technologies. The one that manages to reduce more the direct maintenance cost (DMC) is to be found on this analysis.

Composites offer higher strength-to-weight ratios that enable lighter weight structures when compared to aluminium and other materials. Furthermore composite aircraft structures have improved fatigue, corrosion and moisture resistance, as well as the ability to tailor lay-ups for optimal strength and stiffness in the required directions [8]. Composites are not new to commercial aviation, some examples are the B777, which entered in service in 1995 with secondary structures (e.g. the leading edge, flaps, ailerons...) made of carbon fibres for a total of 10 percent of the structural weight. Or the A380 with a 25 percent of composite structure, used even for primary structures. The latest models like the B787 and the A350 reached both around a 50 percent of structure weight made of composite material. The biggest advantage of composites usage is the weight reduction but other improvements are achieved, for instance, they allow to reduce the maintenance of the fuselage since fatigue effect is reduced when compared to aluminium, especially in high-loaded environments [9]. This effect together with the reduced risk of corrosion that these materials have compared to metal results in a reduction in the amount of regular scheduled maintenance needed [9]. The biggest disadvantage is their high acquisition cost [8]. They also are less efficient when dealing with compression loads and they have more intricate damage mechanisms. Another one of their biggest disadvantages is the susceptibility to accidental damage (e.g. tool dropping during maintenance and repair operations). Object impacts can cause internal damage such as de-lamination or de-bonding, this requires new intrusive inspections and repair activities [10] that can penalize the maintainability.

Natural laminar flow wing (NLFW) consist of making more-aerodynamically-efficient wing profiles in which the flow remains laminar. It is a passive technology improvement (i.e. no extra systems need to be installed) since it is based on refining the shape and surface of the wing. This new technology is one of the many promising fuel efficiency increase technologies [11], and it could be integrated in the next generation of aircraft. Its main principle is based on drag reduction, which translates on less fuel consumption and less emissions. A estimated fuel burn improvement of 10-12 percent could be achieved with this new wing concept [12]. However, NLFW has not been commercially implemented yet. The main reason is the uncertainty of the system performance under realistic operational conditions. One of the factors threatening the operational effectiveness of the NLFW is leading edge contamination with insect debris. It can cause premature transition of the laminar boundary layer and reduce the benefits and aircraft economic viability. Additional wing-cleaning shall be performed in order to preserve the laminar flow benefits. This may reduce the overall cost savings. Another factor is the presence of clouds during flight. Clouds reduce the effectiveness of the NLFW and therefore decreases the drag reduction of the wing. Also, the maximum allowed leading edge sweep angle for an aircraft equipped with NLFW is limited to 15 degrees. Which can lead to an undesirable reduction of the cruise speed in order to control the transonic effects [13]. As a consequence, there is a clear trade-off when designing a wing with NLFW. The benefits appear only for optimum conditions (i.e. laminar flow is limited to cruise flight conditions [14]) and it could require more maintenance time.

The last innovating technology considered is the electro-hydrostatic actuator (EHA). It is a new type of actuator based on the conventional hydraulic one. The main difference is that the EHA has its own local hydraulic circuit that is powered by electrically-driven pumps. This local hydraulic system consists of a three-phase AC power source that drives a variable speed pump together with a constant displacement hydraulic pump [15]. The conventional hydraulic actuators consist of some central hydraulic lanes that provide power to the actuators. These systems are heavy and voluminous and the actuators are pressurised whether or not there is any power demand. In general, actuators do not have power demands during the whole operation so this results in higher energy off-takes [16]. EHA technologies solve this problem with the local hydraulic circuits. The actuator no longer needs a central hydraulic lane and is powered only when it is required, optimizing the operation. These actuators are currently being used in the industry (e.g. A350, A380). This technology allows the removal of all hydraulic actuators and lanes that require more maintenance effort than electrical actuators [17].

1.2 State of the Art: RAMS

The two objectives of this paper are to define the RAMS and maintenance cost of a determined aircraft. RAMS stands for reliability, availability, maintainability and safety. The four concepts are now explained in detail [18]:

- **Reliability**: it describes in a quantitative way how failure-free a certain system is during a determined period of time. The main quantity that represents the reliability of a system is the Failure Rate (FR). It is defined as the number of failures of an item per measure-of-life unit.
- **Maintainability**: is the probability of an item being retained or restored within a given period of time if prescribed procedures and resources are used. It is a characteristic of design and

installation. A maintainability performance index is the Maintenance Man Hours per Flight Hour (MMH/FH). It can be estimated by dividing the labour hours spent to maintain a particular aircraft fleet during a given period, by the flying hours during that period of time.

- **Availability**: is a combination of reliability and maintainability that translates into an index of effectiveness. It is commonly based on the question "Is the equipment available in a working condition when it is needed?". It is usually represented by a representative unit of time.
- **Safety**: is the state where an acceptable level of risk is not exceeded. It represents the absence of catastrophic consequences on the user and environment. It can be defined as the reliability with respect to catastrophic failures. The Safety Failure Rate is typically imposed by the normative.

Several studies have been performed in the aircraft field concerning reliability [18, 19] and maintenance [20]. But they have some limitations. They are all focused on conventional aircraft, not allowing new technologies to be analyzed. They are also based on obsolete statistical data, so a new database shall be updated. Also, they are based on the whole aircraft or on a single-component level, but not applicable at a subsystem level. An update of the models is needed in order to fulfill the scope of this paper and compare the new technologies with the conventional one. The base-study chosen was the one proposed by Chiesa [6]. The main reason is the compatibility with the maintenance cost estimation model and the ease of updating the database and equations to make it suitable for the new technologies.

The first step of the model is the reliability failure rate estimation. Traditionally, this analysis is proposed as a bottom-up approach that consist of calculating the aircraft failure rate as the sum of the subsystems' failure rates. The final value is compared to the design requirement, if not satisfied the number and/or type of equipment and redundancies shall be reviewed. Chiesa proposed a top-down approach in which the whole system's failure rate is defined first in order to secondly define the criteria for the allocation of it at subsystem level. The systems' failure rate is estimated through a statistical equation. This equation estimates the failure rate of an aircraft based on its maximum empty weight, a technological age index (based on the years in which the design process took place), a complexity index (complexity level of the aircraft) and a role index (reporting the importance of the role played by the aircraft). After this analysis, the allocation considers the aircraft as constituted by subsystems in series without any redundancy at subsystem level. The subsystem failure rate is proportional to the global failure rate, the subsystem's weight and the aircraft type (i.e. civil or military).

The safety failure rate estimation proposed by Chiesa is also a top-down approach in which the whole system value is estimated from a statistical analysis to later allocate the subsystem's values. It's estimation is analogous to the reliability failure rate analysis. The parameters taken into account for this estimation are: subsystem redundancy coefficient (varies if the subsystem has redundancies or not), subsystem duty cycle coefficient (expresses the ratio between the subsystem operating time and the aircraft life cycle in terms of flight hours), subsystem criticality coefficient (depends on how strong influence on aircraft safety the subsystem has), subsystem complexity coefficient (considering that a very complex system can have an higher failure probability) and a subsystem technological sophistication coefficient (expresses the technological sophistication of each single subsystem).

Lastly, the maintenance hours per flight hour estimation have their own model, also proposed by Chiesa [6]. This estimation is also based on statistical equations and two of the previous indexes are re-used here, the complexity index and technological age index. However, two other indexes are implemented for the model. One is the maintenance role index, which has statistical results depending on the aircraft type (i.e. civil or military), the other one is the design to maintain coefficient, which depends on the attention given to maintainability during design. With these four indexes and the maximum empty weight, a statistical equation is built that can be used for any conventional aircraft. As for the previous parameters, the subsystem level is achieved by an allocation of the global result.

1.3 State of the Art: Maintenance Costs

After the initial approval of airworthiness, aircraft maintenance has to continuously sustain the airworthiness status by performing required maintenance tasks. This activity has an associated cost which estimation is the main goal of this section. Low operating cost is a key element to airline profitability and maintenance cost is an important part of it. Depending on the aircraft type and range, maintenance costs could represent around a 10 to 20 percent of operating costs. It also represents a noticeable portion of the airplane life cycle cost [21].

Some previous analysis have evaluated this cost, like the one in [21]. The main limitation of these state-of-the art methodologies is that the approach selected for the estimation of maintenance cost, which is subdivided into direct maintenance cost (DMCs) and maintenance burden (MB), do not go into a subsystem level. These methods calculate the contribution to maintenance costs given by only the air-frame and the engines [21]. Moreover, there are no methods in literature estimating the aircraft maintenance cost for the new generation aircraft proposed.

The maintenance cost model that is used in this paper is based on the one proposed by Fioriti [7]. It provides an evaluation of maintenance costs at subsystem level, according to the ATA Specification code. The outputs of the model are the direct maintenance cost (DMCs) breakdown and the maintenance burden (MB) total cost. DMCs include the direct cost of materials and labour that are required for the maintenance activity. The maintenance burden includes the acquisition cost, maintaining equipment and tools, building, facilities, and other indirect costs. It also allows to estimate the impact of the on-board systems architectures on the new technologies. The model is based on equations from previous analysis with the usage of more-current data and can be used at conceptual design stages. With an updated database, the results can reach even more reliable results.

The DMC estimation consists on a set of cost drivers that are variable from one subsystem to another. The cost drivers taken into consideration are: fleet size, aircraft utilisation, flight hours per flight cycle, fuselage length, aircraft cost, age of the type of aircraft, number of seats, average age, number of tires of the landing gear, number of engines and engine thrust. There is also a constant part for each of them. The result is the coefficient of the DMC on a subsystem level. The subsystems considered are: line maintenance, base maintenance, engine overhaul, autopilot, communications, electrical system, furnishing, flight controls, fuel system, hydraulic system, instruments, wheels and brakes, landing gear, APU, navigation and thrust reversals. Hence the results provided by the model are quite precise and concise.

The total cost of the maintenance burden can be expressed as a percentage of the direct maintenance cost. Due to the lack of reliability of the current models the maintenance burden can be estimated as the 40% of the total maintenance cost.

2. Methodology

The methodology consist of developing an automated workflow which has to be able to analyze the RAMS characteristics and maintenance cost of a certain aircraft with or without the new technologies previously mentioned. This section is divided in four parts. First, the RAMS model update is explained more in detail. This model needs to be improved so that it can be used for current vehicles, the same process is shown for the maintenance cost model. Then, both models need to be improved so that they can analyze the new technologies previously commented. At last, once the tools have been fully automated and upgraded, the whole workflow is shown and explained step by step. The workflow can be used to assess maintainability at the design stage. It is intended to facilitate design trade-offs early in the design process when modifications can still be done at lower cost.

2.1 RAMS model calibration and update

The model reported in the state of the art section [6] has been chosen because it can estimate its output at a subsystem level. It still needs to be updated and adapted to the new technologies proposed on this research. The first step is to update the model so that it provides reliable results for current aircraft. Then, a second enhancement is needed for the new technologies.

Small modifications are carried out in order to make the model suitable for current aircraft. First, the database is filled with single civil twin-engine jet transport aircraft and the k_i vector [6] is adjusted. Then, two more subsystems are added to make the model compatible with the maintenance cost one. These two new subsystems are the wheels and brakes and the thrust reversals. With the objective of keeping the proportions of each subsystems, wheels and brakes are considered as a part of the landing gear and the thrust reversals as a part of the engines. Chiesa results for landing gear are now a 80 percent of the whole subsystem while the wheels and brakes consist a 20 percent. Like this the whole subsystem represents the same proportion as before but it is split in two more-detailed parts. The same reasoning is applied to the engine giving the reversal a 5 percent of the subsystem and the 95 percent to the results from Chiesa. Lastly, the maintenance man hours model needs to be also updated since the way of doing maintenance has radically changed in the last years. A constant coefficient of actualization is introduced to make the results match with the current values. This coefficient is 0.167.

Considering the lack of data in the literature regarding reliability, failure rate, maintenance man-hours per flight hour and maintenance costs in case of the new technologies, the first part of this of the methodology is to get as much information as possible through maintenance process modelling. A detailed analysis through Systems Modeling Language (SysML) is performed later for each maintenance process of each new technology. The main points are summarized in section 2.4 and the equations are modified with some indexes to represent the results obtained.

2.2 Maintenance cost model calibration and update

As in the previous section, this model needs an update. Fioriti model [7] was selected owing to its capability to provide results at a subsystem level. The method gives a value for the DMC. An extra step is added in order to have an even more detailed cost breakdown. Once the DMC value is obtained it is divided in two contributions: direct labour cost (cost of the labour performed by the employees that specifically and consistently work on aircraft and its parts) plus material cost (amount of money spent for spare parts) [22]. At the same time, the direct labour cost can be estimated as the maintenance man hours per flight hour multiplied by the labour rate (LR) which is the amount of money per hour, estimated through statistical analysis [22]. The result is shown in equation 1. This integration allows a more in-depth analysis of the effects of the implementation of a certain technology and a direct link between the two models through maintenance man-hours.

$$DMC = MMH/FH \cdot LR + MC \tag{1}$$

A subsystems correlation between the two models needs to be done. The list of subsystems was shown in the state of the art section. The avionics subsystem from the RAMS model consist of the following parts of the maintenance cost model: Instrument panel, automatic flight system, communication, integrated modular avionics and navigation. The structure is composed of the line and base maintenance contributions. The wheels, brakes and thrust reversals have already been implemented in the RAMS method. The last subsystem remaining is the furnishing. The results of the maintenance cost tool consider the air conditioning, anti-ice and classic furnishing as a global furnishing subsystem, this is also split in order to make the correlation.

2.3 New Technologies Update

The three new technologies have an influence on both models (i.e. RAMS and maintenance cost). A separated section is now written for each of them explaining an overall view of the process. Then some qualitative comments are shown and finally the correction indexes proposed for the equations are given.

2.3.1 Composites

Composites have different maintenance processes than aluminium. There are different damage types that significantly reduce the residual strength of composites, they are usually detected with non-destructive inspection (NDI) techniques. These damages include delamination and debonds, fibre breakage, dents, erosion, heat damage and damage from fluid ingress into sandwich panels. Apart from the NDI controls, some visual inspections and cleaning interventions are needed and shall be considered as part of the maintenance process. Once the damage detection and characterization is considered, the appropriate repair process should be selected for each activity. The reparations are also an important part of the maintenance process and should be studied in depth. The two basic types of composite repair processes are bonded (composite part fabrication) and bolted (bolted metal repair). Bonded reparations need the fabrication of new composites plus the posterior quality checks. Bolted metal reparations include for instance metal fasteners. The effect of the bearing stresses on the holes is to be taken into account. Repair process selection can be consulted in documentation. Composites reparations can be delicate. Materials are treated differently if they come from stock or not since extra treatments might be needed. Temperature and humidity conditions shall be under control for some processes. Painting activities are also different from aluminium. Finally, post-repair inspections need to be carried out, usually visual and/or NDI. All these activities are modelled into a SysML environment to represent the whole composites maintenance process and detect the different branches and components. The advantages and disadvantages of composites usage is now summarized in table 1.

PROs	**CONs**	**RAMS impact**	**Maintenance Cost impact**
Fatigue and corrosion resistance	Need to employ new tools and technologies	$(FR)_{structure} \downarrow$	Base Maintenance $\downarrow$
Low structure weight	Special material storage needed [8]	$(MMH/FH)_{structure} \downarrow$	Maintenance Burden $\uparrow$
Reduced number of parts [5]	Delaminations and debonds		
Faster reparations (mostly) [23]	Low superficial resistance [24]		
	Low high temperature resistance		

Table 1 – Qualitative effect of composite materials

Quantitatively, Airbus estimates 10 percent of weight saving in the A350 thanks to the 50 percent composites usage. Boeing declares a 20 percent of weight saving in the Boeing 787 with respect to other aluminum conventional structures [5]. In this case, the 20 percent weight saving resulted in 10-12 percent of fuel efficiency improvement [8]. Furthermore, 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].
Regarding the RAMS equations. The results will be multiplied by correction factors when composites are used. The FR coefficient is set equal to 1 since the effect of the lighter weight is already being taken into account by the weight and balance experts. The positive effect that these materials have is estimated to be roughly a 5 percent of the maintenance man hours per flight hour. Hence the structure MMH/FH factor is 0.95. Opposing effects affect the maintenance cost. As a whole a reduction is obtained after the analysis, this factor is estimated to be a 5 percent reduction on the structure DMC (Structure DMC factor = 0.95).

2.3.2 Natural Laminar Flow Wing

The NLFW is a more complex technology since it is very sensitive to several factors. However its potential advantages are promising. When the flow around the wing is laminar and stable, the drag is reduced. The fuel consumption reduction is estimated to be around a 10 percent. As a result the weight and cost of the aircraft are consequently reduced [12]. The main qualitative results are shown on table 2:

PROs	**CONs**	**RAMS impact**	**Maintenance Cost impact**
Drag is reduced:	Sensitive to dirt and insects	$(FR)_{structure} \uparrow$	Base Maintenance $\uparrow$
- Lower fuel consumption	Sensitive to superficial roughness damage	$(MMH/FH)_{structure} \uparrow$	Line Maintenance $\uparrow$
- Lower weight	More development		
- Lower cost	More production accuracy		

Table 2 – Qualitative effect of natural laminar flow wing (NLFW)

The structural weight of the wing does not change. However, cloud encounter in high altitudes and insect contamination make the fuel efficiency fall down by 1 percent each one, hence the operative fuel consumption becomes an 8 percent lower instead of a 10 like theoretically expected. From a production cost perspective the NLFW aircraft has a higher cost than the conventional, since more development and production accuracy is required.
Translated to the equations. After the analysis, a 2 percent penalty is estimated for the FR coefficient. Hence the structre FR index is 1.02. The higher penalty comes in terms of maintenance man hours per flight hour, owing to the surface problems previously commented. The structure MMH/FH index

is 1.30, meaning than a 30 percent more of maintenance time is needed in order to keep the laminar conditions. Maintenance costs are also increased. The structure line maintenance is increased a 1 percent, with a 1.01 index. In a similar way the structure base maintenance also increases with a correction factor of 1.05.

2.3.3 Electro-Hydrostatic Actuator (EHA)

The maintenance process for an EHA is also modelled on a SysML environment. A comparison with the conventional hydraulic actuator is sought but although EHA is a mature technology, the competition between manufacturers makes that the procedures are not in public domain. Hence, some assumptions are made. The removal and re-installation process of flight control actuator is now explained in 5 phases. The first phase is only needed for the conventional actuators and it is performed before accessing the movable. It consists of isolating the actuator from the hydraulic circuit. An access to the hydraulic bay is needed so that the pressure can be relieved and set to 0 psi. The second phase consists of opening the actuator compartment and disconnecting it from the linkages. Right after, the third phase starts, where the actuator has to be disconnected from the hydraulic system (conventional) or from the electrical system (EHA), then it can finally be disconnected from the actuator control electronics and from the surface, respectively. The fourth phase includes two activities in parallel which are testing the affected actuator and installing the new one. This installation involves the same steps as before but in reverse order. The actuator will be connected to the hydraulic or electric system. A lubrication check is needed in case of the conventional type. Then the rest of connections are performed and the compartment is closed. The conventional one needs a re-pressurization of the system and a check of potential losses which is not needed for the EHAs. The fifth phase is common to both actuation systems and consists of a final operational check performed by technicians before the actuator enters service. Qualitative results are shown on table 3:

PROs	**CONs**	**RAMS impact**	**Maintenance Cost impact**
Less hydraulic system components	Higher electrical system weight	$(FR)_{hydraulic} \downarrow$	$(DMC)_{hydraulic} \downarrow$
- Less complex	Higher electrical system complexity	$(FR)_{electrical} \uparrow$	$(DMC)_{electrical} \uparrow$
- Potentially lower weight	Local cooling could be needed	$(MMH/FH)_{hydraulic} \downarrow$	$(DMC)_{landing\,gear} \downarrow$
		$(MMH/FH)_{electrical} \uparrow$	$(DMC)_{flight\,controls} \downarrow$

Table 3 – Qualitative effect of electro-hydrostatic actuators (EHAs)

The implementation of EHAs allows to have a less complex hydraulic system with lower number of components. The weight of an EHA is higher if compared with a conventional one, but at a subsystem level, since the hydraulic system is reduced, the overall weight is generally lower. By contrast, the electrical weight and complexity are increased [25]. With the usage of EHAs a modular design is possible, this leads to a more simple maintenance process [26]. As a result, EHAs can improve the viability and reliability of aircraft, this brings down the cost of maintenance [27].

Translating the analysis to the equations, RAMS model is not modified. This is decided in order to not take into account the effects twice, since the weight reduction already lowers the results when compared to the conventional architecture. Regarding the maintenance cost the reasoning is different. Flight controls DMC is multiplied by a 0.95 factor, while hydraulic system DMC is reduced by a 40 percent, resulting in a 0.6 index. As commented before, the electrical system maintenance increases, but in a lower quantity. The electrical system results are multiplied by an index of 1.1 if EHA technologies are used.

2.4 Workflow

This paper aims at evaluating how the aircraft maintenance costs and RAMS characteristics are affected by new structures materials, NLF wing and unconventional actuation systems. This evaluation is performed by means of a setup and execution of a Multidisciplinary Design Analysis and Optimization (MDAO) workflow, shown in figure 1.

The MDAO environment belongs to the 3rd generation MDAO [28, 29] and it includes the aircraft conceptual design, aircraft performance, structure design, engine design, On-Board Systems (OBS) design, RAMS and maintenance cost modules. Considering the usual MDAO environments set up for other purpose where aerodynamic and structural design are the main disciplines [30], the present MDAO has the advantage of including OBS, RAMS and cost estimation. All the disciplinary tools are integrated in a process integration and design optimization (PIDO) environment, which allows to easily integrate the MDAO problem [31]. The PIDO environment used for this analysis is RCE [32], developed in DLR. It offers a graphical user interface to connect all the analysis modules and run different stages of the design process.

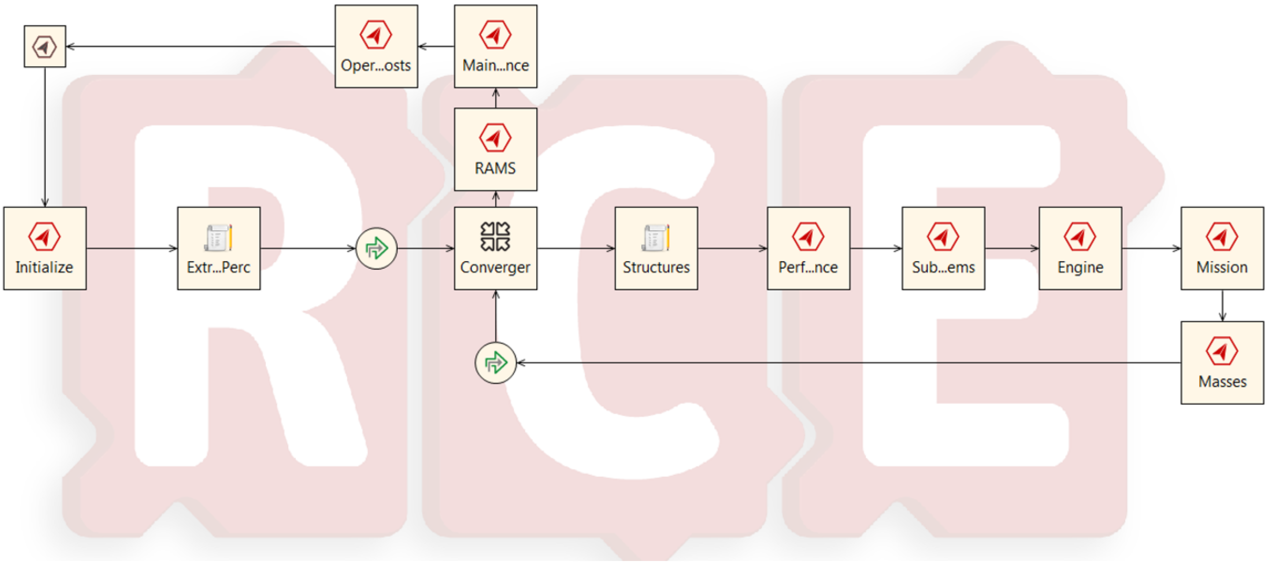

Figure 1 – MDAO Workflow schema

The design process starts with the definition of top level aircraft requirements (e.g. number of passengers, range, runway lengths...). From these requirements, an initial aircraft layout is sketched. In particular, a 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. After the initial layout definition, a convergence loop starts. This internal loop aims to design and size the entire aircraft before the RAMS and maintenance costs analysis are performed. The convergence objective is the aircraft maximum take-off mass. The tools included inside the convergence loop are:

- **Structures**: Consists of a simple script that differentiates the main aspects between composites and metal structures so that they can be properly analyzed in the mass estimation module.
- **Performance**: It calculates aircraft total thrust required for each mission phase (i.e. take-off, climb, cruise, descent, landing). It requires the aerodynamic polar information.
- **On-Board Systems**: Calculates masses and power off-takes. The OBS design is performed by means of ASTRID® tool [33], which is able to size the main aircraft subsystems. ASTRID is sensible to different OBS architecture updating the OBS masses and power off-takes calculated in the workflow.
- **Engines**: Calculates the new engine specific fuel consumption, based on the power off-takes calculated in the OBS tool. Furthermore, it sizes the engine providing the mass, length and diameter values.
- **Mission**: Calculates the amount of fuel required for each mission profile phase (plus reserves) depending on the duration of each and the typology of propulsion system and relative specific fuel consumption calculated in the engine module.
- **Mass Estimation**: Performs a preliminary mass estimation. Takes as inputs the masses of systems, structures, engine, fuel and estimates the new MTOW, taking into account the snowball effect [34].

After the iteration loop the aircraft is properly sized in terms of architecture, masses and dimensions. The rest of the analysis can now be performed. The RAMS tool previously commented is run, providing the results in terms of failure rates and maintenance man hour per flight hour. Then the developed maintenance cost tool is launched, giving the cost results. Another final tool is added. This last tool estimates a preliminary value of the operating cost considering the contribution from maintenance cost, fuel cost (fuel burnt multiplied by its price) and crew cost (depending on a fix index multiplied by the crew number). The results is expressed in dollars per flight hour.

Finally it is possible to observe that in order to manage the different disciplinary tools owned from different experts, and to avoid intellectual property issues, another tool called BRICS® [35] has been used. This tool allows to run other tools from remote without needing access to them, facilitating smooth execution of collaborative engineering workflows.

3. Results

In this section the results are shown. First, the reference aircraft is presented. Then the results for this aircraft, which has a conventional architecture, are exposed. Lastly, the results obtained for the reference aircraft and the other new technologies are compared.

3.1 Reference Aircraft and Architectures

The reference aircraft is used as a baseline. It corresponds to a regional jet developed within the framework of AGILE research project [36]. The selected new technologies are applied to it, obtaining a different variant of this aircraft for each of them. The reference top-level aircraft requirements of the baseline are shown in table 4.

Parameter	Value
Design Range [km]	3500
Passengers	90
Cruise Mach Number	0.78
MTOW [tons]	45
MLW [% of MTOW]	90%
MEW [tons]	23.3
Maximum Operating Altitude [km]	12.5
Fuselage Diameter [m]	3
Fuselage Length [m]	34

Table 4 – Reference civil regional jet requirements

The conventional test case has aluminium structure, conventional hydraulic actuators and conventional wing design. The on-board system architecture is defined from the state of the art, having electric, hydraulic and pneumatic systems. The on-board systems architecture needs to be changed in order to have a reliable estimation when the EHA technology is selected. For this case a more-electric-aircraft architecture is selected. The hydraulic system is removed and Electro-Hydrostatic (EHAs) and Electro-Mechanical Actuators (EMAs) are installed. A schematic comparison between both architectures is shown in figure 2.

3.2 Results for Conventional Aircraft

The results for the conventional aircraft are shown in this section. This corresponds to the baseline aircraft with the conventional architecture, aluminium usage and a conventional wing. Regarding the input, the values that are used are now indicated. In the RAMS analysis proposed by Chiesa [6], a complexity index of 1.5, a technological age index of 0.9 and a role index of 1 are suggested. The maintenance role index is chosen to be 1.5 while the design to maintain coefficient is set to 1. For the maintenance cost analysis proposed by Fioriti [7], the following values are used as an input: fleet size of 511, 10 hours of utilization per day, 45.7 million dollars of aircraft cost, 8.3 years of average age, 40 dollars per flight hours for the labour rate [22] and a crew number of 4. The results of both disciplines at a subsystem level for the conventional architecture are shown in table 5.

It is noticeable that the most complex subsystems (e.g. avionics, engine) have a bigger impact on the global results in terms of reliability. They are also predominant when analyzing the maintenance

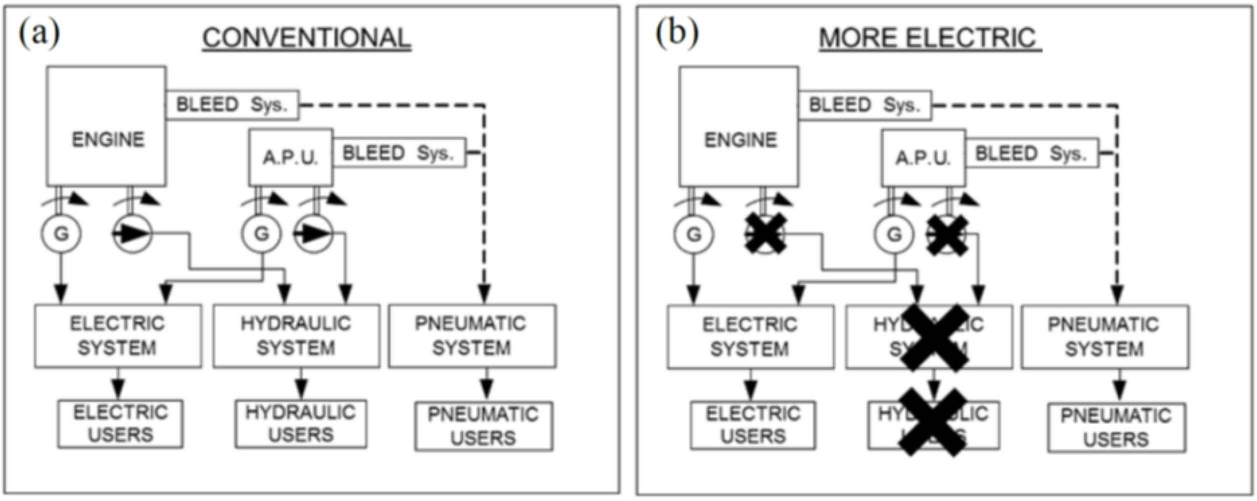

Figure 2 – Comparison between conventional and MEA architectures

	Reliability Failure Rate [failures/1000FH]	**Maintenance Man Hours per Flight Hour**	**Direct Maintenance Cost [$/FH]**	**Direct Labour Cost [$/FH]**	**Material Cost [$/FH]**
Engines	15.5	0.1188	268.4	4.8	263.7
Electrical System	2.1	0.0133	5.4	0.5	4.8
Hydraulic System	2.3	0.0252	5.3	1.0	4.3
Pneumatic & Anti-Ice	2.6	0.0431	4	2.65	1.35
Flight Controls	1.3	0.0547	6.1	2.2	3.9
Fuel System	3.6	0.0376	21.7	1.5	20.2
Avionics	14.5	0.0889	28.5	3.6	24.9
Landing Gear	1.4	0.0307	8.9	0.5	8.5
Furnishing	3.7	0.0888	4	2.65	1.35
APU	0.4	0.0156	25	0.6	24.3
Wheels & Brakes	5.7	0.0307	38.4	2.0	36.4
Thrust Reversal	0.8	0.0063	10.1	0.3	9.8
Structure	2.7	0.1861	95.1 (Line) + 71.3 (Base)	7.5	158.9
Total	**56.6**	**0.74**	**592**	**29.7**	**562.4**

Table 5 – Results for the conventional aircraft at a subsystem level

cost but the structure shows the biggest contribution owing to its importance on this aspect. The engines are the most expensive subsystem to maintain, as it can be seen in the last columns of table 5, followed by the structure. This is due to the fact that the majority of the maintenance time is spent in structural repairs. The global results are now summarized in table 6. The total operating cost value can be found in it.

Cost	**Units**	**Value**
Direct Maintenance Cost (DMC)	$/FH	592
Maintenance Burden (MB)	$/FH	395
Total Maintenance Cost	$/FH	987
Fuel Cost	$/FH	1577
Crew Cost	$/FH	340
Operating Cost	$/FH	**2904**

Table 6 – Global results for the conventional aircraft

3.3 Results for New Technologies

The results for the different technologies are represented in table 7. The value and percentage with respect to the conventional aircraft is shown. Here the impact of each singular technology can be seen. Composites show the biggest operating cost reduction, mainly owing to the weight saving obtained through their utilisation. This leads to a direct maintenance cost reduction but also to a improved fuel efficiency. The lower fuel cost highlights a major cost saving that only through maintenance cost reduction. Maintenance cost savings, in fact are 4 percent, while operating cost ones doubled in rate. The natural laminar flow wing also has promising results. The reduction in fuel burnt is noticeable, this leads to a reduction in fuel cost and in maximum take-off weight. Hence the introduction of NLFW experiences the snow ball effect: the demand of less amount of fuel reflects as a lighter aircraft. This produces that, even though this technology requires more maintenance man hours per flight hour than the conventional, the overall maintenance costs are slightly reduced. 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. The more-electric architecture with EHA technology also experiences an overall weight reduction when compared to the conventional one owing to the hydraulic system removal. As a result the operating cost is also reduced. One effect that could be appreciated through the results is how the engine influence on the maintenance is one of the highest among the subsystems, while the electrical system has a more moderate impact. While the EHA technology increase the electrical system complexity, the reduction in fuel burnt makes the effect on the engines more important than the one in the electrical components, resulting in an overall improvement.

Cost	**Units**	**Conventional**	**Composites**	**NLFW**	**MEA/EHA**
Total Maintenance Cost	$/FH	987	949 (-4%)	982 (-0.5%)	976 (-1%)
Fuel Cost	$/FH	1577	1385 (-12%)	1494 (-5%)	1563 (-1%)
Operating Cost	$/FH	2904	2674 (-8%)	2816 (-3%)	2879 (-1%)

Table 7 – Comparison of results for each new technology

The combined results with the three new technologies are also performed to finalize this analysis. Table 8 summarizes the results obtained, the values are shown with the percentage reduction when compared with the conventional aircraft. The usage of composites has clearly the highest impact among the three of them. The combinations show promising results making it viable to implement the new technologies. A summary of the results is show in figure 3.

Cost	**Units**	**Conventional**	**Composites + NLFW**	**Composites + MEA/EHA**	**NLFW + MEA/EHA**	**Composites + NLFW + MEA/EHA**
Total Maintenance Cost	$/FH	987	945 (-4%)	938 (-5%)	971 (-2%)	935 (-5%)
Fuel Cost	$/FH	1577	1317 (-16%)	1375 (-13%)	1482 (-6%)	1306 (-17%)
Operating Cost	$/FH	2904	2602(-10%)	2653 (-9%)	2796 (-4%)	2581 (-11%)

Table 8 – Comparison of combinations among the technologies

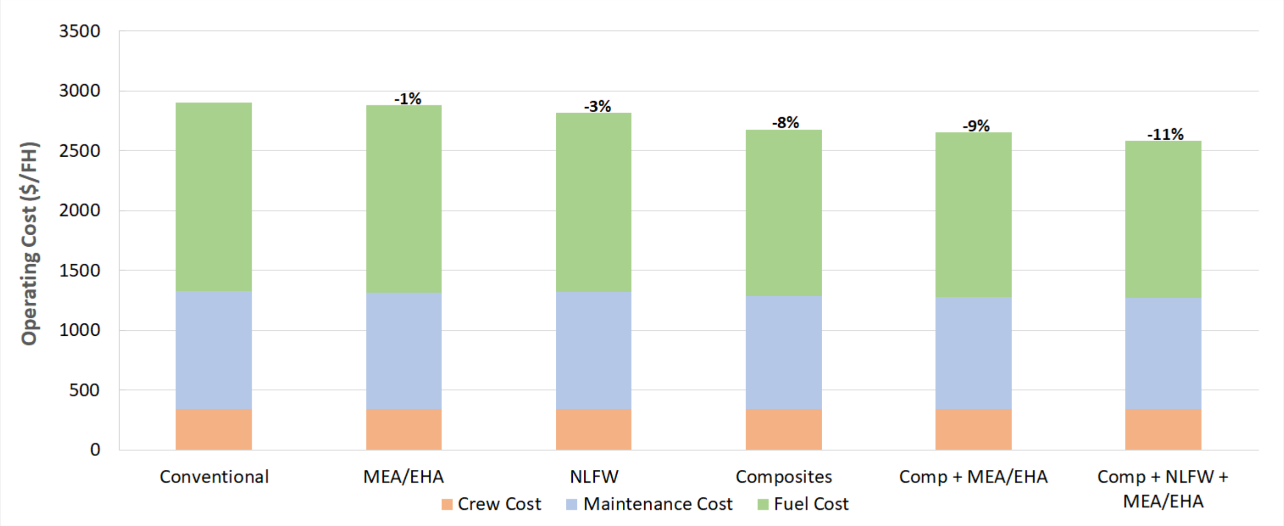

Figure 3 – Comparison between new technologies in terms of operating cost

4. Conclusions

This paper has highlighted the need to develop a new methodology to estimate the RAMS characteristics and maintenance costs of new technologies, which are in particular composite materials, natural laminar flow wing and electro-hydrostatic actuators.

Two models where used from the state of the art: Chiesa's RAMS methodology [6] and Fioriti's maintenance cost estimation model [7]. Both were updated so that they could be used for current aircraft with new technologies and both of them were calibrated so that the results could be applied for the common selected subsystems.

A MDO workflow was used in order to take into account all the different disciplines involved in aircraft design. This provides a reliable and detailed aircraft model before performing the RAMS and maintenance cost analysis. The operating cost was calculated in order to sum all the effects into one comparable result.

This methodology allows to understand the entries that have a major influence on a particular cost parameter and to compare many different solutions. In this way it is possible to conduct different studies, for instance, to understand the influence of design parameters on maintenance costs or to identify the design configuration that minimizes it.

Results showed that the most promising technology is the composites usage. It provides the biggest cost reduction which can be even higher when combined with the other two technologies. Another interesting analysis is that if a new technology needs more maintenance processes than the conventional version, this does not necessarily mean that the cost is higher. A technology that improves the fuel consumption, lowers the fuel weight and cost. This makes the MTOM to be reduced and a result costs are reduced as well. Hence, there is a trade-off between weight reduction and maintenance rise that shall be analyzed before conclusions are drawn.

The execution and evaluation of results presented, showed that the work developed in this paper can facilitate design trade-offs during early design process. 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. Some interesting future work could consist of applying the methodology proposed to analyze more new technologies and systems architectures.

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7. Copyright Statement

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