POLITECNICO DI TORINO

Master's Degree in Aerospace Engineering

Master's Degree Thesis

Development of a Maintenance Man Hours Estimating Relationship during preliminary design of More and All Electric Aircraft

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Summary

Evaluating operating costs is a key step in the successful development of an aerospace project. In particular, maintenance costs represent a very important cost voice for aircraft and many tools for estimating them in the preliminary design phase are publicly available. Since new aviation tendencies and technological improvement are pushing towards the development of More Electric Aircraft (MEA), new cost estimating relationships need be built up in order to replace the conventional ones, that can no longer be exploited in these cases.

The objective of the present work is to investigate the effect of a MEA or an All Electric Aircraft (AEA) On-Board Systems (OBS) on maintenance, trying to assess which are the most impacting systems that drive the Maintenance Man Hours (MMH) variation.

This goal has been accomplished by the development of a Maintenance Man Hours Estimating Relationship (MMHER) which is able to provide an estimate of the amount of scheduled MMH that are saved or added, when going from a conventional OBS architecture to a more or all electric one. The data needed for the MMHER build up have been obtained through two approaches. The first one is literature based and consists of analysing the A320 Maintenance Planning Document (MPD) to identify the tasks that have to be removed, replace or added when the electrification of the systems takes place. By identifying those tasks, it has been possible to evaluate the MMH variation for three MEA and one AEA reference architectures of the A320. The second approach that has been followed is experience based and consists of a series of interviews to maintenance and OBS experts. The goal of the interview is to get a second estimate of the MMH variation that occurs in the electrification process of each on-board system. By doing so, it has been possible to compare the results coming from the two methods and adjust the results basing on the strength and weaknesses of each approach, hence resulting at the end with a more accurate estimate.

The estimated values for the OBS MMH variations have then be used to build up the MMHER, which has been subsequently verified and applied to a use case. Finally, the equation has been integrated into an architecture generating software, ADORE, framework. Several Use Case Architectures (UCAs) were evaluated in

order to understand how different level of OBS electrification could affect the scheduled MMH of each configuration and the UCA with the greatest MMH reduction was identified. This study clearly provides a valid tool to estimate the systems scheduled MMH in a preliminary design phase, when little information is known and few inputs can be given, showing the advantages of going from conventional to MEA and AEA architectures.

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Acronyms

AC Alternate Current

AD Airworthiness Directives

AEA All Electric Aircraft

AL Airworthiness Limitations

APU Auxiliary Power Unit

ATA Air Transport Association

BBA Basic Belief Assignment

CBS Cost Breakdown Structure

CER Cost Estimating Relationship

CMR Certification Maintenance Requirements

CSD Constant Speed Drive

DC Direct Current

DLR Deutsches Zentrum für Luft und Raumfahrt

DMC Direct Maintenance Costs

DOC Direct Operating Costs

EBHA Electrical Backup Hydraulic Actuator

ECS Environmental Control System

EDP Engine Driven Pump

EHA Electro Hydrostatic Actuator

EIDS Electro-Impulse De-icing System

EMA Electro Mechanical Actuator

EMEDS Electro-Mechanical Expulsion De-icing System

EPS Electric Power System

FBL Fly-By-Light

FBW Fly-By-Wire

FC Flight Cycles

FCCs Flight Control Computers

FCS Flight Control System

FH Flight Hours

GPU Ground Power Unit

HP High Pressure

HPS Hydraulic Power System

HSA Hydraulic Servo Actuator

ICAO International Civil Aviation Organization

IDG Integrated Drive Generator

IMC Indirect Maintenance Costs

IOC Indirect Operating Costs

IPS Ice Protection System

LC Labor Cost

LCC Life Cycle Cost

LEHGS Local Electro-Hydraulic Generation System

LGS Landing Gear System

Li-Ion Lithium Ion

LP Low Pressure

MC Material Cost

MEA More Electric Aircraft

MMH Maintenance Man Hours

MMHER Maintenance Man Hours Estimating Relationship

MPD Maintenance Planning Document

MRBR Maintenance Review Board Report

Ni-Cd Nickel-Cadmium

NPRD Nonelectronic Parts Reliability Database

O&S Operation and Support

OAMP Operator Approved Maintenance Program

OBS On-Board Systems

PCS Power Consuming Systems

PDU Power Drive Unit

PGS Power Generating Systems

PoliTo Politecnico di Torino

PTDS Power Transformation and Distribution Systems

PTU Power Transfer Unit

RAT Ram Air Turbine

RDT&E Research, Development, Test and Evaluation

SAA Sensitivity Analysis Architecture

SAF Sustainable Aviation Fuel

SB Service Bulletins

SFC Specific Fuel Consumption

SG Starter-Generator

SL Service Letters

TC Type Certificate

THS Trimmable Horizontal Stabilizer

TOC Total Operating Costs

TRs Transformer Rectifiers

TRU Transfer Rectifier Unit

UCA Use Case Architecture

US Utilisation Scenario

VFG Variable Frequency Generator

VFSG Variable Frequency Starter Generator

WAI Wing Anti Ice

Chapter 1

Introduction

The modern trend of aviation is pushing the design of new aircraft towards greener concepts. The growing concern about environmental problems, combined with the goal of reducing operating costs, has lead to the research and development of new technologies. Innovative fuels, such as sustainable aviation fuels and hydrogen propelled engines are being tested with the hope to reduce emissions, fuel consumption and operating costs. In this scenario, a revolution is happening also from the On-Board Systems (OBS) point of view. New more efficient technologies are being introduced to reduce the power that has to be taken from the engines. Since electric power generation was found to be more efficient than hydraulic one, some aircraft manufacturers are slowly trying to replace hydraulic power users, such as hydraulic servo actuators, with electro hydrostatic actuators or electro meccanical actuators. Some others instead are working to remove the necessity to spill bleed air from the engines so that they can achieve the same performances with a smaller fuel consumption. Both these philosophies aim to the realisation of More Electric Aircraft (MEA) and All Electric Aircraft (AEA), where electric power is respectively the main or the only form of secondary power.

However, the adoption of such OBS architecture affects operating costs not only because of their power efficiency. The architectural changes inevitably lead also to different maintenance tasks, thus having an impact on maintenance cost as well. Since this cost voice has a great impact into total operating costs over the whole operating life of an aircraft, it's fundamental to evaluate this quantity starting from the early design stages. A sufficient number of Cost Estimating Relationships (CERs) assessing maintenance cost has been developed in the past and several methods are available in literature to evaluate this expense for conventional aircraft. Unfortunately, when talking about MEA and AEA way less material and knowledge is available on the topic. Very few CERs are able to address maintenance costs for the aforementioned innovative aircraft concepts and none of them is recent enough to provide accurate results which can be suitable to fit modern aviation maintenance standards and techniques.

Therefore, the goal of this work is to investigate Maintenance Man Hours (MMH) variations due to different OBS architectures in MEA or AEA configurations. The focus hereby is on modern technologies and maintenance procedures of different architectures during the preliminary design phase, when major design choices are made. During this phase, only general information on a high architectural level are available, which is why this study considers only the case when little data is available. By the development of a Maintenance Man Hour Estimating Relationship (MMHER), this study provides a tool, to accurately estimate the maintenance required for different A320 MEA and AEA OBS architectures.

In order to generate this relationship, two different methods were applied to generate a sufficient data basis. Within the first method, a document-based bottom-up approach has been followed. By analysing the A320 Maintenance Planning Document (MPD) it has been possible to link every maintenance task to its corresponding system and to estimate the required MMH per system. By doing so, it has been possible to identify those tasks that have to be removed if electric components and systems are replacing the conventional ones. This allowed the MMH variation evaluation for a set of MEA and AEA presenting different levels of OBS electrification. The second method instead followed an experience-based approach. A series of interviews to maintenance and OBS experts has been conducted to determine the MMH variations of the same architectures analysed with the first method. Finally, the results coming from the two methods have been combined and exploited to generate a MMHER.

Lastly, a set of Use Case Architectures (UCAs) has been selected and two sensitivity analysis on the hydraulic power system and the pneumatic system have been performed to identify the architecture with the greatest MMH reduction and the most convenient system to electrify first.

The remainder of this thesis presents is structured as follows: Chapter 2 contains the literature review, presenting an overview of concepts regarding aircraft maintenance, the estimation of its cost and a more detailed presentation of the different MEA concepts. Chapter 3 collects the detailed description of the OBS architecture that were used as a basis for the present work, as well as the identification of the contributions of each subsystem to the final maintenance effort variation. Moreover, the architecture generating software, ADORE, is here introduced and a model of the A320 OBS design space is presented. In addition, the expert interview procedure is described and the opinions are collected, presented and compared to the results that were already obtained. Chapter 4 focuses on the MMHER definition, while its application to several case studies is presented in Chapter 5. Finally, the main findings and the conclusion of this thesis are exposed in Chapter 6, where suggestions about future works and expansions are proposed as well.

Chapter 2

Literature Review

The knowledge basis upon which the present thesis stands will be presented in this chapter. A general review about Life Cycle Cost (LCC) and maintenance cost estimation techniques will be shown in Section 2.1, while more detailed information about aircraft maintenance will be given in Section 2.2. Section 2.3 will focus on explaining the most important On-Board Systems (OBS) for the objective of this work, while the aircraft configurations this thesis deals with will be illustrated in Section 2.4. Finally, the science gap this study wants to fill and the relative research questions will be presented in Section 2.5.

2.1 Maintenance cost estimation methods

In order to fully understand the main goal of this thesis it's necessary to introduce the concept of Life Cycle Cost, which is "the total cost incurred by an item along its entire life (life cycle)"[1]. Furthermore, it's also important to have a clear idea of the magnitude of maintenance costs among all the costs voices that contribute to the LCC, and more in precisely to the operating costs, of an aircraft.

By looking at the Cost Breakdown Structure (CBS) of an aeronautical product LCC we can have a clear idea of what cost voices are involved in the determination of the expenses from the design to the disposal phase. In fact, as illustrated in Figure 2.1, the CBS is the partitioning of the overall expense required during the whole life cycle of a product into smaller more specific cost elements [2].

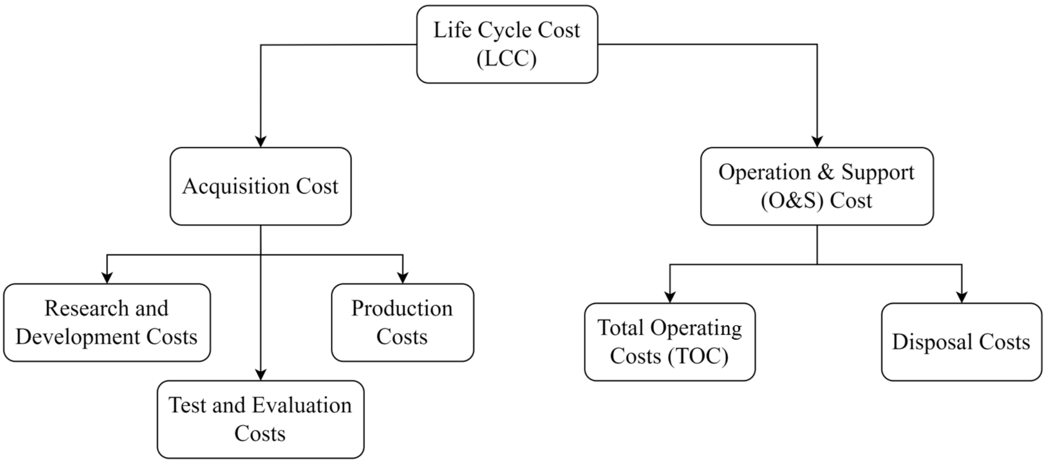


Figure 2.1: Life Cycle Cost

In particular, as reported by Roskam [3], Suwondo [1] and other sources [2][4][5], even if operating costs are highly variable and have a strong correlation to each individual aeronautic product design and operating scenario, usually they represent the biggest contribution to the LCC of a successful aircraft, often being even bigger than the sum of the remaining expenses.

Analysing operating costs more in detail, according to Heisey [6], as reported by [7], maintenance expenses typically represent 10-20% of Direct Operating Costs (DOC), but they can reach even higher values, as shown by [1]. The uncertainty in defining the Direct Maintenance Costs (DMC) is due to the fact that, as being part of the operating costs, they are highly dependent on aircraft utilisation as well. Indeed, Flight Hours (FH) have been identified as the most significant cost driver for this expense [8].

Since the great relevance of maintenance costs among DOC, it's fundamental for the aircraft manufacturers to accurately evaluate such costs during the development of future projects. In fact, the possibility to make use of cost estimation techniques can guide their choices during the different design phases, hence determining the goodness of an aeronautical product since the very early stages of its development.

In the following sections a more detailed overview of the CBS of the LCC will be given, as well as a general overview on the state of the art cost estimation techniques and, more specifically, DMC ones.

2.1.1 Cost Breakdown Structure

As Suwondo states [1], in the case of an aircraft, the first division occurs between acquisition costs and exploitation (or Operation and Support (O&S)) costs.

The former occur prior to the entry into service of the machine and can be divided in Research, Development, Test and Evaluation (RDT&E) costs and production costs. The latter, instead, collect all the expenses related to the aircraft after the beginning of its operation. Among exploitation costs three major categories can be distinguished: operation costs, maintenance costs and retirement (or disposal) costs. In Figure 2.2 it's possible to see how in the operating phase, the Total Operating Costs (TOC) can be further divided in DOC and Indirect Operating Costs (IOC). In particular, DOC strictly depend on the aircraft utilisation, such as pilots and crew salaries, maintenance and fuel and oil expenses. On the other hand, IOC represent those cost voices who are linked to the aircraft but not directly related to its flight schedule. Some examples of IOC are machine depreciation or rent, traffic servicing, general and administrative expenses or advertisement and promotion. Maintenance costs don't fall entirely into DOC but there is still a percentage that is part of IOC, so it is possible to distinguish between DMC and Indirect Maintenance Costs (IMC). The former directly derive from maintenance actions, in terms of Labor Cost (LC) and Material Cost (MC), while the latter are those costs linked to maintenance but not strictly related to one maintenance intervention, such us the purchase of tools, testing instruments, facilities, administration expenses and so on.

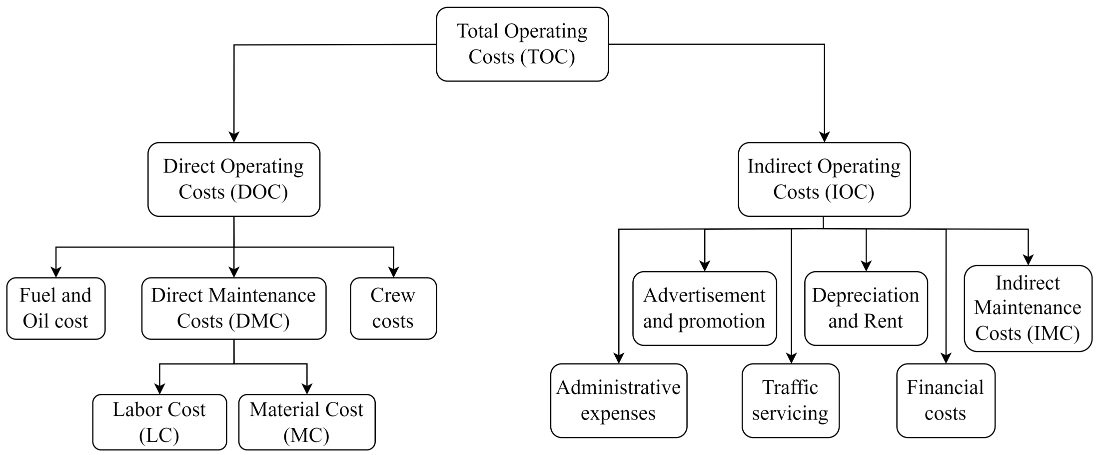


Figure 2.2: Total Operating Cost Breakdown Structure

2.1.2 Cost estimation techniques

Accurately understanding the cost elements that will arise during the life cycle can determine the success or the failure of an aerospace program. For this reason, many cost estimation techniques have been developed. An exhaustive grouping and explanation of the main techniques is presented by Niazi et al. [9]. As show in

Figure 2.3, the main partitioning presented in his work is between qualitative and quantitative techniques. Qualitative techniques are based on the analogy principle between the future project to be developed and past projects. In particular, the case-based and the regression analysis methods fall into this category. They are both based on the concept of linearly escalating the costs from a database of past projects to obtain a rough estimation of the new one's costs in a reasonably quick time and without needing too much data, making them suitable for the very early design phases. On the other hand, quantitative techniques, such as the parametric cost estimation techniques and the breakdown approach, are more accurate but they require a greater amount of time and information to be exploited.

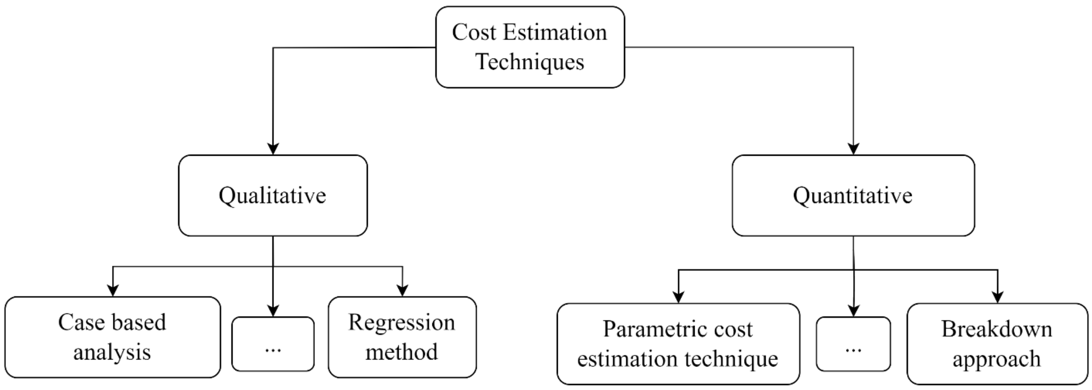


Figure 2.3: Cost estimation techniques breakdown

In particular, the breakdown approach is based on the detailed division of the product cost into smaller cost elements, thus requiring an advanced knowledge of the final components that will be needed. This feature guarantees a highly accurate result at the end, but makes it inapplicable for the preliminary design phase. On the contrary, the parametric cost estimation technique relies on the exploitation of a historical cost database that includes a wide range of past projects, even if with different features from the project of interest (contrarily to the case-based technique). Driven by the assumption that the same factors that affected cost in the past will continue to affect future costs [2], a set of physical characteristics is chosen to represent the *cost drivers*. When all the independent cost variables have been selected, the best Cost Estimating Relationship (CER) that interpolates historical cost data with the highest correlation and the least variation will be picked.

2.1.3 DMC estimation methods

Many authors in the past used one of the previously mentioned methods to come up with an estimation of DMC in the preliminary design phase. A good and wide overview of these works was carried out by Dell'Anna [10] and a short summary of the most relevant works related to the objective of this thesis will be provided in this section.

Looking at the parametric cost estimation techniques, many examples of CERs can be found in literature, but one of the main issue a cost estimator could face is understanding the real applicability of one method to nowadays aviation programs. In fact, many of the most worldwide spread CERs, such as those coming from the NASA-95 method [11] and the studies of Pearlman and Simpson [12], come from the last century and their accuracy might be affected by technology progress and maintenance procedures improvements occurred since their first publication. As a consequence, during the last years many authors attempted to update the already existent methods or to come up with innovative CERs. In particular, Ren et al. [13] propose a parametric model to estimate DMC which is based on an updated version of the CER provided by [11]. In fact, even if keeping the same CER structure, they updated its coefficients in order to consider the variation of the USD currency value and the different Maintenance Man Hours (MMH) labor rate between 1995 and 2020. Another important contribution to the subject comes from a study of Fioriti et al. [14]. In their publication the authors took as a reference the CER provided by [12], but with the consciousness that it comes from 1960 and thus it was exploiting outdated data that couldn't be adjusted with the escalation of some financial parameters. Therefore, they built a new database with actual DMC data from 2013 that was considering the state of the art maintenance technologies and procedures, and using the same cost drivers of [12] (when possible), they created a new CER. Another positive aspect of this equation is that it is able to provide the same detailed outputs, such us a DMC estimation for the main OBS, as the original CER from [12]. Even if of great importance and actual validity, these studies were carried out by considering conventional OBS architectures. Instead, when talking about More Electric Aircraft (MEA) and All Electric Aircraft (AEA) architectures way less studies are available. A relevant work that deepens the understanding of this subject is the one conducted by Howison and Cronin [15], who did an accurate assessment of a large number of technologies that were being researched at their time and could be exploited in a MEA or AEA architecture. The introduction of the Electro Mechanical Actuator (EMA) technology for the Landing Gear System (LGS), the Variable Frequency Generator (VFG) and the Starter-Generator (SG) technology for the Electric Power System (EPS), as well as the electric compressors for the Environmental Control System (ECS) are just a few examples of how the MEA concept in the 80's was not so much different from actual MEA that are flying nowadays, such as the B787. After considering the maturity and the applicability of each innovation, the authors designed several case studies, sorting them by their short term or far term feasibility. Finally, the impact of each group of technologies was evaluated, providing estimations about operating costs, labor and material maintenance cost. Even if the single technologies that have been introduced are well explained and the feasibility analysis that was carried out is valuable, the results are hard to exploit for three main reasons:

- Not every technology that was exploited made it to the present state of the art in the same exact way as it was described by the authors. Moreover, the obtained results are based on data assumptions of technologies that were far from being fully developed at the time.

- When looking to the results, the contribution of each innovation is hard to separate from the others that have been introduced in the same case study. In fact, maintenance costs variations that are presented as a result are not specifying the individual contribution of each subsystem to the overall variation of a specific case study configuration. Only DOC are divided by ATA chapter, but it's not possible to separate the contribution of maintenance costs from the other operating costs constituting the DOC.

- Lastly, the CER that was exploited is not reported and the cost drivers are not known, thus making any attempt to update it with more recent data impossible.

Since these three main reasons, the results have been considered lacking of accuracy and this study was taken in consideration just from the OBS architecting point of view.

Another innovative analysis in this direction was carried out by the McDonnel Douglas Company in 1992 [16]. In this study a preliminary design of an AEA was performed. The company engineers took the conventional MD-11 as a reference and made a series of OBS modifications in order to completely remove the secondary hydraulic and pneumatic power distribution systems from the original project. As a consequence, the EPS design was carried out with the goal of powering those systems that previously required hydraulic and pneumatic power i.e., ECS, engine starting, Ice Protection System (IPS), LGS and Flight Control System (FCS). Contrarily to the previous study from Howison and Cronin [15], detailed information about the sizing of each subsystem as well as the components' failure rate were reported. Final results comprehend a reliability analysis for each Air Transport Association (ATA) chapter, as well as a LCC and a DMC assessment. Once again, as it was for [15], very likely the results are not so accurate for the state of the art maintenance techniques, and since the CER that was used to calculate

DMC was not reported and it's not known, the possibility to update the results according to the progresses that were introduced in this field later on is excluded.

Vercella et al. [17] proposed a parametric cost estimation model for DOC and IOC for an innovative regional jet. In this study the authors gathered CERs from different sources and adapted them to make them sensible to the new OBS architectures that were introduced in their case study. In accordance with the results of [15] and [16], a reduction in DOC is presented as a consequence of reduced Specific Fuel Consumption (SFC) and DMC due to the advantages of the innovative components that were installed on the reference aircraft. Focusing specifically on DMC, it is possible to notice that no real update is made on the reference data provided by [15], hence this specific cost element may turn out not to be accurate enough for subsequent studies.

Recently a new methodology was proposed by Dell'Anna [10]. In his work a breakdown approach was exploited to estimate the DMC variation due to the introduction of an electric powered FCS and the removal of the Hydraulic Power System (HPS) on a conventional A320. Thanks to the large availability of components and maintenance data regarding his reference aircraft, he was able to trace the variations that occurred back to component level. His work consisted in analysing the A320 Maintenance Planning Document (MPD) and removing the tasks related to those component that were completely eliminated from the conventional architecture (mainly the hydraulic ones) and adjusting the tasks of those components that had to be replaced to implement a more-electric FCS and an improved EPS (i.e., FCS actuators, VFGs and Lithium Ion (Li-Ion) emergency batteries). The task calibration for the innovative components was carried out by using a failure rate based analogy between the conventional components and the more-electric ones. Eventually, it was possible to estimate a MMH variation and, by using appropriate labor rates, the LC for the line and base maintenance as well. Finally, the CER proposed by Fioriti [14] was used to estimate the component maintenance cost and, after integrating the routine maintenance cost, Dell'Anna proposed an overall estimation of the DMC of his case study aircraft.

2.2 Aircraft Maintenance

Among the aeronautical regulating authorities, the International Civil Aviation Organization (ICAO) established the basic concept of *airworthiness*, which is "the status of an aircraft, engine, propeller or part when it conforms to its approved design and is in a condition for safe operation"[18] and the idea of aviation maintenance is grounded in this notion. In fact, maintenance is defined by the European Committee for Standardization as the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”[19].

As reported by Ackert [20], these actions are necessary for three reasons:

- To keep the aircraft in a serviceable and reliable condition as to generate revenue.
- To preserve the value of the aircraft by minimizing its deterioration throughout its life
- To respect the regulatory requirements imposed by the aviation authorities that require to establish an airworthiness maintenance and inspection program in order to issue an airworthiness certificate.

Therefore, airliners have the duty to draft a maintenance program that satisfies, at least the requirements imposed by the law. The Operator Approved Maintenance Program (OAMP) definition process is well explained by [20] and it is reported as follows. The first element that contributes to the definition of such program is the Maintenance Review Board Report (MRBR). This document is provided by the Type Certificate (TC) holder and includes all the basic scheduled maintenance tasks that should be performed for that specific aircraft type. In addition, regulating authorities provide the Certification Maintenance Requirements (CMR) and the Airworthiness Limitations (AL) to avoid the generation of excessively dangerous failure conditions and to prevent the most safety critical components to fail. These three documents are gathered in the MPD, that along with Service Letters (SL), Service Bulletins (SB) and Airworthiness Directives (AD), local regulations and vendor manuals constitutes the OAMP, as illustrated in Figure 2.4.

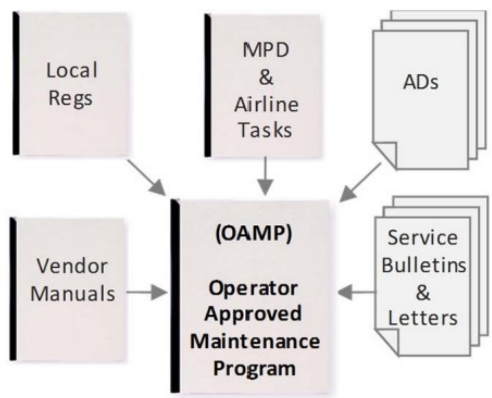


Figure 2.4: OAMP structure by [20]

While the tasks provided by the regulating authorities are mandatory (i.e., CMR, AL, SL, SB, AD) each airliner has the right to chose whether and when to perform those provided in the MRBR and in the vendor manuals [20].

However, scheduled maintenance is just one side of the coin. In fact, alongside with scheduled maintenance, from times to times airliners are called to face also unexpected events that can compromise the airworthiness of their aircraft, such as unpredictable system failures, bird strikes or damages during ground operations. These occurrences require operators to perform unscheduled maintenance which mainly consists of repair activities aiming to restore the original condition of the aircraft [21]. As the scheduled one, unscheduled maintenance also requires material and man work, thus contributing to both MC and LC of DMC.

Depending on the occurrence of each scheduled task, it's possible to group them into different check intervals that require different in-depth inspections accordingly to the frequency they have to be performed with: due to their ease and the accessibility of the involved aircraft zone, some superficial tasks are likely to be performed more often than invasive and detailed operations, thus naturally generating a time-based partitioning of the tasks in different check groups.

A general partitioning airliners tend to adopt is the one comprehending 4 different check types: A-, B-, C- and D-Checks [1]. Each check type contains maintenance actions that require an increasing invasiveness form the A- to the D-Checks.

- A-Checks are performed usually every 750 FH or 750 Flight Cycles (FC) (the first to be reached) [22] and usually require to perform easy and quick tasks, such as visual inspections, fluids level checks and filters replacements.
- B-Checks are no longer commonly used in modern aviation and their tasks have been redistributed between A-Checks and C-Checks.
- C-Checks frequency highly depend on the organisation of each aircraft operator, but they are usually performed in a range between 15 [23] and 24 months [22]. They include accurate testing of many systems, as well as the lubrication of inner components, hence sometimes requiring the dismounting of some parts of the aircraft.
- D-Checks are special C-Checks that have to be carried out usually every 6 and 12 years [22][23]. During these checks the aircraft structure is deeply analysed, requiring as a consequence very long dismounting and testing activities.

In addition to these four tasks groups, there are also pre-flight, transit, daily and weekly checks, which are smaller and faster checks that have to be performed before each flight or on a calendar time basis. These lighter checks are often considered along with the A-Checks, constituting the ***line maintenance***. Since the ease of the involved task, this type of maintenance doesn't require high qualified personnel and can be performed in some dedicated spaces close to the parking area [2]. On the other hand, ***base maintenance***, comprehending the C and D-Checks, requires specific maintenance tools and facilities as well as qualified personnel. This is due to the fact that, contrarily to line maintenance where the main tasks regard visual checks or inspections, during base maintenance activities deep functional and operational checks of the systems are performed, often requiring the dismounting of some parts [24]. Lastly, ***shop maintenance*** gathers all the maintenance activities that require in-depth knowledge of specific components, that can not be repaired locally and need to be then delivered to the component manufacturer.

2.3 On-Board Systems

Aircraft are complex machines for which high performance and safety standards are necessary. Depending on the aircraft size and mission, these requirements may vary, but their respect will generally be ensured thanks to a conventional set of OBS, each of which will contribute to the fulfillment of one or more functions. As a consequence, the implementation of each function is split into different subfunctions that are redistributed among all the different subsystems that are present in a system. Following this logic is easy to understand how many different ways of fulfilling the same function can be implemented, just by organising components and subsystems differently, or by allocating the same low-level function to different components. This complexity led to the need for a common standard to sort and distinguish systems and subsystems in the same way worldwide. Aiming to this goal, in 1956 ATA produced and disclosed the ATA100 partitioning [25], a list of all the systems that can be installed on an aircraft, where each system occupies a dedicated chapter. This sorting system is still valid and used nowadays due to the generic nature of the provided information, which of course outlines the functions linked to each system, but in a way that is open to be reinterpreted in many different concepts, without limiting the system architecting. This feature makes the content of the ATA chapters still applicable to modern systems in every part of the world, even if there are major differences between the OBS architectures for which they were originally conceived and the state of the art OBS. The ATA100 chapters contain many general information about operating procedures, maintenance, aircraft systems, propellers and power plants. A general overview of the chapters partitioning and content is presented below:

- chapters 00-18: useful information about maintenance, airworthiness, ground operations and aircrew.
- chapters 20-49: complete overview of the OBS of an aircraft, from the *power distribution systems* to the *power consuming* (or *user*) *systems*.

- chapters 50-57: grouping of structural components, such as the fuselage, nacelles, pylons and windows.
- chapters 60-67: information about propeller and rotor elements, of relevant interest in the case of helicopters.
- chapters 71-84: listing of the engine related subsystems, such as bleed air, exhaust, oil and starting systems.
- chapters 92-99: focus on military subsystems, such as weapon, crew escape and safety and electronic warfare systems.
- chapter 91, 97, 115 and 116: miscellaneous information about charts, wiring and flight simulators.

Among all the ATA chapters only a few are worthy to be in depth explained for the subject of this thesis. In particular, it's important to mention the air conditioning and pressurization system (ATA 21), the electrical power system (ATA 24), the flight control system (ATA 27), the hydraulic power system (ATA 29), the ice and rain protection system (ATA 30), the landing gear system (ATA 32), the pnuematic system (ATA 36), the auxiliary power unit (ATA 49) and the starting system (ATA 80).

Another typical OBS breakdown is the one adopted by Liscouët-Hanke [26]. In her work she sorts the systems into three categories, based on their function:

- **Power Generating Systems (PGS)**: these systems are designed to contribute to the secondary power supply, which is mainly provided by the engines. The Auxiliary Power Unit (APU) and the Ram Air Turbine (RAT) are two examples of PGS which are employed during on-ground and emergency operations. As reported by [26], even if the battery packs which are part of the ECS have the objective to generate electric power, they are doing it just for a limited amount of time and exploiting a very little consumable energy source. For this reason batteries are considered as a buffering part of the EPS and a PGS on their own.
- **Power Transformation and Distribution Systems (PTDS)**: they comprehend systems such as the HPS, the EPS and the Pneumatic System, which have the purpose to transform the energy extracted from the PGS and deliver it to the Power Consuming Systems (PCS), through a series of regulation processes. In fact, the HPS transforms the mechanical power from the engines and the RAT in hydraulic power by using hydraulic pumps to regulate the pressure and the flow rate of the fluid. The EPS supplies the users with electric power obtained from the mechanical power as well, regulating the properties of the current (Alternate Current (AC)-Direct Current (DC), Low

Voltage-High Voltage). Finally the Pneumatic System transports the bleed air from the engines or the APU and the ram air from the external environment towards the pneumatic users, i.e. the ECS, the IPS and the Starting System, regulating the flow temperature and pressure thanks to dedicated valves and heat exchangers.

- **Power Consuming Systems (PCS)**: these are the systems that exploit the different type of supplied power to accomplish their functions. Some examples of PCS are the FCS, the LGS, the ECS and the IPS.

In the following sections, the aforementioned OBS will be presented in detail starting from the PTDS and proceeding with the PCS.

2.3.1 Electrical Power System

The EPS is described in the 24th ATA chapter and for this reason it is commonly encoded as ATA 24. Its main functions are to collect the energy provided by the engines and the back-up sources (such as the APU and the RAT), then transport and transform it through the distribution lines and finally supply it to all the electric users of the aircraft. Conventional EPS architectures, as those shown in Figures 2.5 and 2.6, adopt several elements to satisfy these requirements:

- **Generators** are installed with the objective to generate electric power by transforming the rotary motion of the engine shaft in high voltage current. In the past, DC generators were used but nowadays brushless AC generators are the most efficient components to generate electric power [27]. The most used solution in commercial aviation is the so called Integrated Drive Generator (IDG) which is an assembly of an AC three-phase generator and a Constant Speed Drive (CSD). The latter is an element able to receive a variable speed motion as an input (which is the case of an airplane engine) and supply a constant speed motion as an output, thus allowing the AC generator to produce constant frequency current. Nowadays, new more efficient technologies are being adopted, such as the VFG. This component is able to convert mechanical energy in variable frequency AC current. The exploitation of this technology was possible because variable frequency current supply is indeed becoming adequate for most of the users, since those requiring constant frequency current are being gradually eliminated. However, until the complete removal of such components the use of this generator will always imply the necessity of installing a complementary frequency converter element, hence increasing the complexity, and consequently reducing the reliability, of the whole system.

- **Batteries** are necessary as redundancies to the generators, since they guarantee the power supply to vital avionic users in emergencies scenarios where both engines and the APU are failed. Their working principle is based on a chemical reaction that transform chemical potential energy into electric energy, thus the importance of the material choice. In fact the materials that are used in a battery determine its performance in terms of specific energy [Wh/Kg], energy density [Wh/m^3] and specific power [W/m^3].

Nowadays, most of the commercial aircraft adopt Nickel-Cadmium (Ni-Cd) batteries, which are known to be reliable even if they don't have great performances. More innovative aircraft are using Li-Ion batteries which have better performances than the Ni-Cd ones. However, their utilisation is very problematic since they tend to overheat and require, as a consequence, a certain number of thermal sensors and a cooling system. These additional components bring the weight and the overall reliability of the battery pack way under the reference values for the conventional Ni-Cd batteries. Nevertheless, many airliners are proceeding to the retrofit of the Ni-Cd batteries in favor of the more innovative Li-Ion ones, thus suggesting that the trade-off analysis is in favor of the latter [28].

The state of the art battery technology is not yet suitable for powering all electrical systems in an aircraft and the sizing of these components is carried out in order to guarantee a power supply to the essential bus as a last resource and for a short amount of time.

- **Bus-Bars** are the elements intended to distribute the generated electric power to the users. Many buses are present in an aircraft, not only as redundancies to improve reliability, but also because currents with different nature or voltage need to be carried on different buses. Hence, it is common to find at least one AC bus and one DC bus on most of the EPS architectures, regardless of the dimensions or the mission profile of the aircraft. Moreover, different buses have also different importance, depending on the safety criticality of the users they feed. In fact, in addition to the main buses that connect almost every electric user, we find find auxiliary buses that supply essential users and emergency buses that connect the batteries to the avionic vital devices.

- **Inverters** and **Transfer Rectifier Units** are components that ensure the transformation of the current from DC to AC and vice versa. Both are necessary in almost every EPS architecture, since the inevitable need to install both AC and DC electric users in an aircraft.

- **Switches** are small elements that consent to properly address the electric power to the different buses in every operating scenario. Thanks to them it is possible to reconfigure the electric power distribution system when some issues arise, prioritizing the energy supply to the most important users.

- **Fuses and Circuit Breakers** represent a safety barrier that protects the electric circuit from unintended and unexpected higher voltage currents. In fact, they absorb the exceeding electric power, minimizing the negative effects on the rest of the circuit. Although the main goal is the same, their working principle is slightly different: while the former destroy themselves when overcharged, the latter can be reconfigured and restored to initial conditions.

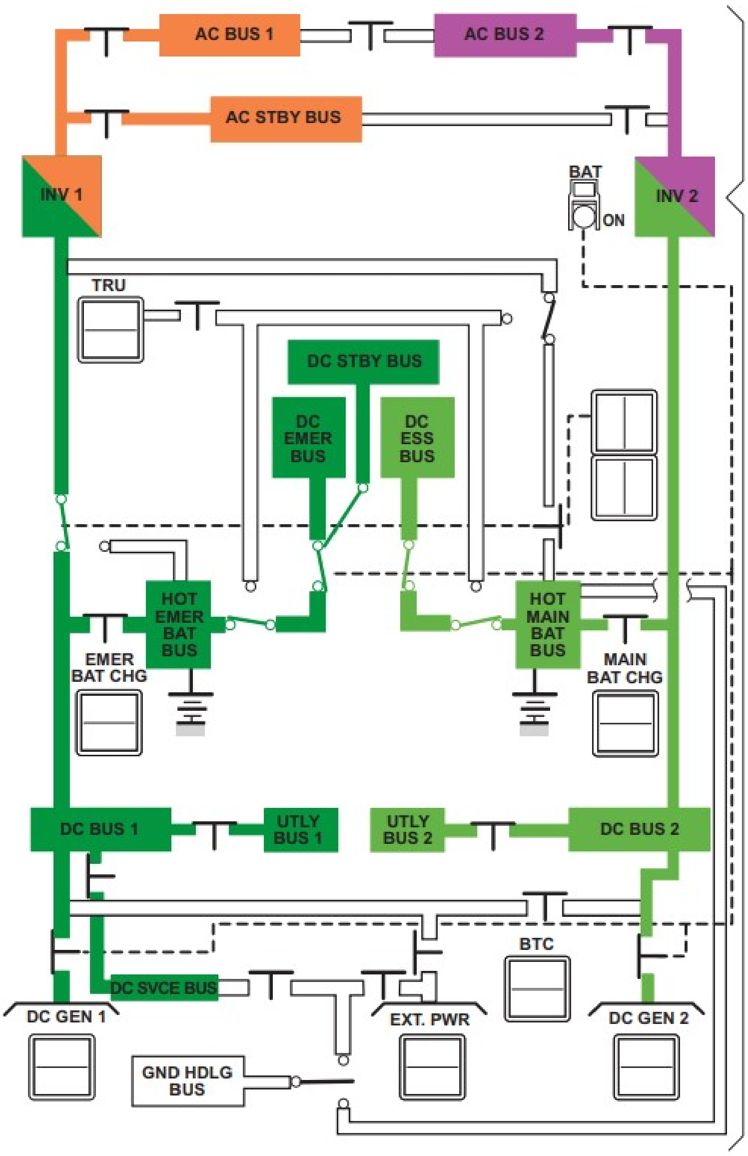


Figure 2.5: ATR42 EPS schematic during normal generation from [29]

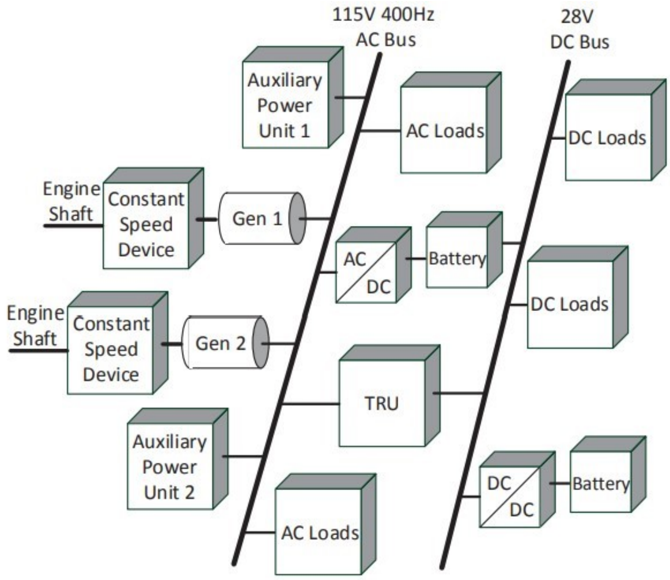


Figure 2.6: Conventional EPS schematic from [30]

2.3.2 Hydraulic Power System

The hydraulic system is described in the 29th ATA chapter and it is commonly referred to as ATA 29. Due to its consolidate utilization in the past and the well known benefits, such as high specific power and high system readiness, hydraulic power is worldwide the most used power distribution system. This technology allows to precisely actuate surfaces and components even under heavy loads, as in the case of the FCS and the LGS. This system may present major differences depending on each aircraft architecture, but there are always some common elements, as can be also seen in Figures 2.7 and 2.8:

- **Hydraulic fluid** is the mean that allows power distribution. Its incompressibility allows the rapid power distribution from the pumps to the actuators, thus providing a quick response of the system. Depending on the operating condition, the chemical composition of the hydraulic fluid to use may slightly change in order to still ensure appropriate viscosity, incompressibility, heat conduction and chemical stability. In fact, one of the main issues related to this element is that if not properly cooled, it tends to form plastic precipitates that might cause system failures.

- **Filters** are necessary to prevent precipitates and other impurities to spread along the hydraulic circuits, causing valves obstructions that finally result in system failures. To avoid this negative occurrence, many filters with different mesh sizes are located just before of any critical element of the hydraulic circuit. Moreover, they naturally provide an easy to read indication on their health status, allowing the possibility to perform on condition maintenance.

- **Reservoirs** are component whose main goal is to store the hydraulic fluid, in order to guarantee its constant availability in different demanding operating conditions. They gather the fluid that comes back from the actuators and the pressure control and relief valves, making it available to be pumped again into the circuit. Usually they are provided with internal flaps to direct hydraulic flow and avoid the formation of gas bubbles. Reservoirs are usually pressurized by the pneumatic system, so that the risk of cavitation is lowered.

- **Pumps** may be of several different types, but they all have the same function: pressurize the hydraulic fluid. The more important pump type is the so called Engine Driven Pump (EDP), because of its direct connection to the engine shaft. The hydraulic system is also provided with other auxiliary and emergency pumps that can be used to reconfigure the HPS when the EDPs fail. In particular, the electric pumps and the RAT pump are installed as redundancies for the EDPs in the case of both engines failure. However, in the case in which just one engine (or the associated EDP) fails, it's worthy noting that a Power Transfer Unit (PTU) can be installed to allow the transferring of hydraulic power between two circuits without any exchange of hydraulic fluid, hence avoiding possible fluid contamination and failure propagation.

- **Accumulators** are safety devices that guarantee a limited quantity of pressurized fluid when several failures lead to the complete depressurization of the hydraulic circuit. These components feed safety critical hydraulic users, such as primary flight control actuators, landing gear actuators and brakes. Moreover, they supply additional hydraulic power in high demanding non recurrent flight phases avoiding the necessity to oversize the system in the design phase.

- **Valves** have the purpose to regulate the fluid flow rate and pressure, guaranteeing the proper control action of the actuators and the safety integrity of the system when overpressurization and pressure loss events occur. Their design is done in order to prevent the fluid from reverse flowing, allowing the possibility to reconfigure the system when a failure is isolated and some elements need to be excluded from the circuit.

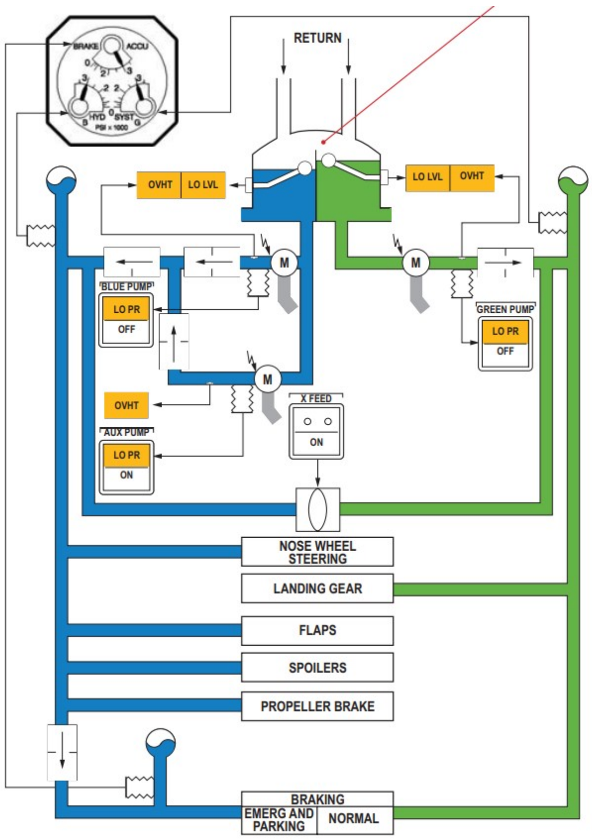


Figure 2.7: ATR42 HPS schematic from [29]

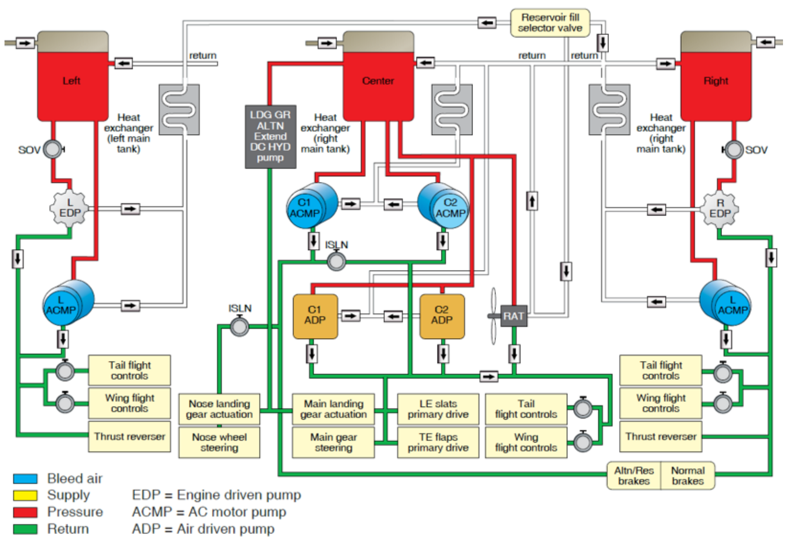


Figure 2.8: B777 HPS schematic from [31]

2.3.3 Pneumatic System

This system is discussed in the 36th ATA chapter, hence it is commonly classified with the ATA36 code. Pneumatic System has the important function to regulate and distribute bleed air from the engines to the ECS and IPS users. In addition, the pneumatic system must provide pressurized air both to fuel tanks and hydraulic fluid reservoirs for safety related purposes. Moreover, a small amount of bleed air is also needed to pressurize water and waste circuits. Pneumatic system comprehends several regulation valves, heat exchangers and filters to guarantee that the air is provided with the proper pressure, temperature and chemical composition.

In Figure 2.9 the Pneumatic System of the B737 is shown as an example.

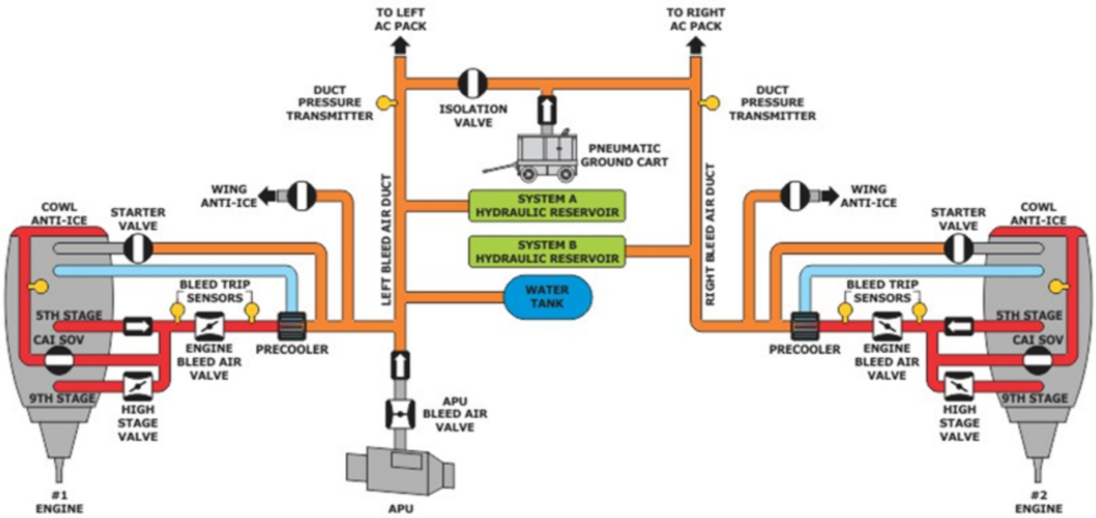


Figure 2.9: B737 Pneumatic System from [32]

2.3.4 Flight Control System

The ATA chapter associated to this system is the 27th, so it is commonly encoded as ATA 27. The Flight Control System is responsible for the ability to control the flight of the aircraft in terms of attitude and trajectory. Even though in the past the accomplishment of this function was fulfilled by a quite simple assembly of levers and pulleys, directly transferring the mechanical power from the pilot to the control surfaces, nowadays many components and several subsystem are required. Since the growing dimensions and speed of airplanes, modern aircraft could no longer be mechanically controlled in normal operations. This technology, which is still used as a backup for small commercial [33] and many general aviation vehicles, has been replaced by hydraulic actuation. The use of pressurized fluid, in fact, guarantees aircraft control even under higher external loads, unlocking the possibility to travel faster while carrying bigger payloads. Despite the advantages, the need of hydraulic power increased the system complexity of airplanes leading to greater weights and maintenance costs. This issue was partially solved by introducing the Fly-By-Wire (FBW) concept [34] where the mechanical command line is replaced by a digital signal [35], as schematized in Figure 2.10. Thanks to this technology pilots inputs are digitally encoded and transmitted to several Flight Control Computers (FCCs), which elaborate the information and provide the proper command to the actuators via electric signal. This technology allows fuel saving by smoothing pilot inputs and enhances safety thanks to the fact that the FCCs are programmed in order to never let the aircraft exceed its flight envelope. As reported by [36], more recent researches are seeking the application of the Fly-By-Light (FBL) concept, an advanced version of the FBW technology where the electric wires are replaced by optic fiber. This new material in fact is not only lighter than copper wires, but it is also not sensitive to electromagnetic disturbances, enhancing safety and security, especially in warfare applications.

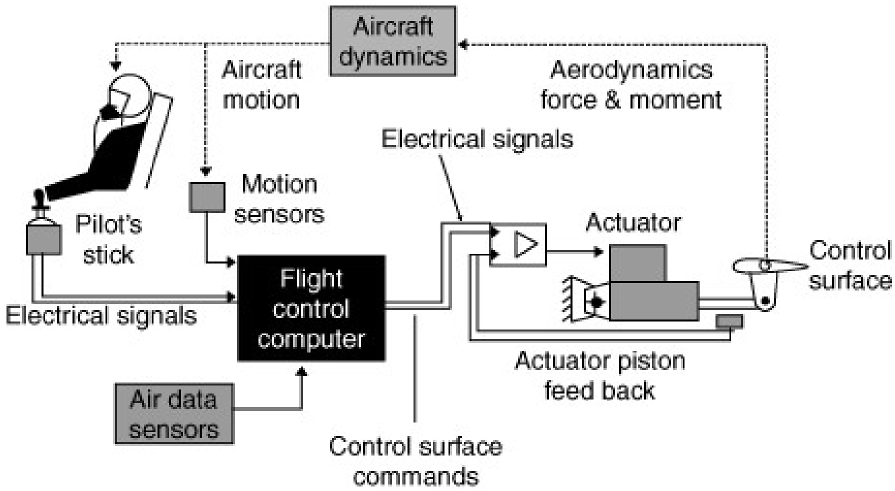


Figure 2.10: FBW schematic from [37]

Control surfaces

The flight control function is exploited thanks to the deflection of control surfaces, which are shown in Figure 2.11. They can be divided in *primary* and *secondary* control surfaces [34], depending on their importance. The former operate during every moment of the flight since they have the important role of regulating the aircraft attitude by controlling yaw, pitch and roll rates. Yaw control is mainly performed by the rudder, a movable surface located in the trailing edge of the vertical fin and controlled by the pilots through the pedals. Instead, ailerons are located at the trailing edges of the last wing sections, close to the tips, and their deflection commands the aircraft roll rate. Their movement is almost perfectly anti-symmetrical and it is regulated by a lateral inclination of the pilots' stick or by the rotation of the yoke. Lastly, the elevator is located at the trailing edge of the horizontal tail plane of a conventional tail configuration and its deflection regulates the pitch rate. Pilots control the pitch rate by moving longitudinally their command stick or by pushing and pulling the yoke. On the other hand, the secondary surfaces are not activated during all mission time, since they have the goal to alleviate pilot workload, allowing better aerodynamic conditions only during take-off and landing, the most delicate flight phases [34]. More specifically, the Trimmable Horizontal Stabilizer (THS) is a moving surface that allows the pilot to perceive the proper amount of feedback on the stick in every payload distribution configuration. Flaps and slats are the so called *high-lift devices*, and have the objective to improve the aerodynamics of the aircraft during low-speed flight phases, such as take-off and landing. On the contrary, spoilers and speed breakers are secondary control surfaces that are intentionally worsening the wing aerodynamics in order to quickly lose speed and altitude when needed.

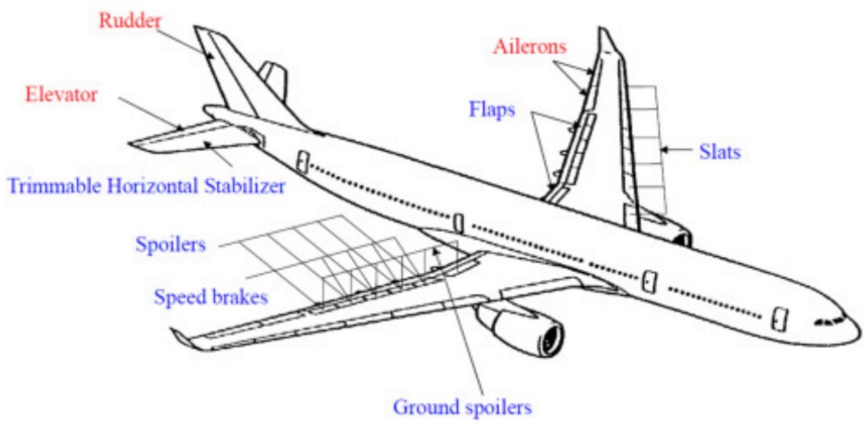


Figure 2.11: Conventional FCS surfaces from [38]

Actuators

FCS actuators are special devices needed to implement the accurate deflection of the control surfaces. The Hydraulic Servo Actuator (HSA) is the most common actuator type for the primary flight control surfaces and the spoilers. Its working principle exploits the hydraulic power provided by the HPS and they usually present three stages, hence taking the name of *three stage actuators*. The first stage is an electric motor that receives a current input and controls a hydraulic servovalve. The goal of the servovalve, which is the second stage, is to regulate the flow of the proper amount of pressurized hydraulic fluid to the jack chamber, which represents the third and final stage.

During the past, flaps and slats used to be actuated with HSAs, as in the case of the ATR42 [29] and the B737 Krueger flaps [39]. Nowadays, a different solution is being implemented: one Power Drive Unit (PDU) commands the rotation of two flaps-dedicated or slats-dedicated shafts (one for the left and one for the right side of the wing) and one ballscrew actuator on each high lift surface transforms the rotary movement of the shaft into linear displacement. As a consequence, all the surfaces are being extracted simultaneously and symmetrically. The application of this architecture on the Embraer 190 is shown in Figure 2.12.

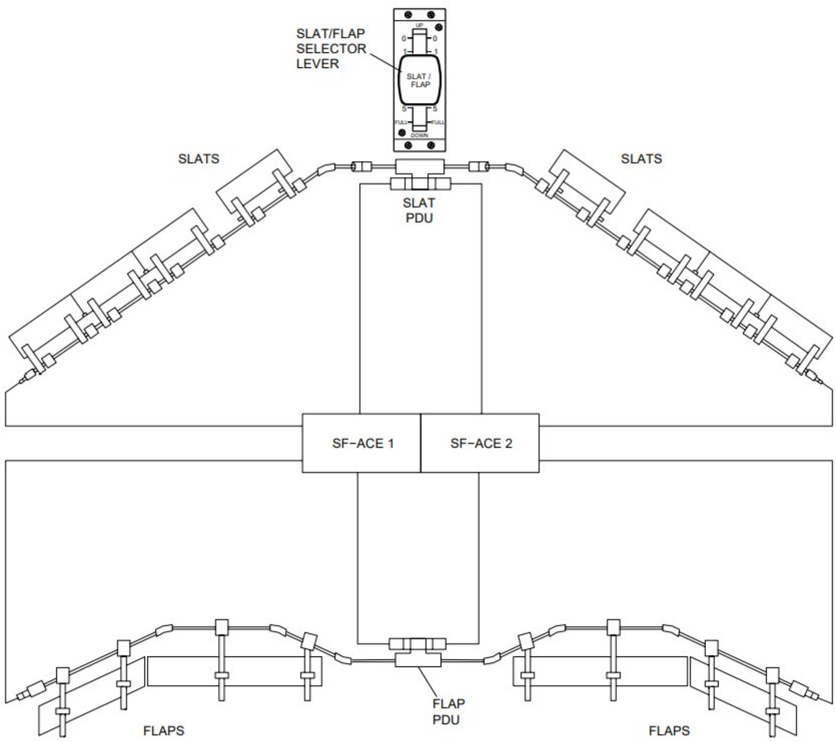


Figure 2.12: High lift devices mechanism from [40]

Conventionally, the PDU is an assembly of two hydraulic motors driving the shafts either directly or through a gearbox, as in the case of the A330 [41] and the B737 [39] (except from the Krueger flaps). However, innovative more electric architectures for this component have been developed: for example, the A380 and the B777 are equipped with hybrid PDUs [42][43], while the Embraer 190 presents an all electric PDU [40]. As illustrated in Figure 2.13, the former feature both one hydraulic and one electric motor, while the latter presents two electric motors.

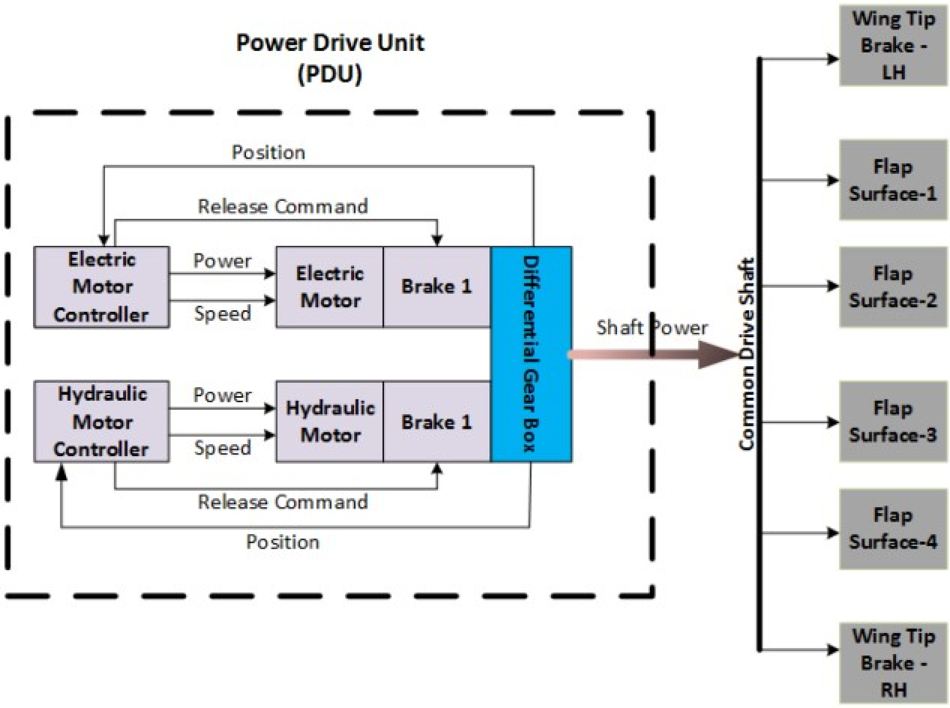


Figure 2.13: Hybrid hydraulic/electric PDU concept from [42]

During the years different types of actuators have been researched and tested. Among those, the Electro Hydrostatic Actuator (EHA) is worth to be mentioned as a valid alternative for the HSA. The adoption of this kind of actuators will allow the removal of the centralized hydraulic circuit. In fact, their working principle relies on a miniaturized hydraulic circuit, locally pressurized by an electric pump, and both components are part of the actuator itself. For what concerns the secondary flight controls, a more electric alternative is represented by the EMA, a particular device that transforms electric power in mechanical power without the need of any hydraulic fluid. EHAs are more reliable than conventional HSAs [44], and their utilization is slowly taking ground in aviation. A first step towards the implementation of this technology has been made by the installation of Electrical Backup Hydraulic Actuator (EBHA)s in the A350 and the A380. The special characteristic of these actuators is that, although they work primarily as HSAs, they have the possibility to be reconfigured in case of failure, beginning to work as EHAs. A clear illustration of such technologies is provided in Figure 2.14.

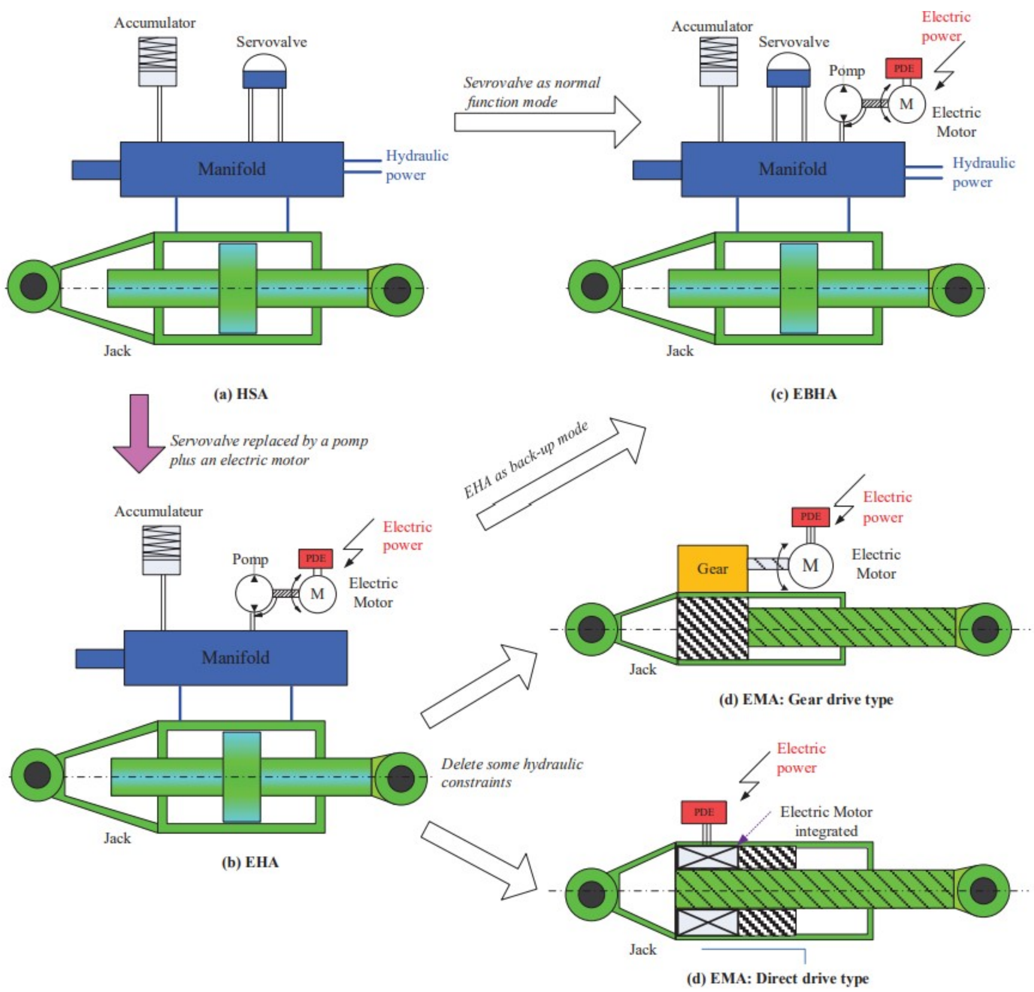


Figure 2.14: Actuator types from [45]

2.3.5 Landing Gear System

The information about the LGS is contained in ATA chapter 32, hence the code of this system is ATA 32. The LGS has the crucial role to support the aircraft vertical loads during take-off, landing and all the on-ground operations. Moreover it is responsible for the braking and steering functions, which are crucial both to ensure safety during take-off and landing and while conducting ground operations. To fulfill its function, the LGS presents one or more shock absorbers and several wheels on each leg, as well as braking and steering actuators for the respective functions [46]. As shown in Figure 2.15, conventionally all the LGS actuators are hydraulically powered, but in MEA architectures, as in the case of the B787, some of them can be replaced by electrical actuators [47].

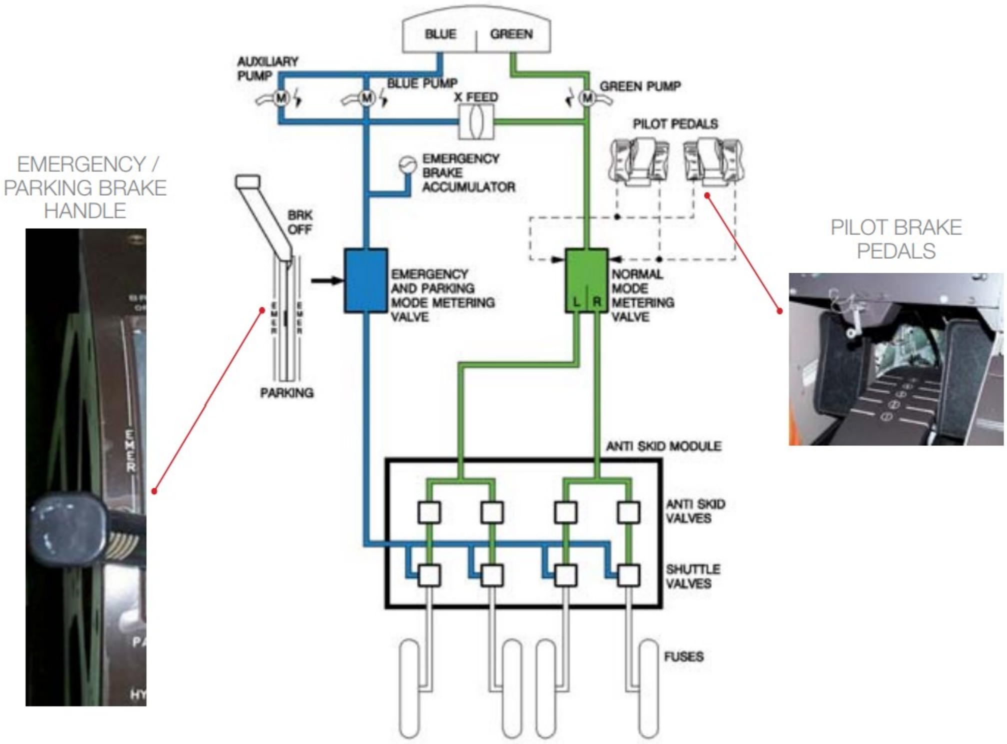


Figure 2.15: ATR42 LGS from [29]

Due to the big dimension and its exposition to the external air, the LGS is responsible for a great aerodynamic interaction that causes high drag. For this reason commercial aircraft are provided with a mechanism that retracts the landing gear inside the fuselage or the wings. This choice leads to the necessity to allocate big vanes inside these areas, which can represent a though challenge for aircraft designers. Moreover, bay doors must be actuated as well in order to close the vanes after the landing gear retraction and improve aerodynamic performances. Aiming to lighter solutions, as shown in Figure 2.16, in some aircraft the wheels themselves constitute a big portion of the landing gear bay cover. During the extraction, the gears are subjected to high aerodynamic forces and there is the risk that they will not stay perfectly in position when landing. For this reason big actuators are needed to contrast aerodynamic loads as well as safety pins to retain them in the proper position in the case of a hydraulic failure involving the actuators. Moreover, ground lock safety devices are installed to avoid the landing gear accidental retraction when the aircraft is on ground.

(a) B737 **(b)** ATR42

Figure 2.16: B737 and ATR42 main landing gear wheels in retracted position from [48]

Braking capability is ensured by an assembly of several rotor and stator discs on each wheel. When braking, a hydraulic actuator squeezes the the discs together, hence reducing the angular velocity of the wheel. An anti-skid device measures this physical quantity and when it is lower then a threshold value, hydraulic pressure in the braking circuit is relieved, avoiding the wheel to skid without rolling.
After the landing, when the brakes are cooled, it is usually possible to isolate braking hydraulic circuits by activating the parking brake. This way, the aircraft is sticking to the ground even if the main hydraulic circuits are depressurized (for example for maintenance purposes). A schematic of the hydraulic circuit implementing the antiskid and parking braking function is shown in Figure 2.17.

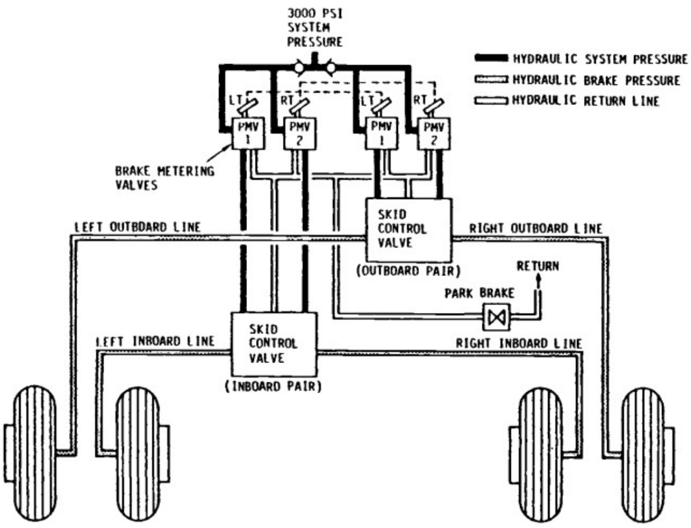


Figure 2.17: Conventional antiskid hydraulic circuit from [46]

Steering function is usually fulfilled by the nose gear, where a rotary gear transforms the linear motion of one actuator in the rotary motion of the nose leg. More complex hydraulic actuators may be installed for big and heavy aircraft. For example, the A380 presents a hydraulic steering actuator linked the the nose landing gear by two flanges and a collar [49]. In addition to this mechanism, the last wheels of the main landing gear are actuated to steer, giving better on-ground mobility to the aircraft. A steering contribution can be provided also by differential braking, which is regulated by rudder pedals when the aircraft has the wheels on the ground.

2.3.6 Air conditioning and pressurization system

The air conditioning and pressurization system, most commonly called ECS, ensures that the crew and the passengers operate in an in-flight environment which is adequate to human physiologic life conditions. The ATA chapter associated to this system is the 21st, so it is commonly encoded as ATA 21. Regulating authorities provided a set of strict requirements on temperature, pressure, humidity and chemical composition of cabin air [32]. Since these parameters heavily effect crew efficiency and passenger comfort, they are strictly controlled and monitored in order to always respect the limits imposed by law.

In conventional ECS architectures, as those shown in Figures 2.18 and 2.19, cabin pressurization is performed by spilling a fraction of compressed air from the compressor stages of both engines. This practice is generally called *bleeding*. The bleed air is then processed through a series of valves and heat exchangers. The former ensure the air to be at the optimal pressure for humans comfort and aircraft structural integrity, while the latter contribute to guarantee the supply of fresh air at the proper temperature.

Generally the sizing of the ECS depends on two cases: the cold case and the hot case [32]. The cold case verifies when external environmental condition and on board heat generation combine to generate the greater heat flow leaving the aircraft. This happens usually during the cruise of transport flights at night, where the external temperature is under 0°C and neither the passengers or the sun can heat the cabin. In order to respect the requirements in the cold case ECS have been provided with a by-pass valve, that allows a portion of the flow to skip the cooling stage in the heat exchangers, thus raising the supplied air temperature. On the other hand, the hot case verifies on ground, when the aircraft is crowded and fully exposed to the sun during the hottest hours of the day, and it is critical for the sizing of the cooling packs. Cabin pressurization and fresh air supply is granted even in the case of an engine failure, thanks to a cross-bleed valve that allows the pressurized air of the operating engine to flow into the pneumatic circuit of the failed one.

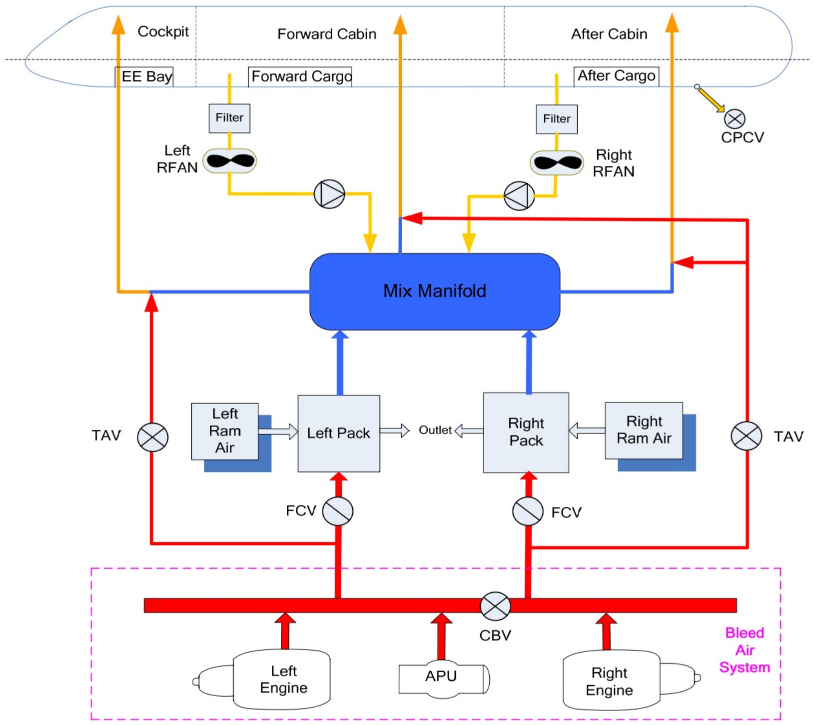


Figure 2.18: Conventional ECS schematic from [50]

Lastly, air quality is ensured by several air filters, guaranteeing that impurities from the external environment don't break through the cabin.

However, not all bleed air is used for environmental control purpose. A fraction of spilled air is diverged from the cabin to the leading edges of wing and tail surfaces and towards engine nacelles. This is done in order to heat the aforementioned surfaces and preventing the formation of ice, which will dramatically reduce engines performances and the aerodynamics of wing and tail [51]. The architecture of the IPS will be postponed to the following chapter.

As one may imagine, removing processed air from the engine leads to a performance deficit, hence implying a higher SFC. Innovative solutions are being explored, especially by Boeing. In fact, the company developed an electrified ECS and IPS, that don't require anymore the engine bleed for cabin pressurization and thermal control, hence taking the name of *bleedless* architecture. The crucial role of the engines in the ram air pressure enhancement is now carried out by a set of additional electric compressors. This choice brings several advantages: electric power generation is more efficient than pneumatic power one [52], implying lower energy required and consequently a lower SFC; in addition, the electric compressors are closer to the air conditioning packs, with respect to the traditional

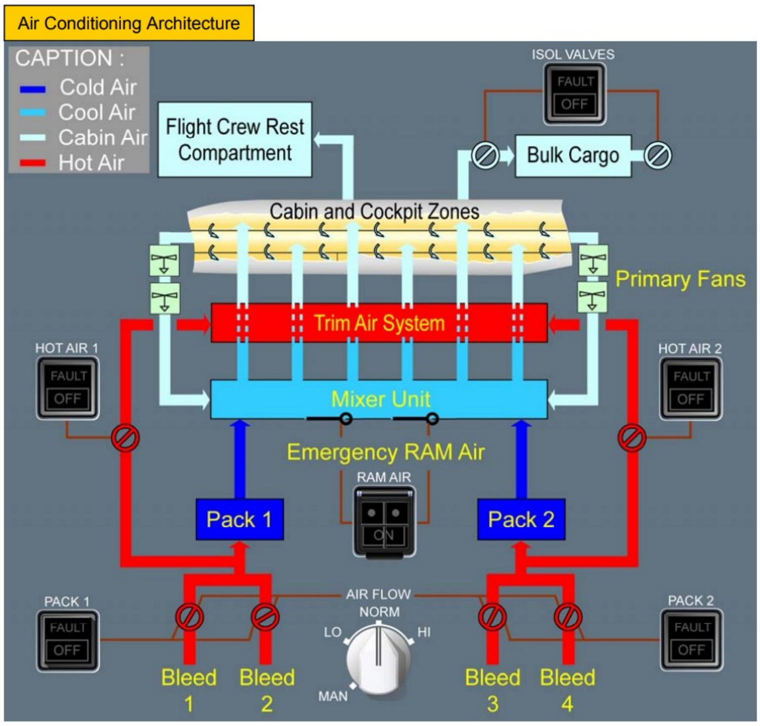


Figure 2.19: A380 ECS architecture

wing mounted engines, leading to a dramatic reduction of the pneumatic pipes length; independent compressor control allows the removal of several pressure regulation valves, such as by pass valves, cross-bleed valve and flow control valves. The removal of such components is globally leading to a more efficient ECS and a lighter aircraft, decreasing operating costs consequently.

Unfortunately, this solution leads also to several disadvantages: the need for ram air inlets spoils the fuselage surface implying higher drag, while the presence of new safety critical elements, such as the dedicated ram air compressors, inevitably comes with higher maintenance cost and increased weight, hence reducing the saving from the removal of the traditional components [53].

2.3.7 Ice and rain Protection System

The 30th ATA chapter contains information about the IPS, so we usually recall this system with the ATA 21 code. Facing the external environment during a flight represents a challenge for some aircraft components. Very low temperatures and humidity can cause the formation of ice in some areas where typically air stagnation occurs [51]. This is the case of wing and tail leading edge, as well as external probes and engine nacelles. The presence of ice spoils the aerodynamics, leading to worsened engine and wing performances. Moreover, it can obstruct probes, causing wrong data reading. One possible solution to prevent ice formation is to heat the sensible components. Traditionally, IPS uses pneumatic or electric power for this purpose, depending on the size of the heated item. For small elements, such as the probes, it is sufficient to provide heat with electric resistances, exploiting the Joule effect. For what concerns the engines cowls and the leading edges, pneumatic power is more suitable. Engine nacelles are heated thanks to dedicated hot air bleed valves in the engines, while instead the wing and tail ice protection, illustrated in Figure 2.20, uses a fraction of the bleed air spilled for cabin pressurization and heating purposes.

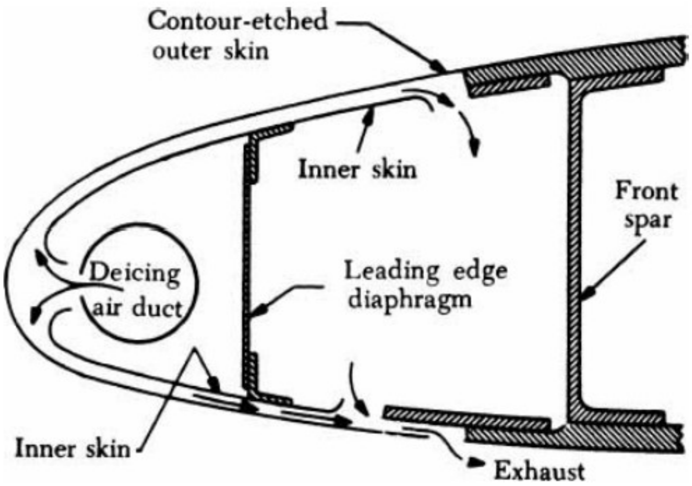


Figure 2.20: Leading edge conventional pneumatic anti-ice from [54]

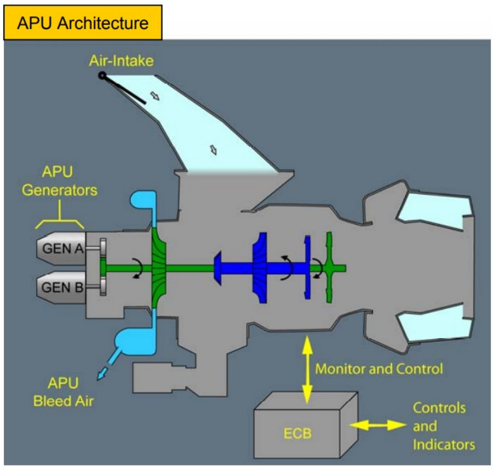
Alternatively, non conventional IPS technology have been developed. Some of them still exploit pneumatic power and some others rely on an electric power supply. An example of the former is the pneumatic deicing boot. In this case, bleed air is periodically used to temporarily inflate a dedicated air chamber in the wing leading edge. The rapid expansion of this chamber causes the ice detachment from the wing surface. On the other hand, Electro-Mechanical Expulsion De-icing System (EMEDS) and Electro-Impulse De-icing System (EIDS) are two examples of more electric IPS technologies [51]. The former is based on the concept of several small electric actuators that shakes the leading edge with a high frequency, resulting in a vibration that detaches the ice layer. The latter instead involves the installation of several layers of different conductive metals in the leading edge skin. An electric impulse then generates repulsive electromagnetic forces in the skin layers that cause an instantaneous deformation of the surface, detaching the ice layer.

2.3.8 Auxiliary Power Unit

Information about this system is contained in 24th ATA chapter and for this reason it is commonly encoded as ATA 24. As can be seen in Figure 2.21, the Auxiliary Power Unit is a small dimension auxiliary engine that has many purposes depending on the operating conditions of the aircraft. The most common APU use is to provide electric power when the aircraft is on-ground and the engines are not working [55] . The power generated by the APU will be mainly used to power the ECS, avionic systems and cabin lights. Moreover, when electric starting is not available, the APU has the crucial role to provide pressurized air to the engine dedicated starting turbine. In this case, a very high percentage, from 70 to 80%, of air will be bled from the thermodynamic cycle of the APU and will be sent to the engines.

This component has a crucial role in aircraft reliability assessment. It serves as an emergency generator for the EPS when both engines are out of use and allows to try an engine restart after a recoverable failure event.

APU is not provided with independent fuel tank, hence linkages must be designed in order to feed the APU with fuel from the wing tanks.



(a) A380 APU schematic

(b) B737 APU

Figure 2.21: Conventional APUs

2.3.9 Starting System

Since the starting system is located in the 80th ATA chapter, its reference code is ATA 80. The starting system has the function to start the main engines. Traditionally, this operation is done by electrically starting the APU and spilling a certain amount of pressurized air to feed an engine dedicated air turbine starter.

This component is mechanically linked to the engine gearbox, driving the rotation of the shaft until the airflow condition inside the combustion chamber are good enough to allow the ignition and consequentially the engine start [34][56]. When an adequate ground equipment is available at the airport, the APU bleeding is replaced by the supply of a dedicated ground compressor. However, this is not the only mean to perform the engine start. For example, the B787 is provided with SGs, a particular type of AC generators that is also able to work as electric motor, driving the rotation of the engine shaft and allowing to start the propellers without any bleed supply.

2.4 Aircraft Configurations

In this section several OBS architectures from different aircraft will be presented. Starting from a conventional architecture in Section 2.4.1, it will be then presented a few examples of the state of the art MEA and AEA concepts. In particular, after a brief general explanation of the MEA philosophy in Section 2.4.2, the A350 and the A380 most relevant systems architectures will be shown in Section 2.4.3. Afterwards, a different MEA application will be discussed in Section 2.4.4, where the B787 architecture is presented, and finally, in Section 2.4.5, an AEA architecture will be discussed. It's worthy noting that while the first four cases represent currently flying aircraft, the last OBS architecture concept is beyond the state of the art, since no AEA has been developed yet.

2.4.1 Conventional Aircraft: A320

The Airbus A320 is a conventional narrow-body twin engine commercial aircraft. It has a long service history, over 40 years since its first deliver on 1988 [57], and its worldwide utilisation enabled it to reach some prestigious milestones, such as being the world most adopted aircraft in 2019 [58]. For these reasons, the A320 was chosen to be the reference point from where explaining the conventional OBS architecture and the basis upon which the present work has been carried out.

Electric Power System

As shown in Figure 2.22, the A320 EPS is based on a conventional architecture. All the information provided for this system comes from [59], where this system is explained in detail. For what concerns the generation, one IDG on each engine and the APU generator provide 115/200-Volt 400Hz three-phase constant frequency AC. Each of the three-normal generators provides up to 90kVA and is able to feed all the aircraft electric users. When normal generation fails, an emergency generator powered by the blue hydraulic line provides emergency AC generation up to 5kVA. If the emergency generation also fails, DC power from two Ni-Cd 23Ah batteries can be transformed in AC power for essential users by one static inverter. For ground operations, an external electric power connector is available.

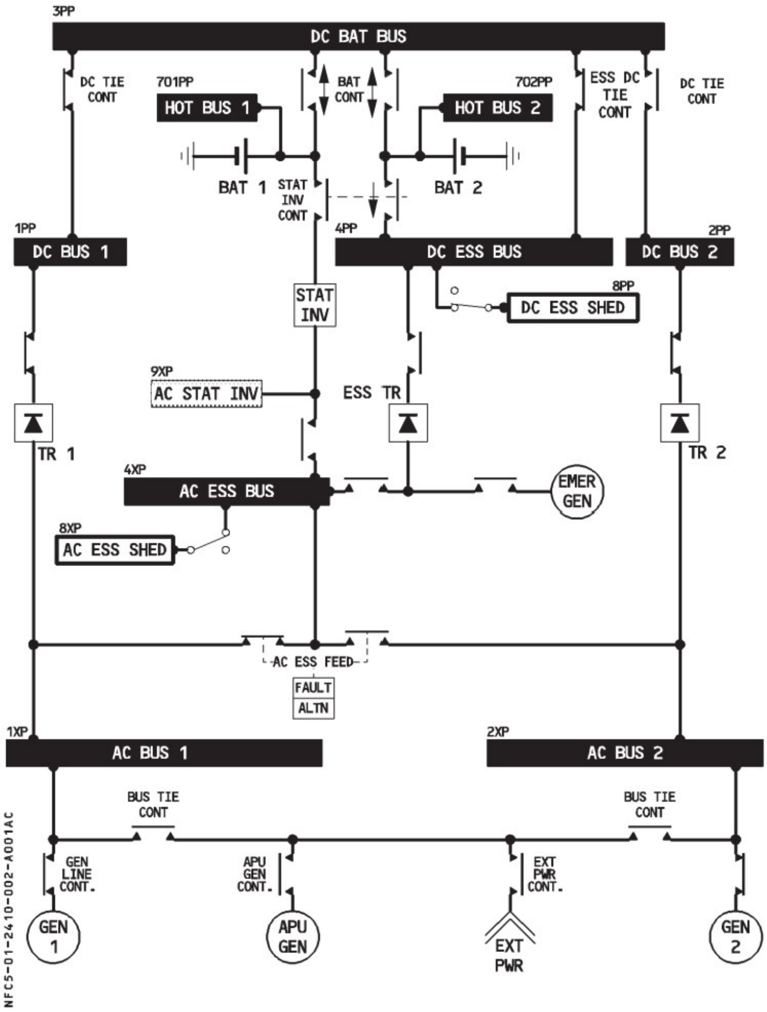


Figure 2.22: A320 EPS from [59]

The electric power is distributed by two main AC buses (one for each engine) and one essential AC bus. In case of a normal generation failure, the main AC buses can be interconnected. Three Transformer Rectifiers (TRs) connect AC and DC buses, transforming AC power in DC power to feed DC electric users. DC buses are linked to one DC battery bus that provides a power supply to recharge the batteries, when needed.

Hydraulic Power System

As illustrated in Figures 2.23 and 2.24 and as extensively described by [60], the A320 HPS consists of 3 hydraulic circuits: blue, green and yellow. Each line operates at 3000PSI and is not hydraulically connected to the other ones. Green and yellow circuits are pressurized by one EDP each, while blue circuit is powered by an electric pump or by a RAT driven pump in emergency conditions. Yellow circuit is also provided with an electric pump to supply the hydraulic actuators during on-ground operations when both engines are not working. Moreover, yellow circuit can be partially pressurized by a hand pump to permit the opening of the cargo doors when no hydraulic power is available. Additionally, all the circuits are provided with a dedicated accumulator, damping the pressure oscillations due to different power demands during normal operations, and a set of filters that keep the pipes debris-free. Each circuit has its own reservoir that is pressurized with bleed air to avoid cavitation damage to the pumps.

A PTU realizes the bidirectional pressurization of the green and yellow circuits when their differential pressure is below 500PSI. This allows the powering of the green circuit during on ground operations, when both engine are shut down and only the yellow circuit is pressurized by the electric pump. Moreover, it improves the reliability of the HPS, since the cross-pressurization of these two circuits enhances the robustness of the system when hydraulic power generation failures occur.

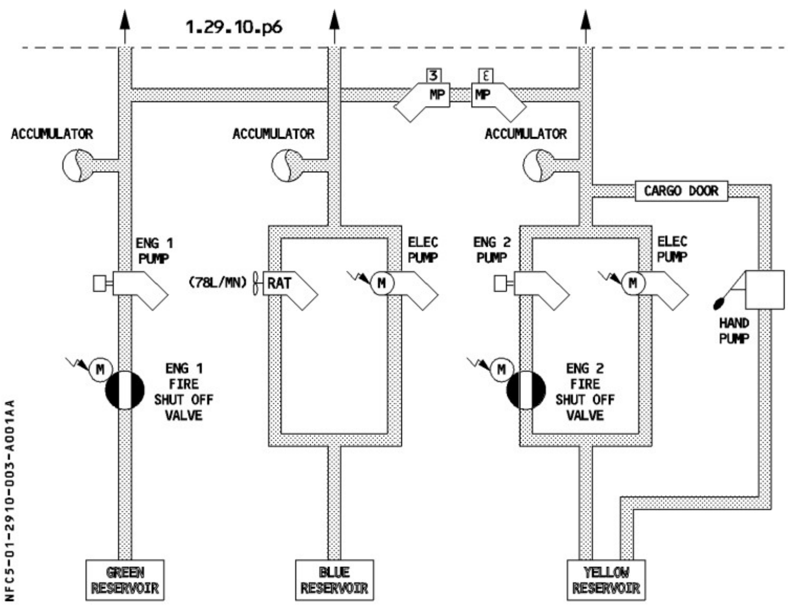


Figure 2.23: A320 hydraulic circuits and pumps

As an additional safety barrier, the A320 is provided with a RAT that can be deployed when electric power is completely lost or both engines fail, providing emergency pressurization of the blue circuit.

For what concerns the valves, the A320 hydraulic system is also provided with priority valves to reduce the power supply to the most power demanding users when the hydraulic pressure is low. In addition, green and yellow lines have fire shutoff valves to prevent fire propagation when the corresponding engine is on fire. All the circuits are provided with leak measurement valves that ensure the rapid detection of leakages and the appropriate reconfiguration of the system.

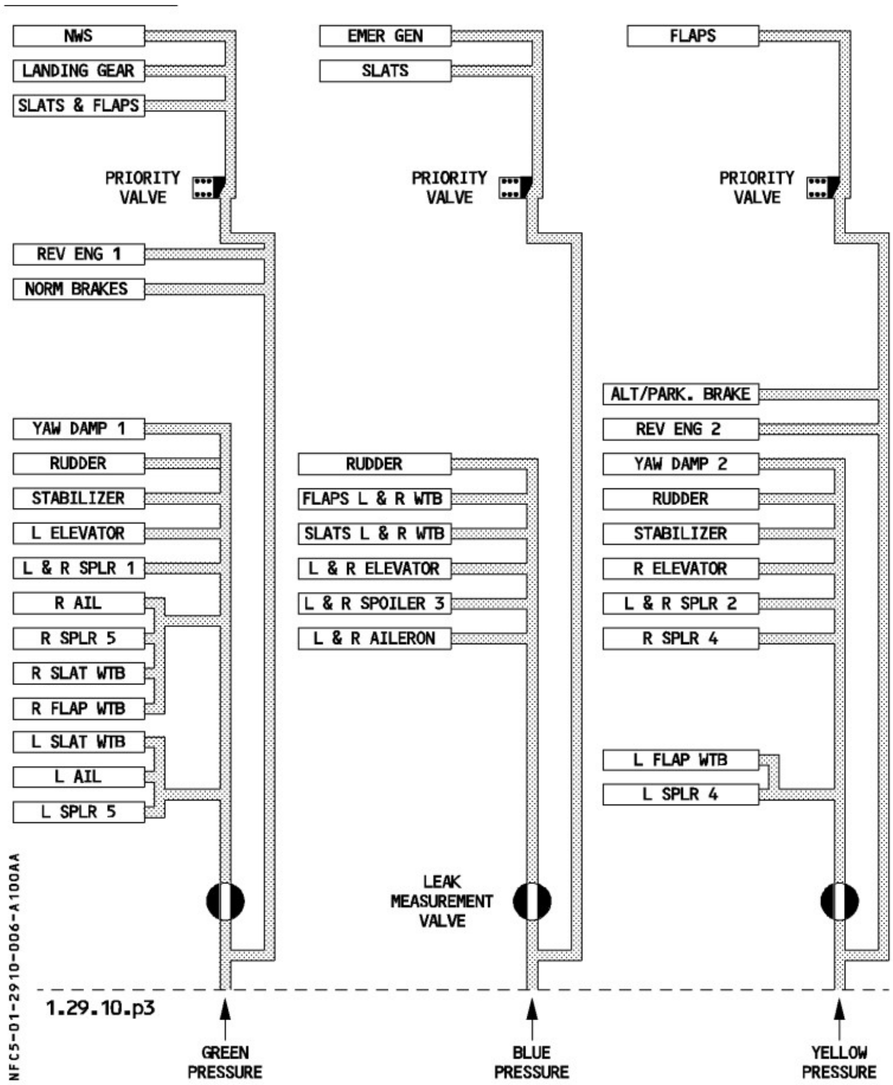


Figure 2.24: A320 hydraulic users

Pneumatic System

As reported on [55], the A320 adopts a traditional pneumatic system that provides hot air for many purposes, such as hydraulic reservoirs pressurization, wing ice protection, air conditioning, engine starting, etc. As clearly shown in Figure 2.25, hot air can be provided by three sources: bleed from the engines, bleed from the APU and High Pressure (HP) air from Ground Power Unit (GPU).
The system is provided with several valves to control bleed air temperature and pressure in order to avoid damages to the pneumatic ducts and to the user systems. Moreover, dedicated valves ensure the HP air not to flow backwards toward Low Pressure (LP) stages of the engine. Additionally, leak detection loops are installed along the hot air supply ducts of the pneumatic system in order to promptly detect any pressure loss, isolate the fault and reconfigure the system [55].

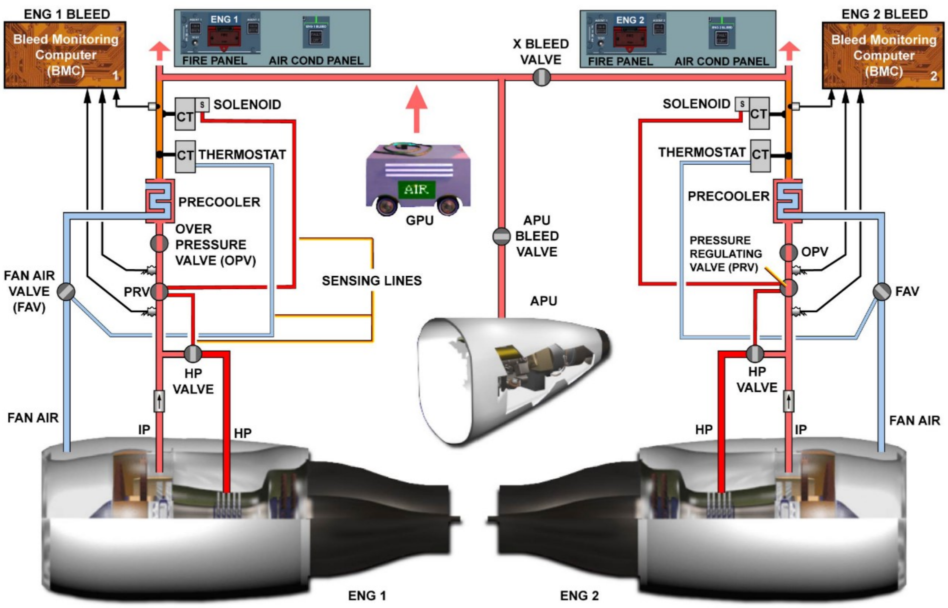


Figure 2.25: A320 pneumatic system from [55]

Flight Control System

The A320 FCS adopts FBW technology but it is still provided with a direct mechanical backup control mechanism [33]. As can be seen in Figure 2.26, the elevator has two symmetric controllable surfaces, each of which is actuated by two dedicated HSAs. The rudder is composed of one single movable surface controlled by three HSAs. One aileron surface is located on each wing, and is moved by two HSAs.

Five spoilers acting as speed brakes and ground spoilers are placed on each side of the wing, and all of them are actuated by one HSA each. The THS is controlled by two dedicated hydraulic motors powering a screwjack mechanism.

Finally, flaps and slats are guided by a conventional mechanism with ballscrew actuators and two hydraulic PDUs.

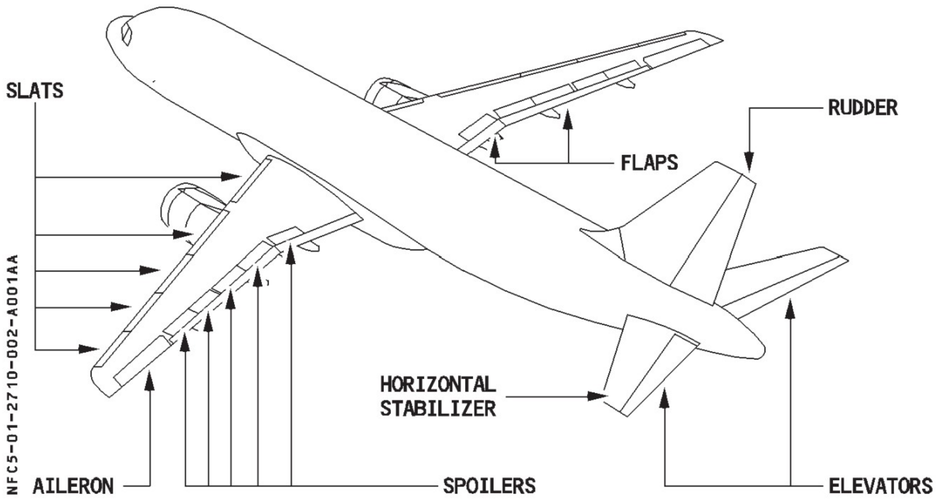


Figure 2.26: A320 control surfaces from [33]

Landing Gear System

An accurate description of the A320 landing gear is provided by [61]. It presents a conventional tricycle architecture with two main legs and one nose leg, where each gear and the relative door are electrically controlled and hydraulically actuated. The main gears have two wheels and an oleopneumatic shock absorber each. In addition, an anti-skid device is installed on each main wheel. The nose gear has two wheels and an oleopneumatic shock absorber as well, but they are not provided with anti-skid devices, since their function is not to slow down the aircraft but to control the direction of his motion while on the ground. For this purpose a hydraulic steering system is installed on the nose gear. On the other hand, the braking system is composed of conventional multidisk brakes on each wheel, hydraulically actuated by the green and the yellow circuit. The latter is also provided with a dedicated backup landing gear accumulator to implement the braking function even in emergencies condition where the dedicated hydraulic circuits are depressurized.

Environmental Control System

The ECS installed on the A320 is conventionally fed with bleed air. The temperature regulation and the cabin pressurization are provided by two pneumatic circuits, one for each engine. As illustrated in Figure 2.27, the hot air flow coming from the engines is split and a fraction goes firstly to the air conditioning packs, where it is cooled exploiting a three-wheels bootstrap cycle with a high pressure water separation system [50]. Further details on this technology is extensively provided by [50] and won't be reported in the present work. After being processed by the air conditioning packs, the cool air flows are sent to the Mixing Unit where they are mixed to recirculating air from the cabin. This cooled air flow finally is sent to the temperature regulation unit. The initial remaining part of bleed air that by-passed the air conditioning packs, and consequently the mixing unit, reaches directly the temperature regulation unit. These hotter flows are used to perform temperature control over the cooled air coming from the mixing unit. The output air flow is sent to all the aircraft air distribution zones. Pressure control is finally performed by simply regulating the conditioned air discharge through one outflow valve in the cabin.

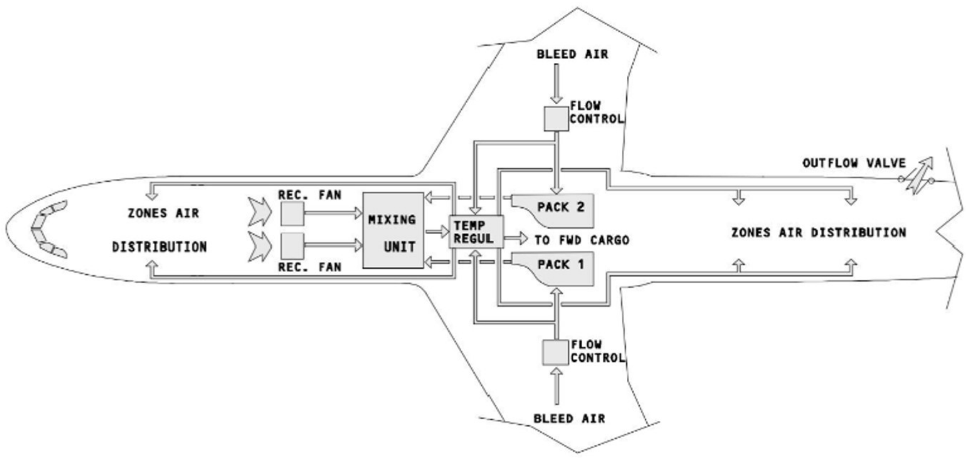


Figure 2.27: A320 ECS from [55]

Ice Protection System

The IPS is a heterogeneous and distributed system, because it comprehends very different elements distributed along all the surface of the aircraft, as can be observed in Figure 2.28. In fact, as accurately explained by [62], the A320 is provided with several ice protection devices, each of which has to perform a different function such as the wing ice protection, the engine air intake protection, the drain mast ice protection, the probes ice protection, the windshield ice and rain protection and optionally the electric ice detection and the water and waste ice protection.

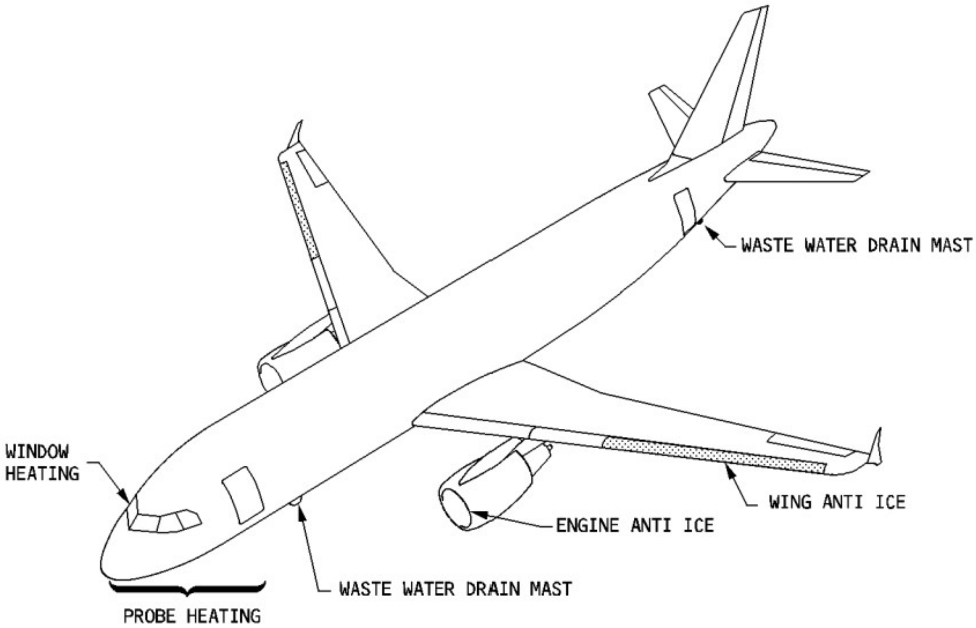


Figure 2.28: A320 IPS from [62]

As it is shown in Figure 2.29, the Wing Anti Ice (WAI) is accomplished by transferring hot air from the engines or the APU to three outboard leading edge slats of each wing. The incoming flow is regulated by a pressure regulating and shut-off valve, the *WAI valve*.
By activating this function, the engine idle is automatically increased and the safety margins on engine performances are properly enhanced in order to compensate the negative effect produced by the air mass subtraction from the engines' thermodynamic cycle.

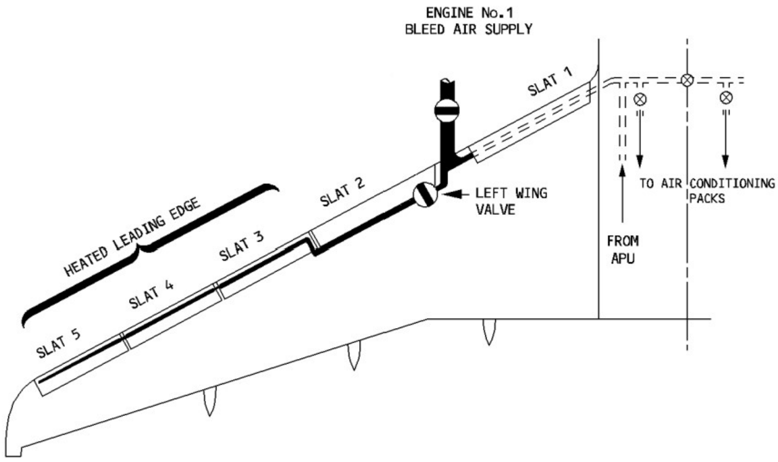


Figure 2.29: A320 WAI from [62]

Engine air intake ice protection is performed independently on each engine by spilling hot air from the HP compressor and recirculating this bleed air inside the nacelles. This bleeding is made by dedicated engine air intake anti-ice valve.
By activating this function, engine idle and TOGA (max thrust) limits are automatically adjusted.

Drain mast ice protection, probes ice protection, windshield anti ice and defogging and eventually water and waste ice protection don't use bleed air as well. Instead, they are performed thanks to electrical heating by providing current to all the dedicated electric resistances.

Starting System

As described in the previous paragraphs, A320 pneumatic system must deliver HP air supply for the engine starting. This traditional architecture involves the installation of a dedicated air turbine and a gearbox on each engine shaft, in order to transfer the torque to the compressor, thus generating the adequate pressure condition for the ignition in the combustion chamber [56].

2.4.2 More Electric Aircraft concept

Growing attention to global environmental condition and the seeking for operating costs reduction push aviation technology research toward exploring new aircraft concepts. Of course many disciplines are involved in this process and the aircraft designs are being optimized under every aspect. For example, from a structural point of view, the introduction of more complex and resistant composite materials is aiming at the lightening of the airframe structure; on the other hand, propulsion innovation has led to the demonstrated possibility to fly relying entirely on Sustainable Aviation Fuel (SAF). In this scenario, aircraft manufacturers are gradually proposing new OBS architectures on their products, following the MEA philosophy. In fact, the reduction and eventually the elimination of the hydraulic and pneumatic power systems is expecting to lead to lower operating costs, due to higher operating efficiency and less expensive maintenance [47].

MEA philosophy leaves space to many different design variations. In fact, a good number of MEA architectures can be designed depending on the electrification of one system rather than others. Of course, the successful reduction of DOC strictly depends on this design choices and it is always reasonable to electrify the various systems in order to completely remove the power distribution system they were originally supplied by. Nevertheless, it may not always be feasible to follow this suggestion, because of the raising weights and the safety related issues of the state of the art technology. As a consequence, this aspect implies the need to perform a trade-off assessment to evaluate the benefits and the disadvantages of the introduction of such technologies.

In the following sections two examples of MEA are presented. The next section explains the OBS innovation of the A350 and the A380, while the following one will discuss about the MEA architecture adopted by Boeing in developing of the B787. Finally, a conceptual overview of the AEA concept is given.

2.4.3 More Electric Aircraft: A350/A380

Airbus implemented the MEA concept in two aircraft, the A350 and the A380, in order to test and demonstrate the potential of this technology. In these airplanes, as illustrated in Figure 2.30, the FCS was modified by completely removing one hydraulic line and the associated flight control actuators. At their place EHAs were installed, thus switching from a "3H" architecture to a "2H/2E" architecture, where the "H" represent the number of the hydraulic lines and the "E" the number of the electric ones. This choice allowed a weight saving due to the removal of one hydraulic line components set (pump, reservoirs, pipes, accumulator, etc.) as well as a reduction in maintenance costs due to the higher maintainability of electric components [63][64][65]. Additionally, the introduction of a new power source in flight control actuation reduced the risk of common cause failures (due for example to maintenance errors) [66]. The elimination of the third hydraulic line and the FCS electric power supply led to the replacement of the RAT driven hydraulic pump with a RAT driven AC emergency generator.

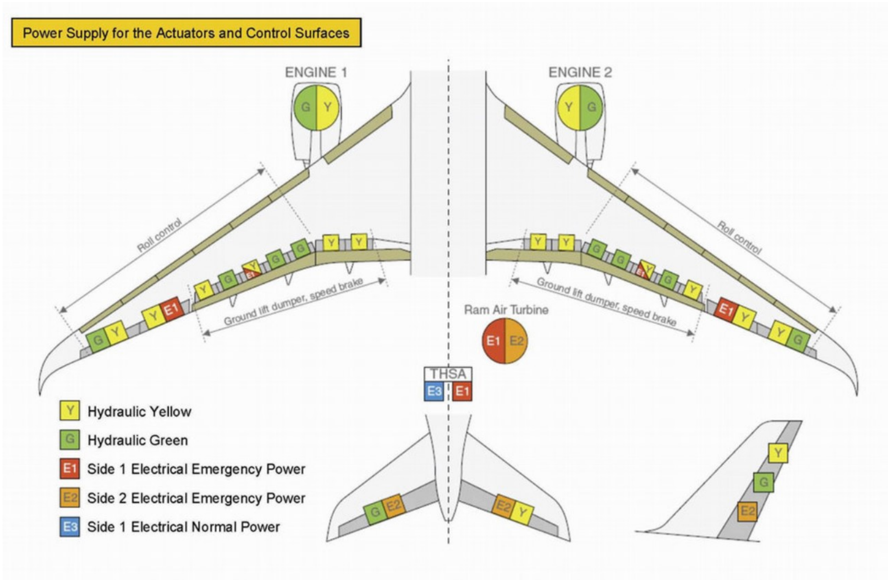
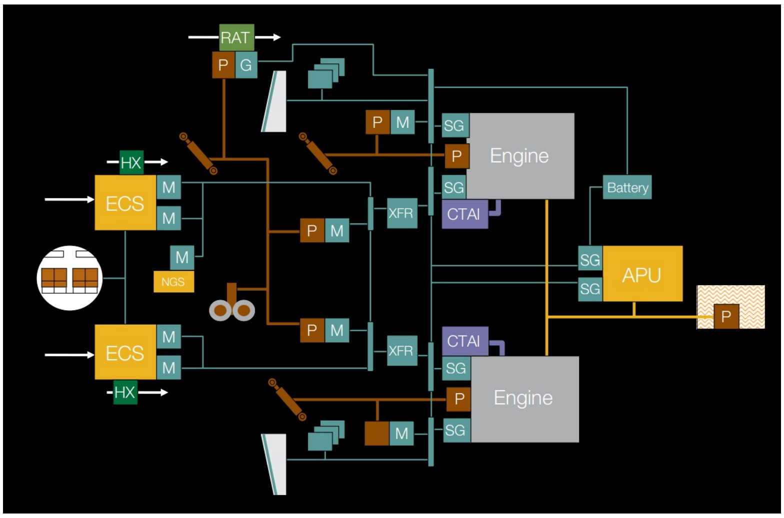


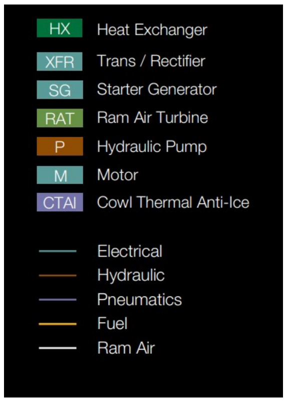
Figure 2.30: A350 power supply for FCS actuators and control surfaces from [67]

2.4.4 More Electric Aircraft: B787

On the other hand, Boeing proposed a different approach to the MEA philosophy. Instead of electrifying the FCS, the company developed a twin engine aircraft that doesn't require any pneumatic power: the *bleedless* B787. This airplane adopts two Variable Frequency Starter Generator (VFSG)s on each engine unlocking the possibility to perform an electric engine starting without requiring bleed from the APU. Moreover, the ECS was electrified as well: instead of using hot air from the engines, the B787 presents two electric cabin air compressors driven by an electric motor. This feature allows the system to adjust its performances depending on the passengers number, hence always having the optimal energy consumption. In fact, instead of discharging exceeding pressure (as it was for conventional ECS), with this ECS architecture it is sufficient to control the speed of the electric motor to regulate the air conditioned airflow. In addition, also the IPS was completely electrified by replacing hot air ducts in the wing leading edges with electro-thermal devices. The utilization of thermal blankets constitutes a great advantage in terms of reduced energy consumption and smaller maintenance cost due to the removal of small and complex pneumatic ducts [52][68].
As shown in the B787 OBS schematic in Figure 2.31, the combination of these three innovations, VFSGs, E-ECS, and E-IPS, led to the complete removal of the bleed system and a major simplification of the pneumatic system, involving a non-negligible reduction of weight and maintenance effort [68].



(a) *Bleedless* B787 systems schematic



(b) Acronyms and color legend

Figure 2.31: B787 system architecture by [52]

Lastly, B787 is provided with an innovative electric braking system, thus demonstrating the possibility to adopt non-hydraulic actuators for this safety critical function. However, the main and nose landing gear actuation still remained hydraulically controlled, as well as the nose steering.

2.4.5 All Electric Aircraft concept

The extreme projection of the MEA philosophy consists of an OBS architecture where all the systems are electrified and there is no more pneumatic or hydraulic power generation. This concept is called AEA.

In an AEA all the FCS actuators are electric (EHA or EMA) as well as the landing gear actuators for the deployment, braking and steering functions. Electric generation will rely on SGs, in order not to need an APU bleed-based system for the engine start. The IPS and the ECS will present similar architectures to the ones installed on the B787, so that a pneumatic engine bleed system will no longer be needed.

Although many AEA conceptual designs have been carried out during the years [15][16], no commercial AEA has been produced yet. This is due to the uncertainties linked to operating costs of such innovative aircraft and to the safety issues that derive from an all-electric FCS. Moreover, EMAs are not safe enough for the landing gear actuation: the jamming failure mode of these actuators excludes the possibility to actuate the gears in any other way, which is, of course, not acceptable. However, as technology progress advances and new generations of safer and more reliable

HSAs and EMAs are being developed, this architecture that nowadays is beyond the state of the art could become feasible soon.

2.5 Science Gap and Research Questions

The growing importance of OBS electrification is playing a key role for modern aircraft design, since this aspect can ensure better efficiency and therefore a remarkable fuel saving. During the past years, many authors provided their contribution to estimate such variation in operating costs, but what happens more specifically to maintenance costs when going from a conventional aircraft to a MEA is still an open question. Although the need to have accurate tools to estimate DMC in the preliminary design phase is essential, no adequate maintenance cost estimation method is existing for MEA and AEA applications. In fact, even if many CERs are available for conventional aircraft, there is still a lack of availability of such instruments when talking about these innovative aircraft configurations.

The present work wants to contribute to the filling of this science gap by providing a first parametric equation capable of estimating the maintenance variations, in terms of MMH, for different more electric variants of one reference aircraft, the A320. The results of this study come from the analysis of several research questions.

The main one aims to understand which subsystems have the biggest impact on maintenance when progressive electrification of OBS occurs, quantifying the answer in objective terms and providing a concrete amount of MMH variation. The solution to this question has been carried out through the application of a breakdown approach that made possible the identification of the maintenance tasks to be deleted or replaced.

The second research question is focusing on understanding the effects of a partial electrification of some subsystems (such as the FCS or the LGS) by analysing and evaluating hybrid architectures.

Future development of the present work could comprehend an extension to the range of applicability of the proposed parametric equation, by replicating the data generating process on different aircraft. This could also lead to a greater variety of reference data that can be used to adjust the parametric equation, introducing new inputs and making it sensible to different parameters. By doing so, the applicability range can be enlarged and by integrating the missing cost aspects, such as labor rate, material cost and unscheduled maintenance, the final CER could represent an accurate tool to estimate DMC of MEA and AEA of different dimensions and with different mission profiles. Moreover, an evaluation of high voltage EPS influence on DMC is strongly suggested, as an electrified FCS and LGS would very likely require the introduction of such technology.

Chapter 3

Data Generation

In order to identify an estimation relationship evaluating the MMH variation occurring when switching from conventional to MEA OBS architectures, firstly it has been necessary to generate a minimum amount of data that has served as a reference basis for the build up of the targeted parametric equation. In Section 3.1 the five reference aircraft configurations that have been chosen for this purpose are presented. These architectures are based on the ones adopted in the A320 and present an increasing electrification of the OBS, going from conventional to all electric. Their scheduled MMH variation has been evaluated with the methodology proposed by Dell'Anna [10] and the results are presented in Section 3.3.

Complementary to this literature based approach, an experience based analysis has been carried out. A series of interviews to experts in maintenance and OBS architecting has been performed and it is reported in detail in Section 3.4. Lastly, results coming from both methodologies are compared in Section 3.5.

By exploiting these results it has been possible to create a parametric model to estimate scheduled MMH variations for a large number of different aircraft configurations. This process is presented in chapter 4.

3.1 Reference architecture definition

In this subchapter, the configurations that have been used to obtain the starting data are explained in detail. All of them are based on the reference aircraft for this study, the A320, and the MEA configurations have been generated by applying real rife MEA OBS architectures to this aircraft.

The first architecture that has been chosen is the conventional A320 configuration, and proceeding with increasing OBS electrification, the “2H/2E”, the “MEA-I”, the “MEA-II” and the “AEA” constitute the other reference points that have been used to derive the Maintenance Man Hours Estimating Relationship (MMHER).

3.1.1 Conventional A320

This architecture reflects the state of the art of the A320 OBS technology and its OBS have been already discussed in detail in Section 2.4.1. Since no modifications have been implemented, this configuration represents the benchmark value from where the MMH variations of the other architectures have been calculated.

In Figure 3.1, a schematic representation of the A320 OBS is provided. It's worthy noting that not every system is shown in this illustration, but just the ones relevant for the objective of this thesis are represented. As indicated by the legend, the three colors that appear are indicating the power source that it is distributed by the lines (in the case of the arrows) or exploited by the users (in the case of the boxes).

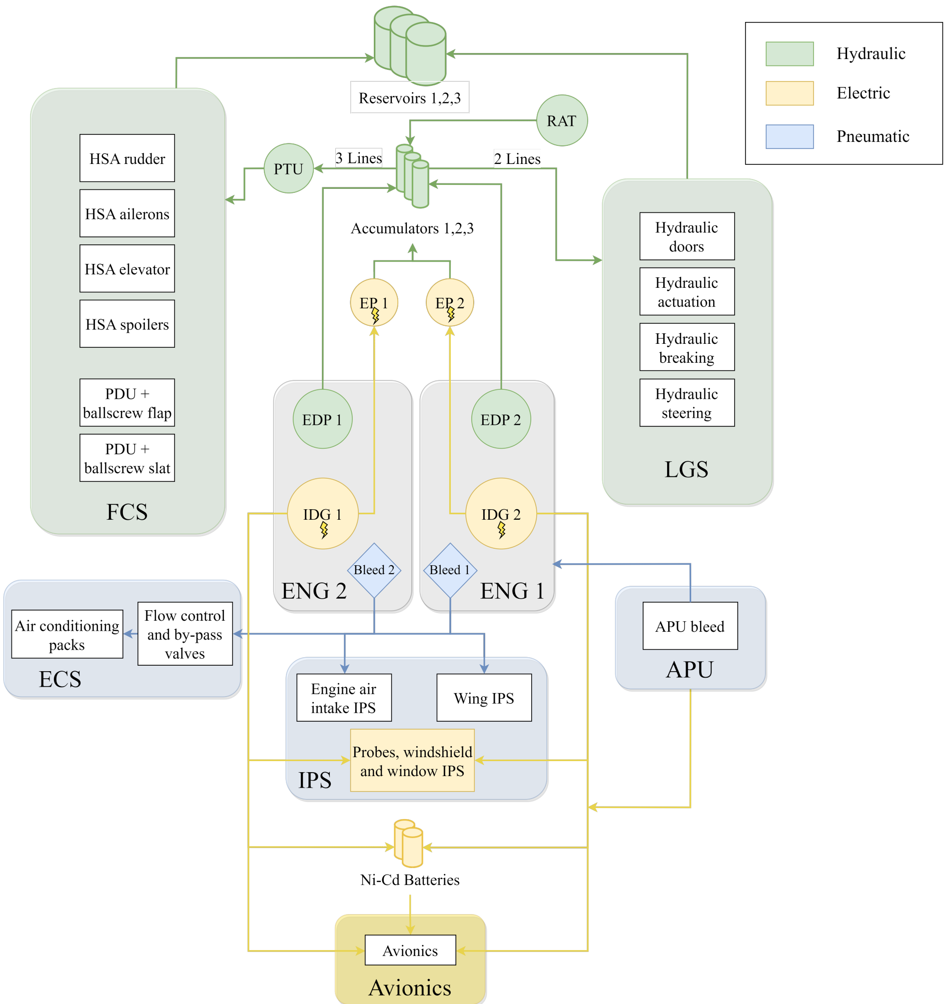


Figure 3.1: A320 OBS schematic visualization

3.1.2 2H/2E

The “2H/2E” is the first MEA architecture to be presented and its OBS architecture is schematized in Figure 3.2. Its name derives from the fact that one hydraulic line has been removed and two electric lines are now feeding the FCS, comparable with the A350 and the A380 architecture. The difference in this case lies in the fact that, contrarily to the two aforementioned aircraft, the complete electrification of the FCS has been assumed for the “2H/2E” configuration of the present study.

This means that the FCS actuators for the primary control surfaces and the spoilers are EHAs, while EMAs are installed for the THS. Finally two full electric PDUs implement the actuation of slats and flaps through conventional ballscrew mechanisms. As a consequence, the two remaining hydraulic lines are not needed to supply this system, but they are used only to power the LGS. By eliminating one hydraulic line, the hydraulic fluid reservoirs and the accumulators have been accordingly reduced from three to two. Moreover, the PTU and one of the two electric powered pumps have been removed as well. Additionally, the EPS has been modified too. The two conventional IDGs have been replaced by two VFGs and the Ni-Cd batteries have been substituted with a set of Li-Ion batteries. Lastly, the hydraulic pump connected to the RAT has been removed and replaced by an AC generator, in order to provide an additional emergency power supply to the FCS.

Every other system has been maintained unchanged from the conventional architecture and all the changes that have been introduced are summarized in Table 3.1.

Table 3.1: “2H/2E” architecture changes

	Conventional	**“2H/2E”**
Hydraulic lines	3	2
Reservoirs	3	2
Accumulators	3	2
Electric pumps	2	1
FCS actuators	HSAs, hydraulic PDUs and hydraulic motors for the THS	EHAs, electric PDUs and EMAs for the THS
Electric generators	IDGs	VFGs
Batteries	Ni-Cd	Li-Ion
RAT driven emergency power supply	Hydraulic pump	AC generator

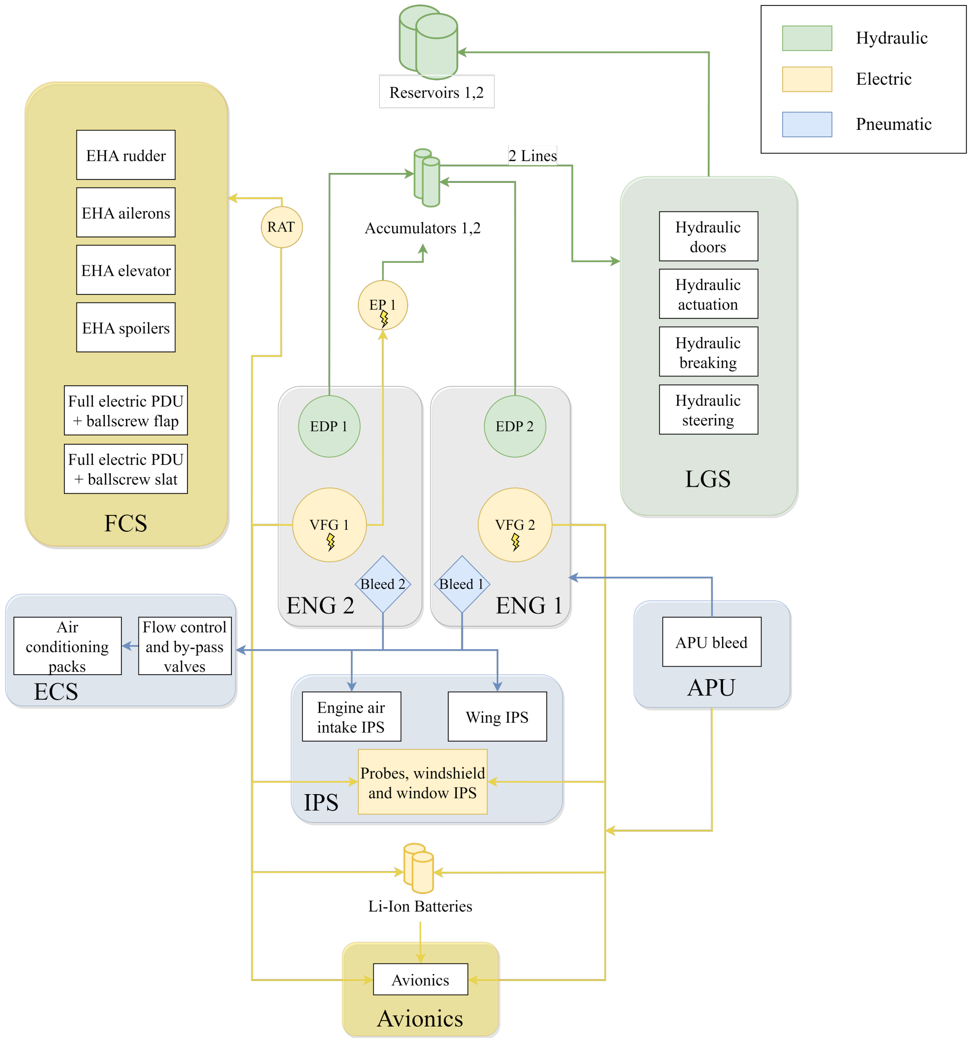


Figure 3.2: "2H/2E" OBS schematic visualization

3.1.3 MEA-I

The "MEA-I" represents an evolution of the previous "2H/2E" architecture. In fact, while all the variations of the previous configuration have been retained, i.e., electrified FCS, electrified RAT, VFGs and Li-Ion batteries for the EPS, more actions have been taken in order to eliminate the need of the hydraulic power supply, as can be seen in Figure 3.3.

For this purpose, the last hydraulic powered system, the LGS, has undergone several modifications. The actuators for the doors opening and closing have been replaced by EMAs, as well as the nose gear steering actuator. Moreover, also the braking function is now fulfilled by electric actuators installed on the main gear. For what concerns the landing gear extraction and retraction, in the "MEA-I" configuration the hydraulic actuators are still present. Nevertheless, the high pressure hydraulic fluid doesn't come from a general distributed hydraulic system, but is locally pressurized by one dedicated Local Electro-Hydraulic Generation System (LEHGS) [69] on each leg.

All the OBS that are not mentioned in this section are remaining unchanged from the conventional architecture.

In Table 3.2 all the variation between the conventional and the "MEA-I" architecture are explicitly listed.

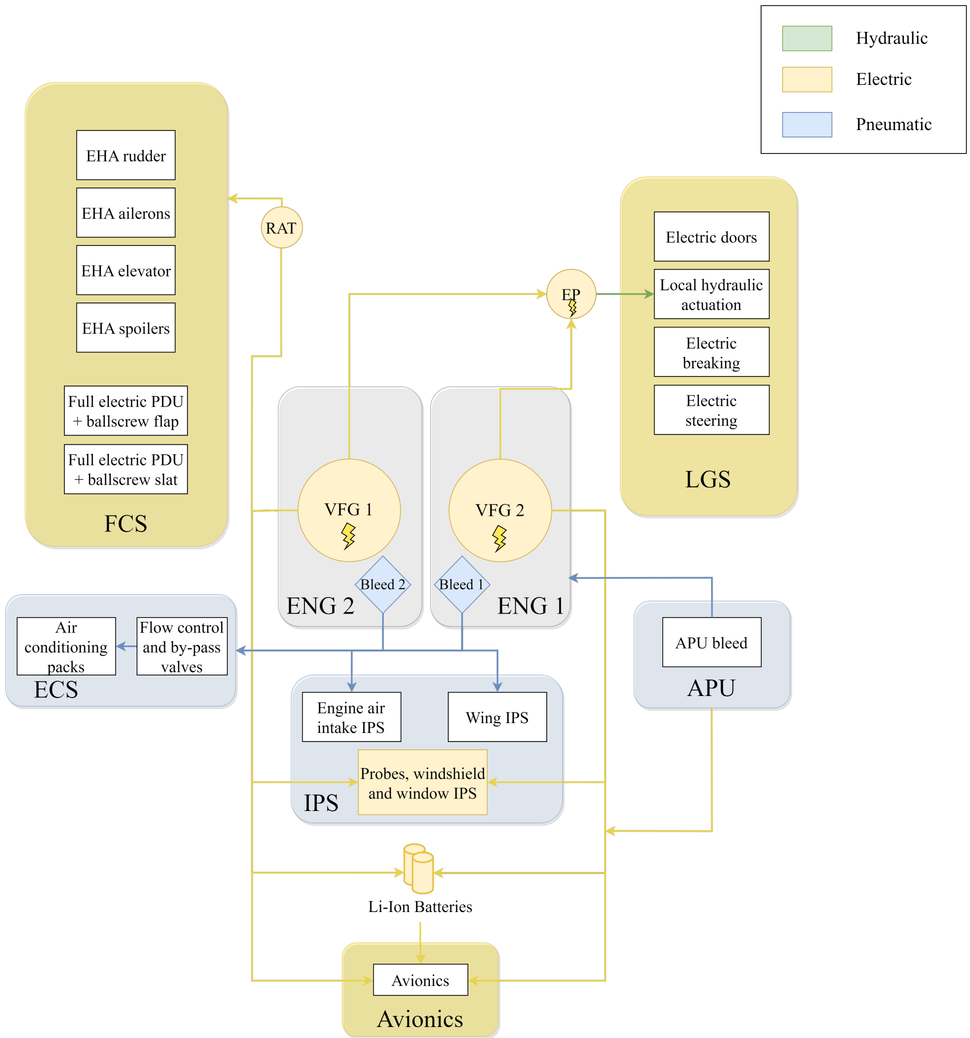


Figure 3.3: "MEA-I" OBS schematic visualization

Table 3.2: "MEA-I" architecture changes

	Conventional	**"MEA-I"**
Hydraulic lines	3	0
Reservoirs	3	0
Accumulators	3	0
Electric pumps	2	1 (LEHGS)
FCS actuators	HSAs, hydraulic PDUs and hydraulic motors for the THS	EHAs, electric PDUs and EMAs for the THS
Electric generators	IDGs	VFGs
Batteries	Ni-Cd	Li-Ion
RAT driven emergency power supply	Hydraulic pump	AC generator
Doors actuation	Hydraulic	Electric (EMAs)
Gears actuation	Hydraulic distributed	Hydraulic local (LEHGS)
Braking	Hydraulic	Electric (EMAs)
Steering	Hydraulic	Electric (EMAs)

3.1.4 MEA-II

The "MEA-II" represent a different interpretation of the MEA concept with respect to the first two MEA configurations that have been presented until now. As can be seen in Figure 3.4, in this case the goal is not to remove the hydraulic system but the bleed one, reflecting the *bleedless* B787 OBS architecture.

Aiming to remove the bleed air supply, the ECS has been modified in order to be fed with ram air coming from the external environment. Consequently, two *ram air compressors*, emulating the B787 cabin air compressors, are pressurizing the air to be supplied to the cabin at adequate pressure and temperature conditions. Eventually, two air conditioning packs are ensuring the compliance with the ECS thermal requirements during the hot case.

The bleed air based IPS used in the conventional aircraft has been replaced by a thermo-electric IPS, where the wing and tail leading edge heating is provided by thermal blankets. Nevertheless, the nacelles ice protection is still based on the engine bleed air, as in the case of the B787. This choice is due to the fact that this surface is very close to the compressor stage of the engines, therefore, the pneumatic ducts that are required don't have to cover a long distance and their removal is not expected to bring much weight saving. Moreover, the bleed air required for the nacelles ice protection is little compared to the total amount needed for all the other bleed air users, i.e., conventional wing and tail ice protection and ECS. As a consequence, the engines performance is expected to be very close to the one obtained where also the nacelle ice protection is electrified as well.

For what concerns the EPS, two SGs were used instead of the traditional IDGs.

This allows the electric starting of the engines, hence implying the possibility to remove the bleed system on the APU and the pneumatic lines connecting this component and the engines dedicated starting turbines. Similarly to the two previous MEA architectures, the "MEA-II" configuration also replaces the Ni-Cd batteries with Li-Ion ones.

By electrifying the starting system, the IPS and the ECS, most of the pneumatic lines have been removed and they only remain as part of the ECS for the distribution of ram air to the compressors or pressurized air to the cabin. On the other hand, the pneumatic ducts feeding the nacelles with bleed air have been assumed as part of the engines themselves and not part of an independent self-standing IPS.

Lastly, all the systems that are not explicitly specified in this section are implemented in the same way as in the conventional A320 configuration. In particular, all the variations that occurred between the "MEA-II" and the traditional architecture are shown in Table 3.3.

Table 3.3: "MEA-II" architecture changes

	Conventional	**"MEA-II"**
ECS	Bleed + air conditioning pack	Ram air compressor + air conditioning pack
IPS	Hot air for wing and tail ice protection	Thermal blankets for wing and tail ice protection
Electric generators	IDGs	SGs
Batteries	Ni-Cd	Li-Ion
Starting mechanism	Bleed based	Electric (SGs)

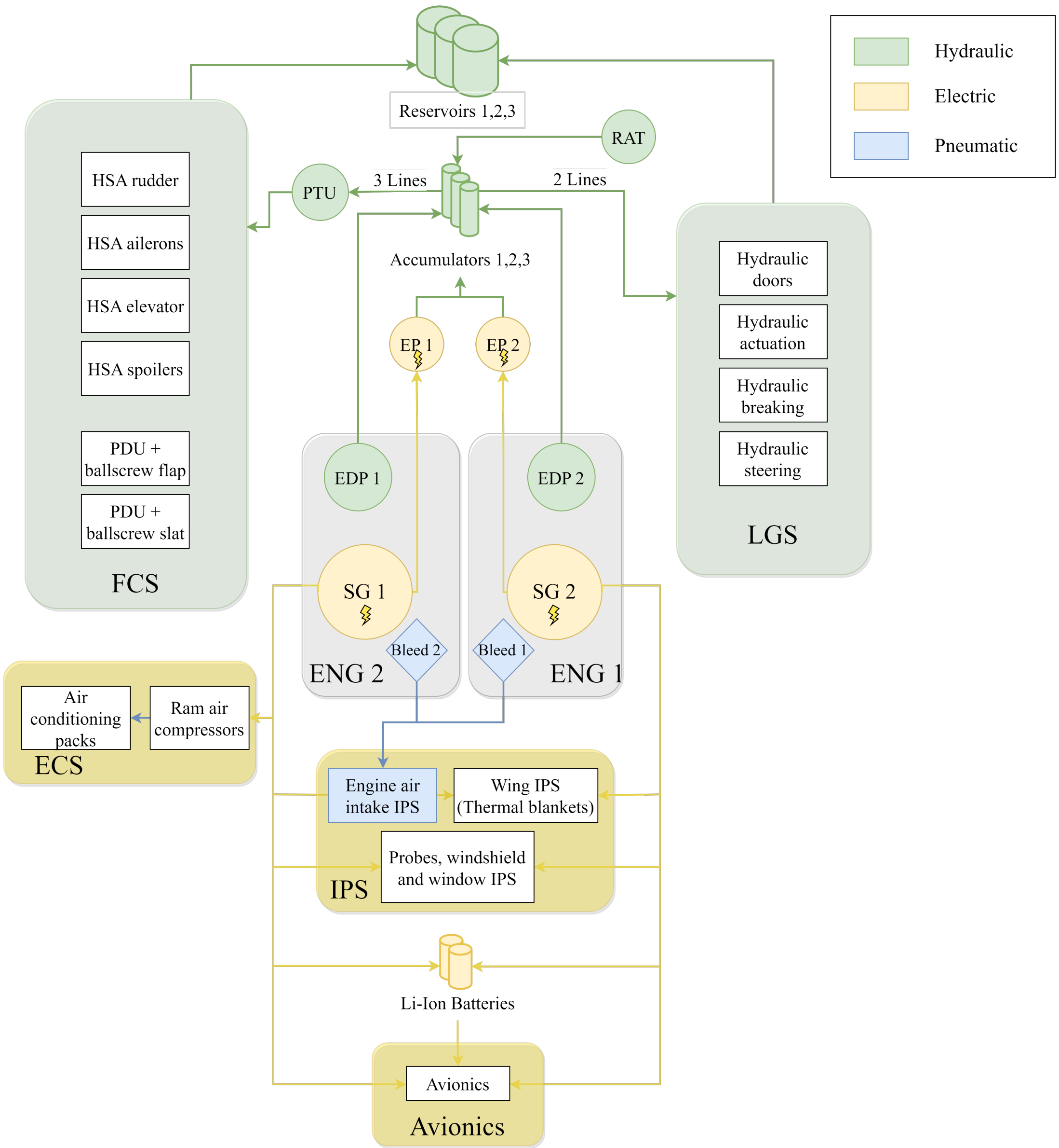


Figure 3.4: "MEA-II" OBS schematic visualization

3.1.5 AEA

The final reference architecture is the all electric version of the A320. The OBS structure of this configuration reflects the peculiarities of an AEA: the generation of secondary power is performed only in the form of electric current, hence eliminating the need for generating pneumatic and hydraulic secondary power. As can be schematically seen in Figure 3.5, the AEA architecture combines the modifications applied on the "MEA-I" and "MEA-II" configurations, in order to remove both the hydraulic and the pneumatic secondary power sources. As a consequence, the FCS and the RAT have been conserved from the "2H/2E" architecture, while the ECS, the IPS, the EPS and the starting mechanism have been retained from the "MEA-II" configuration, thus preserving the absence of pneumatic power generation. Nevertheless, a new variation has been introduced in the LGS. In fact in this case, contrarily to the "2H/2E" and the "MEA-I" architectures, the hydraulic actuators for the extraction of the gears have been replaced by EMAs. Consequently, the LEHGS has been removed as well. The complete list of the applied changes is reported in Table 3.4

Table 3.4: "AEA" architecture changes

	Conventional	**"MEA-II"**
Hydraulic lines	3	0
Reservoirs	3	0
Accumulators	3	0
Electric pumps	2	0
FCS actuators	HSAs, hydraulic PDUs and hydraulic motors for the THS	EHAs, electric PDUs and EMAs for the THS
Electric generators	IDGs	SGs
Batteries	Ni-Cd	Li-Ion
RAT driven emergency power supply	Hydraulic pump	AC generator
Doors actuation	Hydraulic	Electric (EMAs)
Gears actuation	Hydraulic distributed	Electric (EMAs)
Braking	Hydraulic	Electric (EMAs)
Steering	Hydraulic	Electric (EMAs)
ECS	Bleed + air conditioning pack	Ram air compressor + air conditioning pack
IPS	Hot air for wing and tail ice protection	Thermal blankets for wing and tail ice protection
Electric generators	IDGs	SGs
Batteries	Ni-Cd	Li-Ion
Starting mechanism	Bleed based	Electric (SGs)

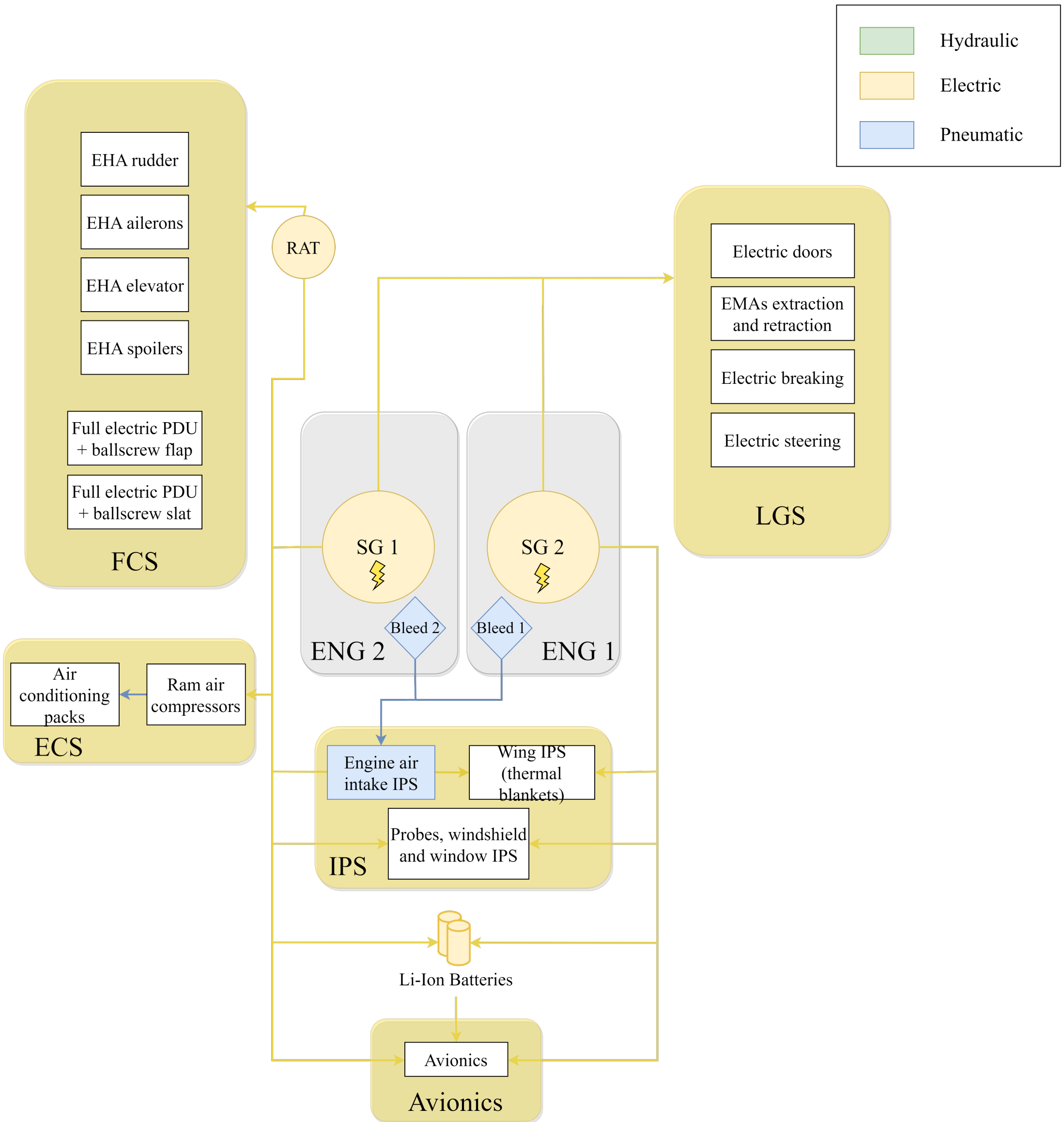


Figure 3.5: "AEA" OBS schematic visualization

3.2 System Architecting: ADORE

The choice of the systems architectures is one of the first decisions that must be taken during the design phase. Typically, a small number of configurations are chosen and further evaluated, selecting the most promising one for the final product. The architectural design space represents all the different architectures that can be adopted by a certain system, including all the possible components, subsystems and architectural decisions. Modelling such design space can be a challenging task and, because of that, a system architecting approach is usually recommended and used [70]. This process starts by identifying the main function that the system needs to fulfill and assigning one or more components that are needed to fulfill such functions. These components in turn need other induced functions to properly perform as well, hence also implying the need for further components, and so on. This functional approach makes the process more generic and removes bias from the designer [70]. Moreover, it also allows to perform a bigger exploration of the design space, even during early stages of design.

Once the design space is modelled the different architectures can be generated from it. In this thesis, a Deutsches Zentrum für Luft und Raumfahrt (DLR) in-house tool called ADORE is used for this purpose [71]. This tool visually supports the design space modelling, also allowing the user to automatically generate architectures from it and connecting them to an evaluation framework. The evaluation metrics can be provided back to ADORE, connecting them to optimization algorithms that generate new architectures from the previously created design space. The OBS architectures of the A320 were modelled with this tool and the whole design space is shown in Appendix A. The blue lines that can be seen in the figures indicate the possible decisions that can be taken, while the red ones represent an incompatibility link.

As can be seen in Figure A.1 different architectural choices can be taken to protect the external surfaces from ice, start the engines and regulate the cabin pressure, thus leading to different architectures of the IPS, ECS and the starting mechanism. In Figure A.2 the FCS and LGS design space can be seen. This portion of the model contains several incompatibility links because it was necessary to exclude all the combinations of choices that could possibly lead to all the unfeasible architectures. In particular, accordingly to the assumptions made in this work, the possibility to have an hybrid LGS has been removed, hence imposing the use of LEHGS or EMAs when introducing electric actuators for the braking and the steering. For what concerns the FCS, the possibility to have chose among a conventional full hydraulic, a full electric and a hybrid actuation was given to the user. By doing so, a series of incompatibilities with the RAT power generation was included in order to let this component generate the proper form of power according to the assumptions made. Additionally, more incompatibilities ensure also the correct installation of two or three hydraulic supply lines. All the available configurations for the HPS and the EPS are shown in Figure A.4, including the choice of the battery (Ni-Cd or Li-Ion) and the generator type (IDG, VFG or SG).

ADORE also provides further information about the design space itself. Table 3.5 contains a few statistics of the ADORE design space created for this work, showing the number of decisions that build the design space and the total number of possible architectures that can be created.

Table 3.5: Design space statistics

Decisions	13
Valid Design Space	276480
Declared Design Space	276480
Discrete Choices	13

The decisions that are needed to generate the architectures can be taken by an external algorithm (e.g. an optimization algorithm) or manually by the user. Appendix G contains one example of a manually generated architecture that is presented and analysed in Chapter 5.

This model in ADORE can be utilized in further analyses in which more output metrics can be included to the study. Adding performance indicators, for instance, could lead to a two-objectives optimization problem. Adding certification constraints could filter the valid design space. However, these analyses are not the scope of this thesis but it's worthy pointing out that the use of ADORE facilitates the re-usability of the models here created. This improves the value of the work presented and eases the possible further works needed.

3.3 MPD task analysis

In this subchapter the methodology that has been applied to generate the MMH variation for each reference architecture is explained. More specifically, the breakdown approach proposed by Dell'Anna [10] has been exploited to analyse the A320 MPD and calculate the changes in terms of required maintenance time (MMH) for each system of each architecture. Accordingly, a selection of the A320 MPD tasks has been made in order to identify those that had to be eliminated or replaced, as they are associated to components that were either no longer present or had been replaced with something else.

3.3.1 General introduction to methodology

In this work two different operating routines have been considered to determine the effect of FH/FC and FH/year ratios on the MMH variation. The first Utilisation Scenario (US), which has been called US 1 adopts an aircraft utilisation of 2800 FH/year and a FH:FC ratio of 2.59, according to the data provided by Aircraft Commerce [23]. As reported in the same article, even if grater than the average value, this ratio is indeed still adopted by some low-cost airlines, such as jetBlue, easyJet, Frontier and Air Asia.

In the second US, which has been named US 2, more recent information coming from Aircraft Commerce [22] have been used. According to the values provided, an utilisation of 3100 FH/year and a FH:FC ratio of 1.91 have been considered.

As the maximum A320 operating life exceeds 20 years [24], for the present study an operating life of 24 years and 9 months has been assumed in both USs. This choice is due to the fact that with this lifetime, in both USs, two complete C-Checks cycles can be performed, providing enough time to continue operating the aircraft after the 16th C-Check without having to begin a whole new C-Check cycle and, in the case of US 1, without truncating any A-Check cycle. In fact, as airliners are still adopting a 18 month time interval to perform each C-Check [23], the completion of one C-Check cycle (8 C-Checks) occurs every 144 months and the same time interval has been chosen for this work. For what concerns the A-Checks, a 750 FH interval for each check has been assumed, accordingly to Aircraft Commerce [22], thus implying the completion of one full A-Check cycle (4 A-Checks) every 3000 FH. While for US 1 exactly 23 A-Check cycles have to be performed, for US 2, they sum up to 25.5 due to the higher FH/year ratio.
A visualisation of the intervals for every check cycle is provided in the Table 3.6.

Table 3.6: A- and C-Check cycles time intervals

	A1	A2	A3	A4
Interval	750 FH	1500 FH	2250 FH	3000 FH

	C1	C2	C3	C4	C5	C6	C7	C8
Interval	18 months	36 months	54 months	72 months	90 months	108 months	126 months	144 months

	C9	C10	C11	C12	C13	C14	C15	C16
Interval	162 months	180 months	198 months	216 months	234 months	252 months	270 months	288 months

Defining the maintenance intervals was important to assign every MPD task to the appropriate A- or C-check, basing on the frequency it has to be performed. As shown in Figure 3.6, this information can be easily read in the MPD, along with other useful details, such as the identification code of the task, its description, the required number of workers, the forecast intervention time and the aircraft applicability.

Figure 3.6: MPD task sample from [72]

TASK NUMBER	PREPARATION	ZONE	DESCRIPTION
275100-03-1	FLAPS EXTENDED;	575 675	FLAPS CHECK OF FLAPS TRANSMISSION SHAFTING INTEGRITY, INCLUDING INSPECTION OF SEAL WITNESS DRAINS.

SAMPLE THRESHOLD	SAMPLE INTERVAL	100% THRESHOLD	100% INTERVAL	MEN	TASKM. H.	ACCESSM.H .	PREP.M. H.	APPLICABILITY
			108 MO OR 12000 FH	1 1	0.40 0.40	0.02 0.02	0.02	A318 OR A319-PAX OR A320 OR A321

In particular, the first two digits of the task identification code specify the ATA chapter associated to the component to which the task refers to. Exploiting this feature, the tasks have been initially sorted depending on their ATA chapter and have been additionally grouped into the following categories:

- Electric Power System (ATA 24)
- Pneumatic System (ATA 36)
- Hydraulic Power System (ATA 29)
- Ram Air Turbine (ATA 29)
- Flight Control System (ATA 27)
- Landing Gear System (ATA 32)
- Ice Protection System (ATA 30)
- Environmental Control System (ATA 21)
- Starting (ATA 80)

It's worthy pointing out that, for the purpose of this thesis, the ATA chapter partitioning has not been followed strictly, but has served just as a preliminary tool to distinguish between tasks referring to different systems. For this reason, it has happened to consider some tasks related to a certain ATA chapter, into the calculation of a system with a different associated ATA code. For example, the maintenance tasks to be performed on the water and waste air compressor or the filters for the galley cooling, have been considered contributing to the pneumatic system, even if their associated ATA code was 38 (Water/Waste) and 25 (Equipment/Furnishing), respectively.

After having identified and sorted all the tasks that could be affected by the electrification process occurring in the proposed MEA and AEA architectures, the calculation of the MMH variation has been carried out, following the methodology proposed by [10].

3.3.2 Task removal and replacement

By comparing the conventional A320 architecture with the MEA ones, it is immediately clear that some components are no more present. As a consequence, all the tasks associated to the components that have been removed are eliminated as well, implying a MMH saving. Instead, in some other cases, such as for the EPS generation or the FCS actuators, a replacement takes place.

Since defining from scratches new tasks for the added components is not a trivial process, the analogy approach based on the failure rates proposed by Dell'Anna has been followed. In particular, it has been used to estimate the MMH of the VFGs, the SGs, the Li-Ion batteries, the EHAs and the RAT AC generator. The failure rates values, λ, have been taken from the Quanterion database [44] and the Nonelectronic Parts Reliability Database (NPRD) [73] and are summarized in Table 3.7.

Table 3.7: Failure rates and failure rate ratios from [44] and [73]

Conventional component	**λ conventional (10^{-6})**	**Innovative component**	**λ innovative (10^{-6})**	**λ ratio**
IDG	8.25	VFG	7.78	0.94
IDG	8.25	SG	7.78	0.94
Ni-Cd battery	4.29	Li-Ion battery	9.32	2.17
HSA	95.0	EHA	59.0	0.62
RAT hyd. pump	6.29	RAT AC generator	13.20	2.10

To provide an example of this methodology, as can be appreciated in Figure 3.7, when considering the replacing of the IDGs with the VFGs, the tasks regarding oil levels and pressure indicators, such as the task *242100-07-1*, have been completely removed. On the contrary, tasks involving IDG attachments' inspections or operational checks, such as the task *242100-09-1*, have not been deleted, but their required MMH have been escalated with the failure rate, λ, ratio between the IDG and the VFG.

It's worthy remarking that, as originally assumed by Dell'Anna [10], also in this case it has been considered that components' weight and dimensions are not responsible for MMH variations.

$$[MH]\_VFG = \mathbf{0.94} \cdot [MH]\_IDG$$

TASK NUMBER	DESCRIPTION	100% INTERVAL	MEN	TASKM.H.	ACCESS M.H.	APPLIC ABILITY
242100-07-1	INTEGRATED DRIVE GENERATOR CHECK IDG OIL LEVEL AND DIFFERENTIAL PRESSURE INDICATOR NOTE: DEPENDING ON OPERATING ENVIRONMENT AND OPERATORS EXPERIENCE, A LESS FREQUENT OR MORE FREQUENT INITIAL INTERVAL MAY BE USED.	2 MO OR 300 FH NOTE	1 1	0.02 0.02	0.04 0.04	IAE
242100-09-1	INTEGRATED DRIVE GENERATOR OPERATIONAL CHECK OF INTEGRATED DRIVE GENERATOR (IDG) DISCONNECT AND RECONNECT FUNCTION. NOTE: TASK TO BE PERFORMED AT OPPORTUNITY OF ENGINE CHANGE OR IDG CHANGE.	NOTE	2 2	0.20 0.20		IAE

TASK NUMBER	DESCRIPTION	100% INTERVAL	MEN	TASKM.H.	ACCESS M.H.	APPLIC ABILITY
242100-07-1	************** TASK DELETED **************					
242100-09-1	INTEGRATED DRIVE GENERATOR OPERATIONAL CHECK OF INTEGRATED DRIVE GENERATOR (IDG) DISCONNECT AND RECONNECT FUNCTION. NOTE: TASK TO BE PERFORMED AT OPPORTUNITY OF ENGINE CHANGE OR IDG CHANGE.	NOTE	2 2	0.19 0.19		IAE

Figure 3.7: Task removal and replacement from [72]

In some architectures additional components are installed, meaning that new maintenance tasks have been added. In the case of the "MEA-II" and "AEA" architectures, for example, the more electric IPS involves the installation of thermal blankets for the WAI and of course no conventional maintenance task on the A320 MPD is associated to such component. To deal with this issue it has been assumed that three additional local electrical circuits are fulfilling the WAI function (one for the left wing, one for the right wing and the last one for the tail). It has also been assumed that their maintenance is performed similarly to the one carried out on the electrical resistances for the probes' anti ice. Therefore, the task *303100-01-1* reported in Figure 3.8, has been assumed to be adopted for these three electrical ice protection circuits as well.

303100-01-1	PROBE ICE PROTECTION FUNCTIONAL CHECK OF THE INSULATION RESISTANCE OF THE PITOT PROBE HEATER

Figure 3.8: *303100-01-1* task from [72]

Similarly, the ram air compressor's tasks for the two aforementioned architectures have been assumed the same as those required for the pneumatic compressor for the pressurization of the water and waste system.

The detailed list of the removed, replaced and added tasks for each architecture is provided in the Appendix B.

3.3.3 MMH variation results

By applying this methodology to the reference architectures, it is possible to estimate the variation in MMH for each system that has been electrified in every architecture. It's important to note that all the results account the variations occurring at the end of the operating life.

Firstly, the original total amount of scheduled MMH for each system has been calculated. Afterwards, the absolute and percentage variations in each architecture have been also evaluated and are illustrated in Figure 3.9 and Table 3.8 for US 1 and in Table D.1 of Appendix D for US 2.

By comparing the results obtained in the two scenarios it can be noted that, as one may have predicted, US 2 leads to higher total MMH and ΔMMH per system. This is due to the fact that in this case the aircraft has an higher FH/year ratio, while retaining the same operating lifetime. As a consequence, more FH will be flown and of course the aircraft will require more MMH.

What is interesting to point out is that the same increase that we have in total MMH per system is reflected also in the amount of MMH changing due to the removal or the replacement of the system maintenance tasks. Therefore, it can be noted how the percentage of MMH changing over the total MMH required for a system is remaining almost perfectly the same in both USs. In other words, the effect of the FH/FC ratio is affecting equally the MMH evaluation of the conventional A320 OBS architecture and the MEA ones. Consequently, when the ΔMMH is calculated, those effects are cancelling each other almost perfectly, resulting in very small percentage differences.

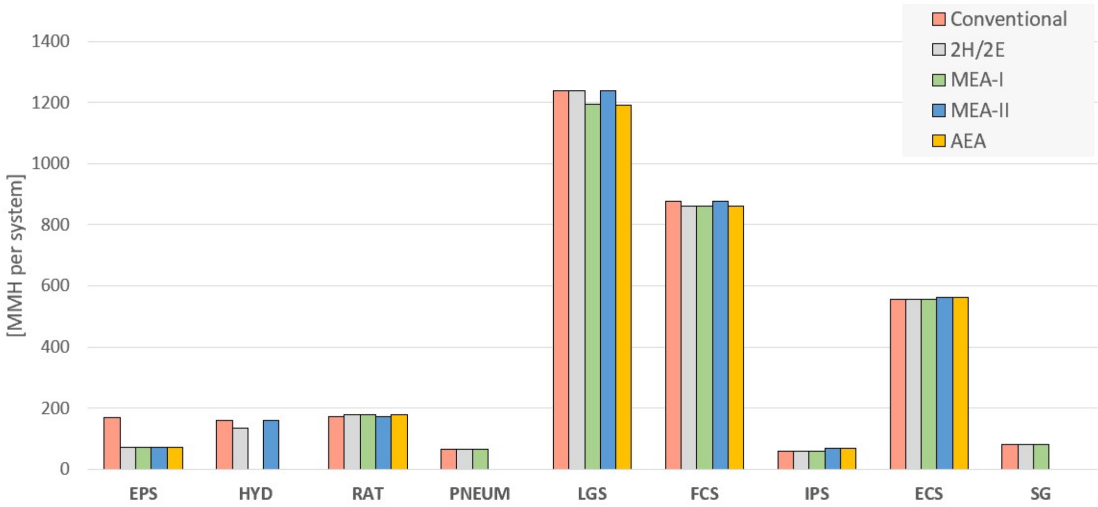


Figure 3.9: MMH absolute variation per system per architecture over the entire operating life in US 1

Table 3.8: MMH percentage variation per system per architecture in US 1

	EPS	HPS	RAT	Pneumatic	FCS	LGS	ECS	IPS	Starting	Overall
1. Conv	-	-	-	-	-	-	-	-	-	**-**
2. 2H/2E	-58.13%	-16.43%	+7.74%	-	-1.74%	-	-	-	-	-3.74%
3. MEA-I	-58.13%	-100%	+7.74%	-	-1.74%	-3.66%	-	-	-	-9.04%
4. MEA-II	-58.13%	-	-	-100%	-	-	+1.15%	+13.71%	-100%	-6.82%
5. AEA	-58.13%	-100%	+7.74%	-100%	-1.74%	-3.99%	+1.15%	+13.71%	-100%	-13.07%

By observing these preliminary results coming from the data generation it's worthy highlighting a few aspects:

- The removal of the frequent oil tasks for the IDG has led to a significant MMH decrease in the EPS.
- Even if in the "2H/2E" architecture one hydraulic line out of three has been completely removed, the associated MMH reduction is way below the 33% one could have had initially hypothesized. This is due to the fact that some checks have still to be performed, independently of the number of lines.
- The introduction of an electric generator driven by the RAT is expecting to lead to an increase in MMH because of the lower reliability of the electric component with respect to the hydraulic pump. Nevertheless, it has to be noted that even if the overall maintenance effort for this component has increased, the fact that the operator doesn't have to deal with hydraulic elements, such as toxic oils, filters and sealings, is expected to allow some

time saving, thus mitigating the total increase for the electrification of this subsystem. However, this aspect has not been assessed in this study.

- The pneumatic and the starting systems have been completely removed in the “MEA-II” and in the “AEA” architecture, leading to a MMH saving comparable to the one linked to the removal of the hydraulic system (147 MMH for the pneumatic and starting systems versus 160 MMH for the HPS).
- No big difference is expected between an EMA actuated and a LEHGS actuated landing gear and more generally, the impact of the electrification on this system is little because many MMH are required for visual inspections, lubrication of movable parts and functional checks for elements, such as the shock absorbers, that will be present even in the more electric architectures.
- The IPS and the ECS present a slightly increase in maintenance effort due to the addition of new components that will require scheduled maintenance, i.e. the WAI thermal blankets and the ram air compressors.
- By looking at the overall reduction in the OBS maintenance for each architecture, the removal of the hydraulic system is expected to have a more important effect on the scheduled maintenance (-9.26% for the “MEA-I” architecture) compared to the removal of the bleed and pneumatic systems (-6.82% for the “MEA-II” architecture).

3.4 Expert Interviews

Even if the method proposed by Dell’Anna is very accurate in evaluating the MMH to be removed when going from a conventional to a more or all electric OBS architecture, it’s not possible to say the same for the evaluation of the maintenance tasks that need to be added in such architectures. Although the proposed approach is of course reasonable, the results may be still lacking of accuracy and are heavily affected by the goodness of the failure rate database that a user might access.

To overcome this issue, in the present work two methods have been applied. As already presented, the first one is the academic literature based approach that exploits the methodology proposed by Dell’Anna [10] and whose results for the five reference architectures have already been shown in the previous section. The second approach is instead experience based and relies on the collection and elaboration of maintenance experts’ opinions. The experts’ belief has been used to compare the results obtained with the literature based method and eventually correct the data coming from the replacement and the adding of new components, whose associated MMH were evaluated with the failure rate analogy.

In order for the final results to be as more objective and unbiased as possible, a group of five experts having different backgrounds has been chosen. Two of the experts have an academic background and work mainly in the research field for the DLR and the Politecnico di Torino (PoliTo); a third one is a member of the DLR but has been working in an operating environment for a long time; while the last two experts are members of the Airbus company.

The interviews have been conducted between December 2023 and February 2024 and consisted of a brief explanation of the objective of the present thesis, followed by an accurate description of the five reference architecture that have been used. After this introductory phase, the experts were asked to estimate the MMH variation for each system in each architecture, without knowing the results achieved with the literature based approach and their answers were finally collected in confidence tables.

3.4.1 Confidence Tables

The confidence table is a support tool that helps gathering someone's opinions about one topic. More specifically, the confidence table presents several intervals, where the person who answer can put a certain percentage of his belief. Therefore, it is a useful support to use when it's very hard to provide a specific value as an answer and it consents the responder to spread his belief into multiple intervals at the same time, hence reflecting the uncertainty of his answers, which often is inevitable. An example of such tables, where the belief of three people is reported, is shown in Figure 3.10.

In this case *Blue* is quite sure about the 10°-25°C interval and he thinks that the correct temperature value is laying even more probably in the 12°-20°C interval. On the other hand, *Green* is quite unsure and spread his belief over many different intervals. He thinks there is a chance for the temperature to have been fallen in the 0°-15°C interval, likely in the 7°-15°C interval, and more probably in the 10°-12°C and 12°-15°C intervals. Lastly, *Red* is very sure about one answer and put all his belief in the associated interval.

The confidence tables that have been used for the actual interviews have the same structure as the one provided in the previous example, but they are based on percentages instead of absolute values, as can be seen in Figure 3.11. Each confidence table comprehends the interval in which the value obtained via the literature based approach lies, but all the tables have been centered on random values in order not to influence experts' answers.

It's worthy noting that different intervals and different scales have been used for each question, but the same intervals and scale have been used for the questions regarding different architectures of the same system.

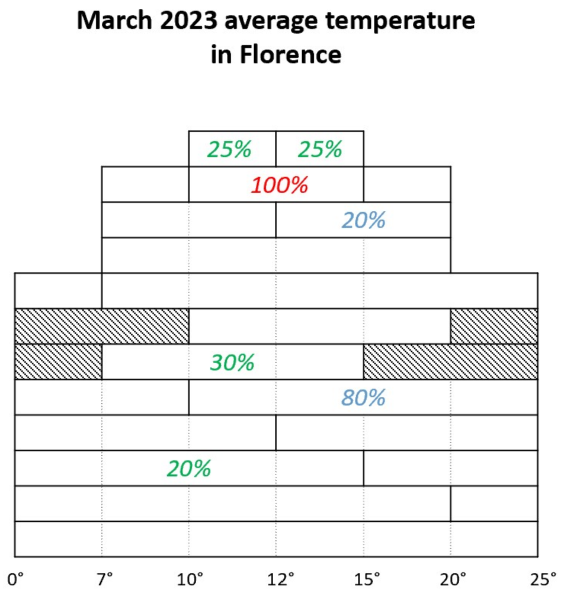


Figure 3.10: Confidence table example with answers from three different experts

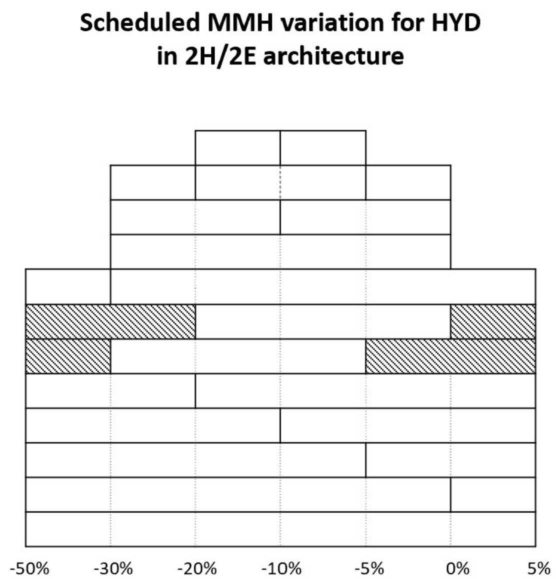


Figure 3.11: "2H/2E" HPS confidence table

3.4.2 Collected opinions

Due to the lack of knowledge on the subject and the lack of justification for the given answers, one expert has been classified as an outlier and has been excluded from the analysis. The opinions of the other experts have been reported anonymously in the Appendix E.

In addition to the answers, experts were encouraged to provide some additional comments regarding useful knowledge they could possibly share in order to validate their beliefs. In particular, the following opinions were commonly shared among the majority of the experts:

- ECS ram air compressors are more complex to control and to maintain than bleed regulation valves and their utilisation would likely lead to a rise in scheduled maintenance effort.

- An electrified IPS that relies on thermal blankets for the WAI would not need additional tasks. This is due to the fact that these components can be easily checked with the same task in which the probe and windshield ice protection resistances are, since they will likely be part of the same electric circuit.

- The expected saving from the removal of the hydraulic system is higher than the one coming from the removal of the bleed and pneumatic system.

3.4.3 Summary

In order to elaborate experts' opinions and extract numeric values from them, an uncertainty quantification method has been exploited. In particular, evidence theory [74] (for which more insights can be read by Ramm [75]) has been applied. As well described by [75], this method implies the translation of each experts' answer into a Basic Belief Assignment (BBA). More specifically, each BBA contains the information about one interval suggested by one expert and his associated confidence level. Every BBA from one expert is then divided by the width of its interval, hence defining a Belief density function. Consequently, the repetition of this process for all the statements of one expert generates a Belief space for each uncertain input. Experts' beliefs are then combined and multiple cumulative density functions are generated. This passages have been automatised within the `dste` Python package by DLR [76], which has been used in the present work.

After generating the cumulative density functions, a large number of samples have been created and used to conduct a Monte-Carlo simulation. This process has finally led to the results that are shown in the following chapter.

3.5 Comparison of the estimates

As can be observed in table 3.9, the results coming from the experts are in line with the ones obtained from the MPD analysis for most of the architectures since just the "MEA-II" presents a significant spread between the two estimations.

Table 3.9: MMH variation comparison

[ΔMMH]	2H/2E	MEA-I	MEA-II	AEA
MPD analysis	-127	-306	-231	-442
Experts' belief	-111	-290	-95	-463

This can be explained by looking at the percentage OBS MMH variations in Table 3.10 and at the total amount of MMH required for each system in Table 3.11. Actually, it can be noticed that this distance is mostly originated by the estimation differences in the starting system and in the EPS, while the different estimations on the ECS and the pneumatic system are equalised by the one on the IPS.

Although the "AEA" adopts the same aforementioned systems as the "MEA-II", this situation doesn't occur again because of the experts' belief on the LGS in the former architecture. In fact, in experts' opinion, the adoption of a full electric LGS is expected to bring an extra -10.18% with respect to what evaluated with the MPD analysis and since the LGS is the most time consuming system to maintain, this difference is sufficient to fill the gap that was introduced with the "MEA-II" EPS and starting system.

Table 3.10: Percentage OBS MMH variations

	FCS	HPS (2 lines)	RAT	EPS (VFG)	HPS (0 lines)	LGS (LEHGS)
MPD analysis	-1.74%	-16.4%	+7.74%	-58.1%	-100%	-3.66%
Experts' belief	-3.89%	-21.3%	-16.5%	-8.45%	-81.3%	-6.74%

	Pneumatic	ECS	Starting	EPS (SG)	IPS	LGS (EMA)
MPD analysis	-100%	+1.15%	-100%	-58.1%	+13.7%	-3.99%
Experts' belief	-84.4%	+4.38%	-23.9%	-10.1%	-46.4%	-14.2%

In order to improve the accuracy of the study and mitigate the uncertainties inevitably coming from either the literature based and the experience based approach, it has been decided to take the mean value between the results of both methods. The mean value has been chosen because each approach has its own strengths and weaknesses and none is clearly better than the other. Therefore, their results have

Table 3.11: Total OBS required MMH

	FCS	HPS	RAT	EPS	LGS	Pneumatic system	ECS	Starting system	IPS
Total MMH	876	160	172	169	1240	65	560	82	60

exactly the same weight. However, a few exceptions have been made in those cases where there were evidences that one method was more accurate than the other. In particular, this has happened for the following systems and subsystems:

- **RAT**: in this case the results from the MPD analysis are suggesting an increase in MMH. This is due to the fact that every task related to the RAT has been escalated with the failure rate ratio, which is coming in part from the exploitation of the NPRD [73], that is almost 50 years old and might not contain updated data, and the Quanterion Database [44], that instead, in this specific case, is not providing enough detailed information to ensure to be referring to the proper component. Additionally, the latter is mostly reporting military components which might undergo higher loads and more severe operating conditions than civil components.

  On the other hand, all the experts agree on the fact that a MMH reduction has to be expected from the changes operated on this subsystem.

  Since these two reasons, it has been decided to assume that no changes were to be expected from the MPD analysis and the MMH variation that has been used for the realisation of the MMHER is the mean between 0% and the value provided by the experts. The decision to take the mean value instead of the estimation provided by the experts is justified by the fact this way a more realistic and conservative assumption has been made.

- **HPS (0-lines architecture)**: in this case, the experts results have been affected by a bias during the elaboration phase. In fact, during the interviews most of the experts were pretty much sure about expecting a -100% reduction in MMH for this system. However, due to the confidence tables that have been used to collect their answers, they had to put all their belief in the -100%/-75% interval, thus generating also samples with smaller reductions than the one they specifically indicated, during the elaboration phase. Since also the MPD analysis converged to the -100% reduction to be expected, this value has been taken as the valid one for the MMHER build up.

- **Pneumatic system**: also for this answer the same phenomenon as the previous system repeated and the same decision has been taken. The -100%

expected from the MPD analysis and the experts has been used as definitive value.

- **IPS**: in this case, during the study of the MPD tasks it was assumed that the electric IPS used in the "MEA-II" and the "AEA" architectures required additional tasks for the monitoring of the electric resistances. On the contrary, all the experts either agree on the fact that this system likely won't require additional tasks but can be maintained with the same task that is already implemented or, otherwise, on-condition maintenance can be performed thanks to the ease of installing a health management device on such system. Similarly to the RAT, also for this system it has been assumed that the adoption of an electric IPS would not produce any MMH variation from the MPD analysis and the final value that has been chosen is again the mean between 0% and the one resulting from the expert opinions. This choice is again justified by the fact that this way a more conservative assumption has been made.

The final values that have been used for the development of the MMHER coming from US 1 are gathered in Table 3.12, while those generated in US 2 are shown in Table D.2 of Appendix D.

Table 3.12: Final MMH expected variations

	FCS	**HPS (2 lines)**	**RAT**	**EPS (VFG)**	**HPS (0 lines)**	**LGS (LHEGS)**
%	-2.82%	-18.9%	-8.25%	-33.3%	-100%	-5.20%
ΔMMH	-25	-30	-14	-56	-160	-64

	Pneumatic	**ECS**	**Starting**	**EPS (SG)**	**IPS**	**LGS (EMA)**
%	-100%	+2.77%	-62.0%	-34.1%	-23.2%	-9.08%
Δ MMH	-65	+15	-51	-58	-14	-113

Once again, as firstly affirmed in Section 3.3.3, it can be confirmed that no relevant differences occur between the results of the two scenarios. In fact, the absolute MMH differences between the two cases are mostly due to the different total MMH required and not because of the percentage spread occurring in some systems. This quantity can indeed be easily considered negligible over the whole operating lifetime of the aircraft.

Since this conclusion, from now on, the arguments discussed in the following chapters are no more taking into account US 2 and are sticking to the data coming from US 1.

Chapter 4

Method Development

The following step that is needed to build the MMHER is identifying the quantities that influences the estimation, in other words, the MMHER independent variables or, more simply, MMH drivers. Of course, each of these maintenance drivers requires also a different coefficient to reflect its impact on the final result. The methodology that has been followed to determine such quantities is illustrated in Sections 4.1 and 4.2. Lastly, the equation has been implemented on a Python code and verified. This process is described in Section 4.3 and Appendix F.

4.1 MMH drivers definition

Since all the architectures that have been analysed are based on the same aircraft (the A320), many of the most common and widely used variables, such as the aircraft's geometrical dimensions and weight, are not suitable for this estimating equation. This is due to the fact that such variables are expected to remain more or less the same among the architectures upon which the MMHER is based on. Moreover, the assumption that has been made during the data generation phase that dimensions and weight are not responsible for MMH variations ensures us that eventual weight oscillations are not affecting the MMH evaluation.

On the contrary, the MPD analysis and the expert interviews provided a good amount of information about the scheduled MMH required for each system in either conventional and more electric architectures. For this reason, systems themselves have been chosen as inputs for the equations. More specifically, one or more discrete variables have been defined for most of the systems, in order to be able to represent all the possible more electric configurations. In almost every case the variables are binary, which means that they can assume either the value 0 or 1. The only exception is represented by the variable related to the FCS, for which integer values between 0 and 21 can be chosen.

A list of the variables and what they represent is provided below:

- ***Batt***: this variable specify the chemical composition of the emergency batteries, thus indicating whether they are Ni-Cd or Li-Ion batteries.
- ***Gen***: it indicates whether an innovative generator (i.e. a VFG or a SG) is installed or not.
- ***SG***: this variable reflects specifically the presence of Starter-Generators instead of any other generator technology.
- ***EHA***: this quantity represents the number of EHAs that are installed for the FCS. In fact, the possibility to have a hybrid actuated FCS has been contemplated and this variable assesses the electrification degree of this system.
- ***Lines***: the user can decide whether a hybrid FCS using both EHAs and HSAs needs to be supplied by two or three hydraulic lines. This choice has been allowed because the surfaces that are still actuated by the HSAs are not specified. Therefore, the choice of three hydraulic lines could be mandatory for safety reasons (for example in the case where we still have four HSAs for the surfaces of the elevator) or maybe just two lines are sufficient (for example in the case of four HSAs moving the spoilers).
- ***LGS***: this variable carries the information about the presence of EMAs for the actuation of the landing gear doors, the braking function and the steering function. It's worthy pointing out that a hybrid satisfaction of these functions with either HSAs and EMAs has not been contemplated. Also, note that if these functions are satisfied with hydraulic actuators, the gear extraction is assumed to be performed with HSAs as well.
- ***EMA***: when the gear actuation is satisfied by more electric components, this variable indicates whether this function is performed with EMAs or with a LEHGS.
- ***IPS***: it includes the information about the installed IPS, specifying whether it is bleed based or it adopts thermal blankets.
- ***ECS***: it reflects whether the ECS is bleed based or relies on ram air compressors.

Since the architectural choices of the RAT and the power distribution systems are strictly dependent on the users that have to be fed, the RAT, the EPS, the HPS and the pneumatic system have not been represented by an independent maintenance driver.

4.2 Equations definition

The equations that have been used to evaluate the MMH variations for each system and subsystem are presented and explained below. Lastly the MMHER is shown in Equation 4.10.

The general idea behind the equation definition is that it is firstly necessary to identify the variables that have an impact on each system. Then, they should be combined with the coefficients in such a way that, if a more electric architecture is analysed, the expected MMH variations shown in Table 3.12 are provided as a result.

Lastly, a multiplicative factor of three has been applied at the beginning of each expression because, as reported by [77], the MPD provides the ideal amount of MMH required to accomplish each task. Therefore, a corrective factor must be applied for real life applications. On average, this quantity is assumed to be 2.5 for the A320, but values up to four (and higher for start-up maintenance providers) can also be reached [77]. For these reasons, a corrective factor of three has been adopted in the present study.

- **FCS**

  The only variable affecting the Flight Control System MMH evaluation is the *EHA* variable. In particular, it has been assumed that the saving expected for this system are directly proportional to the number of electric actuators that are installed. As a consequence, the saving reported in table 3.12 is achieved when all 21 FCS actuators are EHAs. The *EHA* variable can range from 0 (for a conventionally actuated FCS) to 21 (for a full electric FCS). As can be seen in Equation 4.1, in order to assess the MMH variation for this system, the *EHA* variable is firstly divided by 21, i.e. the total number of actuators, and then is multiplied by the total expected saving for the system.

$$\Delta MMH_{FCS} = 3 \cdot (-24.71 \cdot \frac{EHA}{21}) \tag{4.1}$$

- **LGS**

  The variables influencing the Landing Gear System MMH evaluation are *LGS* and *EMA*. The former can be set either to 0 or to 1 and, as can be seen in Equation 4.2, it multiplies a quantity in brackets. In particular, this term can provide either the forecast savings for a LGS architecture actuated with LEHGSs or EMAs. By doing so, if a conventional architecture is adopted, the *LGS* variable will be set to 0 and no MMH variation is accordingly provided. Otherwise, it will be set to 1 and the MMH variation associated to the LEHGS actuated architecture will be automatically provided. If also the *EMA* variable is set to 1, an additional contribution is unlocked in order to reach the MMH variation expected for this technology. If instead EMAs are not installed for the gears actuation, the *EMA* variable has to be set to 0 and the additional contribution won't be provided.

A particular case can occur if the user decides by mistake to set the *LGS* variable to 0 and the *EMA* variable to 1. The adoption of EMAs contradicts the fact that a conventional architecture has been chosen and the equation ignores the actuators choice, providing the conventional architecture output.

$$\Delta MMH_{LGS} = 3 \cdot (-LGS \cdot (64.48 + 48.11 \cdot EMA)) \tag{4.2}$$

- **IPS and ECS**

  The equations for the evaluation of the IPS and the ECS variations have been built in a similar, but simpler way and are reported in Equations 4.3 and 4.4. The involved variables are *IPS* and *ECS* and they can assume just the values of 0 and 1. Therefore, it's sufficient that they multiply directly the correspondent amount of MMH that change due to their electrification.

$$\Delta MMH_{IPS} = 3 \cdot (-13.92 \cdot IPS) \tag{4.3}$$

$$\Delta MMH_{ECS} = 3 \cdot (15.43 \cdot ECS) \tag{4.4}$$

- **RAT**

  The RAT equation is based on the same idea of the previous ones. The RAT electrification only depends on the complete electrification of the FCS, that is when all 21 actuators are EHAs. Therefore the equation needs to distinguish when this condition is verified and when it is not. The solution to this problem comes from the application of the function *Floor* to the ratio $\frac{EHA}{21}$. In fact, the quantity *Floor(*$\frac{EHA}{21}$*)* is equal to 1 only in the case where the *EHA* variable is set to 21, indicating a full electric FCS. On the contrary, in any other case, it is equal to 0. With this idea in mind, as shown in Equation 4.5, it's sufficient to multiply the function *Floor(*$\frac{EHA}{21}$*)* by the amount of MMH that are saved by electrifying the RAT.

$$\Delta MMH_{RAT} = 3 \cdot (-14.23 \cdot Floor(\frac{EHA}{21})) \tag{4.5}$$

- **Starting**

  The evaluation of the MMH variation due to the engine starting technology depends on the two variables *Gen* and *SG*. In fact, the two conditions regarding these variables must be true at the same time in order to achieve the electric starting saving. Therefore, the aforementioned variables must multiply each other and the correspondent MMH variation. If just one variable is different from 1, that is when an innovative generator is not installed or it is installed but it isn't a SG, then the output will be null.

$$\Delta MMH_{Starting} = 3 \cdot (-50.55 \cdot SG \cdot Gen) \tag{4.6}$$

- **EPS**

  As can be appreciated in Equation 4.7, the EPS MMH estimation depends on three variables (*Batt*, *Gen* and *SG*). In particular, it can be calculated as the sum of two contributions, one coming from the battery choice and one from the generator choice. The evaluation of the former is easily done by setting the variable *Batt* to 1 when innovative Li-Ion batteries are installed and to 0 in the other case. Then, it's sufficient to multiply it by the MMH variation expected for the installation of the Li-Ion batteries. The second term is depending on the two binary variables *Gen* and *SG*. More specifically, this quantity is built in a way that if the IDGs are installed the former variable is set to 0 and no variation occurs. In the opposite case, a first MMH variation, the one linked to the VFG, is provided as an output. Then, if the generators are SGs the *SG* variable is set to 1 and a second contribution to achieve the MMH change associated to such technology is unlocked.

$$\Delta MMH_{EPS} = 3 \cdot (16.99 \cdot Batt - Gen \cdot (73.36 + 1.41 \cdot SG)) \tag{4.7}$$

- **Pneumatic**

  The MMH variation linked to the pneumatic system has been evaluated in Equation 4.8 as the sum of one contribution coming from the APU pneumatic lines and one coming from the engines pneumatic lines. The former is accounted when the APU bleed is no more required for the engine starting, that is when SGs are installed and the *SG* and *Gen* variables are set to 1. Therefore, these variables multiply the MMH variation associated to the APU pneumatic lines removal. The latter contribution, instead, is achieved when bleed air from the engines is no more required for the ECS and the IPS, that is when both *ECS* and *IPS* variables are set to 1. As a consequence, the MMH change due to the removal of the engines pneumatic lines is multiplied by both of these variables.

$$\Delta MMH_{Pneumatic} = 3 \cdot (-49.84 \cdot ECS \cdot IPS - 15.54 \cdot SG \cdot Gen) \tag{4.8}$$

- **HPS**

  For what concerns the HPS, the elimination of one or three hydraulic lines depends on the architectural choices taken for the FCS and the LGS. As a consequence, as reported in the Equation 4.9, the variables affecting the HPS MMH evaluation are *EHA*, *Lines* and *LGS*. In particular, similarly to Equation 4.5, the function $Floor(\frac{EHA}{21})$ has been used to distinguish the architectures in which the FCS is not requiring any hydraulic line. In fact, these are the only cases where all the actuators are EHAs and the aforementioned function is assuming the value 1. Moreover, it has been decided to let the variable *Lines* be binary, so that when just 2 lines are needed for the FCS it is set to 1 and while instead all three lines are needed it has to be set to 0. However, it can happen that the user decides that 2 hydraulic lines are sufficient for the FCS ($Lines$=1), but an hydraulic LGS is present as well (LGS=0). In this case, it has been conservatively assumed that all three hydraulic lines have to be retained for safety reasons.

  It's important to note that when no EHAs are installed the variable must be set to 0. This is mainly because of two reasons. The former is that it's logically and architecturally wrong to put $Lines$=0 when EHA=0, since powering a conventional FCS with two hydraulic lines is not feasible due to safety reasons. The latter is because the MMHER is not designed to recognise whether the inputs are legit or not and it will produce an output which is not correct.

  By looking at the combination of the *LGS*, *Lines* and *EHA* variables in Table 4.1, it has been possible to distinguish the cases where three, two or no hydraulic lines are needed and the corresponding MMH variations should be provided accordingly.

Table 4.1: Possible combinations of *EHA*, *Lines* and *LGS* variables

	$Floor(\frac{EHA}{21})$	***Lines***	***LGS***	**Hydraulic lines**
Case 1	0	0	0	3 lines
Case 2	0	1	0	3 lines
Case 3	0	0	1	3 lines
Case 4	0	1	1	2 lines
Case 5	1	-	0	2 lines
Case 6	1	-	1	0 lines

In particular, this has been implemented in Equation 4.9 through the sum of two contributions. The former evaluates the HPS savings when the FCS is fully electrified, and, depending on the LGS actuation, provides the MMH variation associated to the removal of either one or all three hydraulic lines. The latter, instead, gives as an output the MMH variation associated the the removal of one hydraulic line when the LGS is electrified and the FCS is supplied by two hydraulic lines. If one of those two conditions is not true, then the result of the estimation is zero because all three hydraulic lines are needed and nothing is changing from the conventional configuration. It's important to specify that both contributions can not be different from zero at the same time, hence excluding the possibility to evaluate twice the HPS MMH variation.

$$\begin{aligned} \Delta MMH_{HPS} =& 3 \cdot (Floor(\frac{EHA}{21}) \cdot (-30.17 - 129.86 \cdot LGS)) + \\ & - (1 - Floor(\frac{EHA}{21})) \cdot 30.17 \cdot LGS \cdot Lines \end{aligned} \tag{4.9}$$

- **Aircraft**

  Equation 4.10 gathers the MMH changes provided by each system and evaluates the total variation associated to one specific OBS architecture.

$$\Delta MMH_{Aircraft} = \sum \Delta MMH_{systems} \tag{4.10}$$

4.3 MMHER verification

In order to automate the calculation process, the MMHER has been implemented in a Python code. The script takes the equation variables as inputs and provides the MMH variations for each system and for the overall architecture as outputs.

The equation has been verified ensuring that in any case the results coming from the code, the MMHER and the ones reported in Table 3.12 are consistent with each other.

A few configurations that have been used in the verification process are reported in Appendix F along with the comments justifying the process correctness.

Chapter 5

Use Cases

In this chapter the MMHER has been applied to several use cases. Firstly, the architecture presenting the greatest MMH reduction is described and analysed in Section 5.1. Then, five architectures with different degrees of electrification have been chosen and compared. A few comments regarding the most relevant OBS are collected in Section 5.2. Lastly, a sensitivity analysis has been carried out on the HPS and the pneumatic system. Its description and results are presented in Section 5.3.

5.1 Greatest MMH reduction

The first application of the MMHER is performed on the Use Case Architecture (UCA) that maximizes the MMH saving to find out what is the greatest amount of maintenance hours that can be removed by adopting the optimal OBS architecture. This configuration, which will be called UCA 1, is easy to identify because it is sufficient to set to 1 the binary variables that are multiplied by negative terms and to 0 those which will provide a positive contribution to the ΔMMH. Two special cases are represented by the *EHA* and *ECS* variables. In fact, the former is not a binary variable and in order to obtain the biggest saving at the end, it must not be set to 1, but to 21. In the latter case, the *ECS* variable is multiplied by a positive term in Equation (4.4) and by a negative term in Equation (4.8). This way the saving introduced by the pneumatic lines removal are bigger then the MMH raise due to the ECS electrification. Therefore, in order to achieve the architecture with the biggest overall MMH reduction, it is necessary to set the *ECS* variable to 1.

The features of this configuration are listed below:

- Full electric FCS (21 EHAs).
- Electric actuated LGS for door opening, braking and steering.

- Landing gears extracted and retracted by EMAs.
- Thermal blankets for the IPS.
- Electric ram air compressors installed in the ECS.
- Electric engine starting provided by two Starter-Generators.
- Ni-Cd batteries and SGs for the EPS.
- AC generator connected to the RAT.
- No hydraulic lines.
- No pneumatic lines.

It's relevant to point out that this UCA is different from the AEA architecture that was used for the data generation process in Chapter 3. In fact, contrarily to what it was expected at the beginning, the Li-Ion batteries that were used in that architecture later resulted to be disadvantageous from the maintenance point of view. On the contrary, every other technology that was installed in the AEA architecture of Chapter 3, resulted indeed to be the best choice to achieve the lowest scheduled MMH.

The UCA 1 OBS configuration is presented in Appendix G. It has been realized starting from the A320 ADORE model that was presented in Section 3.2 to demonstrate the possibility to integrate the MMHER within this virtual environment. In fact, the inputs needed for the MMH evaluation are specifically provided as outputs by the architectures generated by the software. This feature could indeed result to be very useful for future studies that aim, for example, to conduct multi-objective analysis or multi-objective optimizations on the same model, hence enhancing its reusability and the traceability of the results.

The MMHER variables have been chosen accordingly to the UCA 1 features and are reported in Table 5.1, while the MMH variations for each system are collected in Figure 5.2.

Table 5.1: MMHER inputs for UCA 1

	Batt	*Gen*	*SG*	*EHA*	*Lines*	*LGS*	*EMA*	*IPS*	*ECS*
UCA 1	0	1	1	21	1	1	1	1	1

By looking at the results in Figure 5.2, it is evident that around 1500 scheduled MMH are expected to be saved over the aircraft operating life, if the aforementioned all-electric configuration is adopted.

In particular, it can be noted that the complete removal of the hydraulic lines is expected to save more scheduled MMH than the removal of pneumatic lines.

Moreover, if we also compare the savings introduced by the electrification of the user systems (i.e. the FCS and the LGS for the hydraulic power and the ECS, IPS and the starting system for the pneumatic power), this spread is greatly amplified.

The changes introduced with this architecture lead to a 14.8% reduction of the total OBS scheduled MMH needed for the conventional A320, which can be obtained by summing the total MMH per system reported in Table 3.11.

In addition, as can be also noted in Figure 5.1, the HPS and the LGS are the systems where the biggest amount of MMH can be saved. With smaller impact, but still very important, the EPS, the pneumatic and the starter system lead to intermediate savings, while the IPS, the FCS and the RAT have the smallest effect on the forecast scheduled MMH variation. However, it must be remarked that even if these systems by themselves don't provide a great contribution, their electrification allows the partial or total removal of the associated power distribution lines and the distribution systems ΔMMH is far from being negligible.

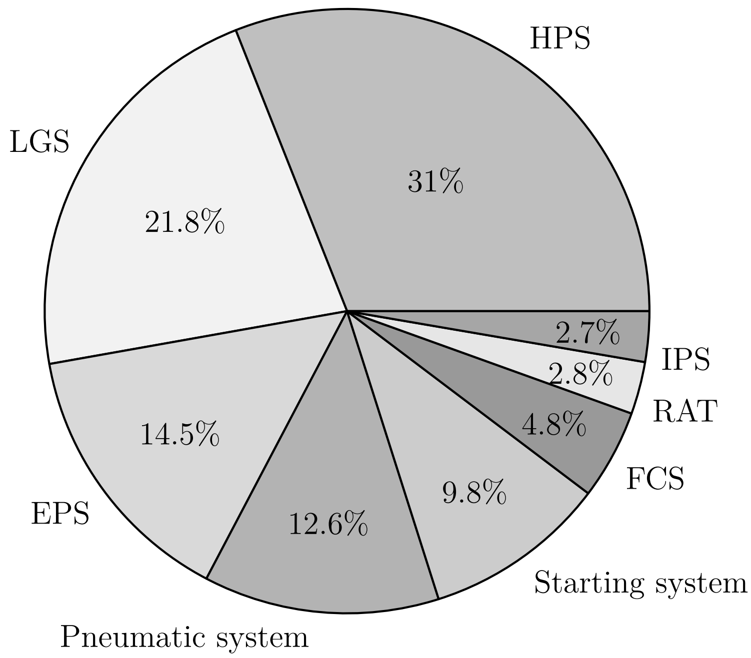


Figure 5.1: MMH saved per system over the total MMH saved in the UCA 1

5.2 Hybrid architectures

A set of five UCAs has been created with the inputs shown in Table 5.2. These configurations have been chosen reflecting different electrification levels and assessing a few combinations of different more electric systems. It's worthy noting that the UCA 1 is exactly the same one that has been previously introduced in Section 5.1.

The correspondent outputs from the MMHER, showing the ΔMMH per system for all different UCAs, are gathered in Figure 5.2.

Table 5.2: MMHER inputs for UCAs from 1 to 5

	Batt	*Gen*	*SG*	*EHA*	*Lines*	*LGS*	*EMA*	*IPS*	*ECS*
UCA 1	0	1	1	21	1	1	1	1	1
UCA 2	0	0	1	21	0	1	1	0	1
UCA 3	0	1	0	11	1	1	0	1	1
UCA 4	1	1	1	0	0	0	1	0	0
UCA 5	1	0	0	0	1	1	0	1	0

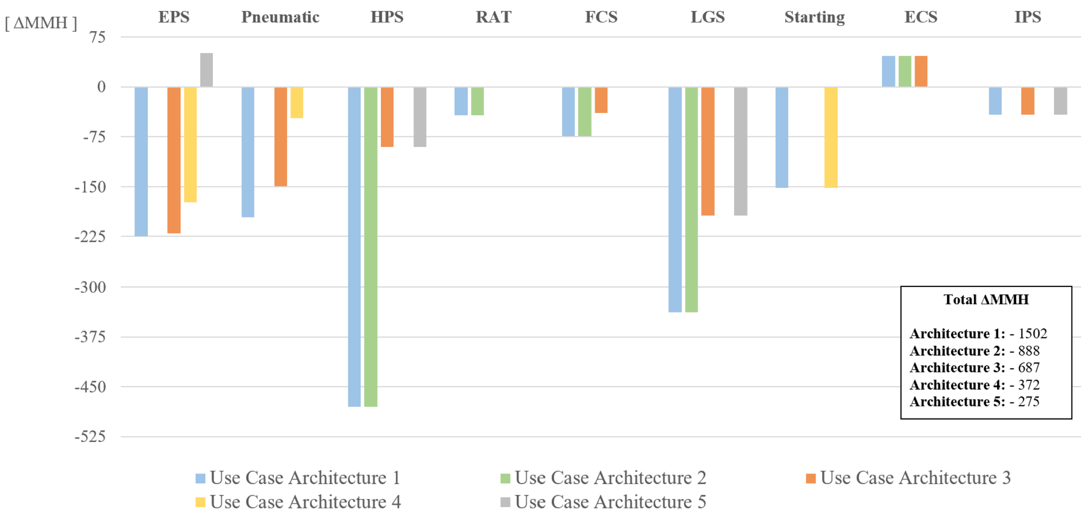


Figure 5.2: MMHER outputs in terms of ΔMMH for UCAs from 1 to 5

Comparing the UCAs with the help of the graph in Figure 5.2, it can be observed that the greatest differences in MMH reduction among the five configurations come from the HPS, the LGS and the starting system. In particular, it can be observed how a partial removal of the HPS in UCAs 3 and 5 is expected to bring a very small contribution with respect to the one that can be obtained by fully removing all three hydraulic lines, as in the case of UCAs 1 and 2.

For what concerns the LGS, UCAs 3 and 5, which are equipped with LEHGS, are reaching nearly half of the savings unlocked by UCAs 1 and 2, which instead have installed EMAs for the landing gear actuation. Therefore, the replacement of the former technology with the latter is expected to bring MMH savings comparable to those already obtained by UCAs 3 and 5 by electrifying the door, the steering and the braking actuators.

By looking at the pneumatic system results it can be noted how the UCA 3 achieves a big part of the MMH saving that is also obtained by the UCA 1. On the contrary, the savings achieved by the UCA 4 are very small compared to those of the aforementioned configurations. In particular, in the first UCA all the pneumatic lines were removed because of the electrification of the ECS, IPS and starting system. On the other hand, the third architecture presents electrified ECS and IPS, while still retaining a conventional starting system. Lastly, the UCA 4 adopts SGs and conventional ECS and IPS. As a consequence, by looking only at the pneumatic system, this comparison suggests that the removal of the engine bleed ducts has a grater impact than the removal of the APU bleed lines.

However, these changes can also be analysed from another point of view. In fact, the MMH variations resulting from the electrification of the ECS and the IPS in UCAs 1 and 3 nearly compensate each other, while the removal of the conventional bleed based starting system highlighted by UCAs 1 and 4 is instead expected to bring a remarkable MMH decrease. Therefore, it is clear that the advantages of introducing an electric engine starting mechanism (UCA 4) don't have an impact on the pneumatic system as great as the ECS and IPS have (UCA 3), but it becomes evident when looking at the maintenance of the system itself. By summing the contributions coming from the IPS, the ECS, the starting and the pneumatic system, it can be finally concluded that the adoption of the SG technology is expected to lead more benefits that the electrification of the IPS and the ECS.

5.3 Sensitivity analysis

In Section 5.3.1 a sensitivity analysis is performed to see how the HPS is affected by the progressive electrification of the FCS, the choice of the dedicated hydraulic lines and the electrification of the LGS. The same process is repeated in Section 5.3.2 for another use case where, instead, the pneumatic system variation is studied. In this case a more electric ECS, thermal blankets for the IPS and SGs are installed in different architectures each time in a different order.

5.3.1 Hydraulic Power System

In the HPS sensitivity analysis the effect of the FCS and LGS electrification has been evaluated. More specifically, starting from the conventional FCS architecture, one actuator at a time has been electrified until a full electric configuration is reached. Moreover, the number of the FCS dedicated hydraulic lines has also been changed to evaluate the effect of this variable on the HPS ΔMMH.

The electrification of the LGS has been assumed to occur in different moments of the FCS electrification process. In particular, four scenarios have been analysed. In the first one it has been assumed that the LGS is always retaining a conventional architecture. For the other three scenarios an early, mid and late electrification of this system has been simulated. From now on they will be named, respectively, *early*, *mid* and *late* in order to simplify the notation. In the *early* scenario, an electric EMA actuated LGS is installed prior to the introduction of the first FCS EHA. In the *mid* scenario the same LGS architecture is introduced after the installation of the eleventh EHA, while in the *late* scenario this change occurs after all the FCS HSAs are replaced by EHAs.

Each Sensitivity Analysis Architecture (SAA) is identified with a number that specifies the EHAs that are installed for its FCS. Moreover, the architecture where the LGS is electrified for the first time is indicated by the letter *E*, and the number of its EHAs is the same as the one of the previous SAA. All the architectures following the SAA E are retaining its electric LGS configuration.

Figure 5.3 reports the results for the case in which the LGS is always retaining a conventional architecture, while the results of *early*, *mid* and *late* scenarios are shown in Figure 5.4, 5.5 and 5.6, respectively. In these images the consequences, in terms of ΔMMH, of adopting two or three hydraulic lines for the FCS are shown. In particular, for each of the four different LGS electrification scenarios, the total MMH and those saved just by the HPS are compared either when two lines are sufficient or when three are necessary instead.

By analysing the data in Figure 5.3, it can be noted how the choice of using two hydraulic lines instead of three has no effect neither on the total MMH variation nor in the HPS one. This is due to the fact that even when just two hydraulic lines are required for the FCS, it's still necessary to install three lines because of the LGS hydraulic power supply. Only when all the FCS actuators are replaced by EHAs one line can be removed and a sensible reduction can be achieved.

In the *early* scenario, instead, a great MMH saving is obtained at the beginning either when two or three hydraulic lines are needed for the FCS. When the first HSA is replaced a small variation occurs if three hydraulic lines are still needed for the FCS. On the contrary, when two lines are sufficient an extra reduction of nearly a hundred MMH is achieved thanks to the possibility to remove one hydraulic line.

From this point on, the configurations with two and those with three FCS hydraulic lines follow the same trend, but they always keep a constant MMH spread coming from the HPS. The same variation is eventually obtained at the end when all 21 FCS actuators are EHAs and all three hydraulic lines can be removed in every configuration.

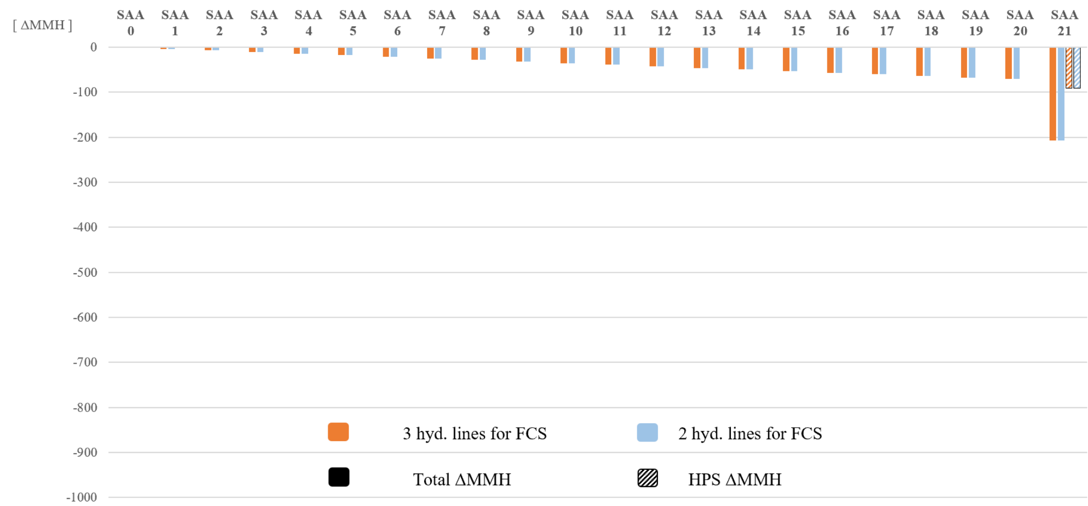


Figure 5.3: HPS ΔMMH if the LGS is never electrified

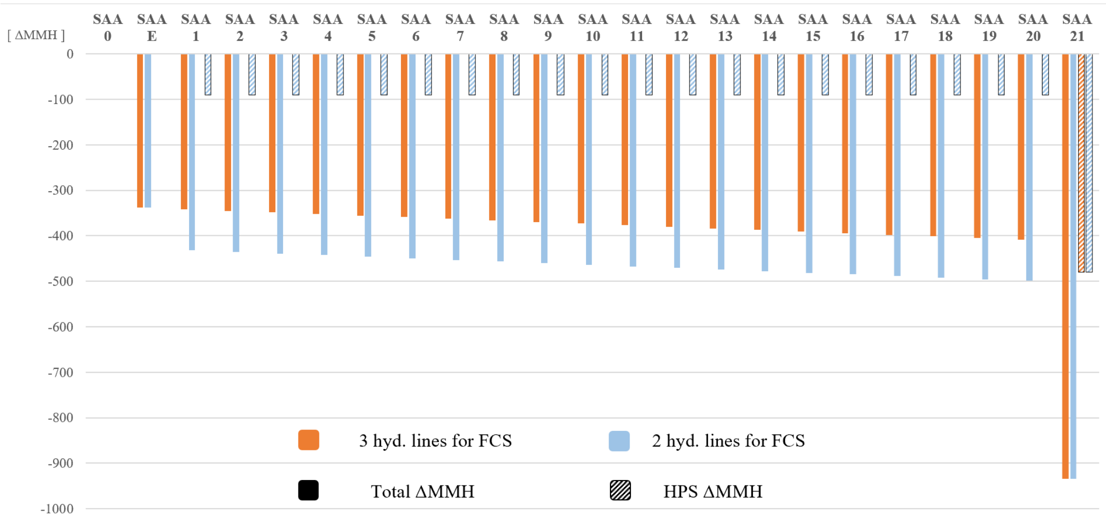


Figure 5.4: HPS ΔMMH in the *early* scenario

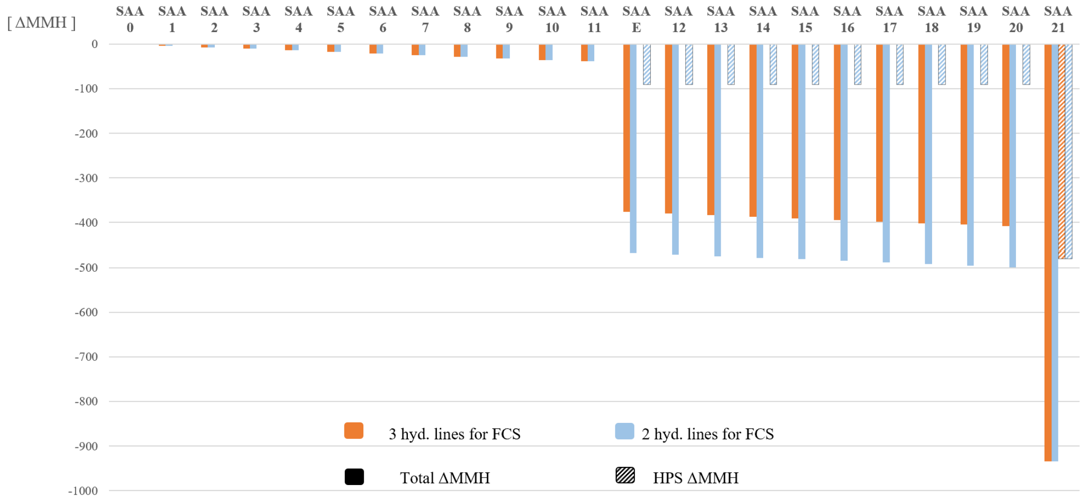


Figure 5.5: HPS ΔMMH in the *mid* scenario

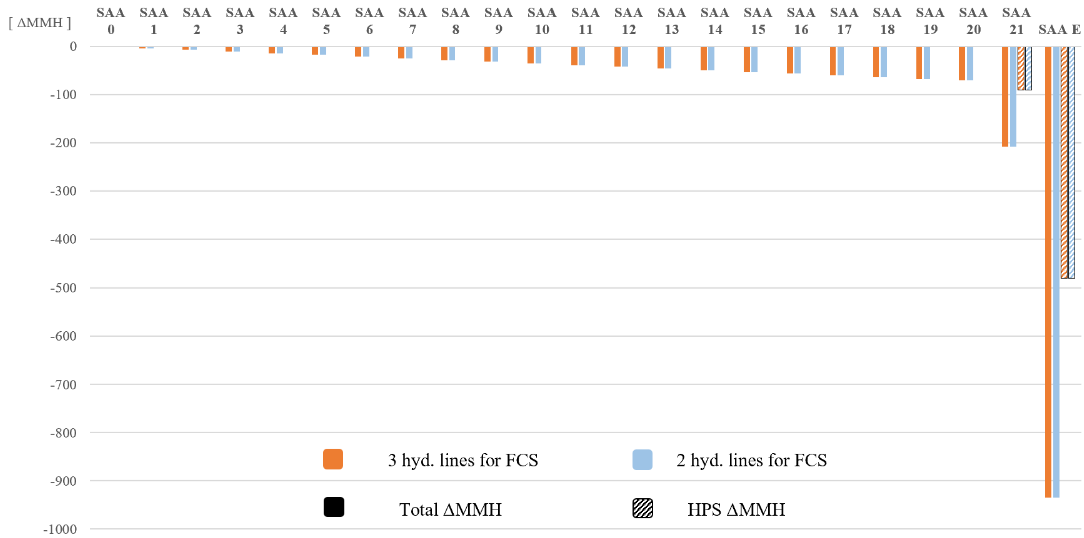


Figure 5.6: HPS ΔMMH in the *late* scenario

By looking at the results presented in Figure 5.5, it can be noted how relatively small MMH savings are achieved until the LGS electrification. The choice of having two hydraulic lines instead of three is not affecting the final result before this event. After that, it can be noted how a much greater MMH reduction is forecast and if the FCS is designed in order to need the hydraulic power supply just by two lines, the maintenance benefits are even greater. Again, the outputs provided by the MMHER when only EHAs are installed are clearly not depending on the number of FCS hydraulic lines because the architecture doesn't need hydraulic lines at all.

Lastly, it can be noted in Figure 5.6 how small savings are achieved until all the HSA are replaced by EHAs. A big reduction is then forecast as soon as the LGS is also electrified. It's worthy noting how in every SAA the number of hydraulic lines needed by the FCS is not having an effect on the MMH variation, since three hydraulic lines are still required until the complete electrification of the FCS.

From the analysis of the four presented scenarios, it can be concluded that focusing on the installation of an electric LGS can lead to greater benefits with respect to those introduced by the replacement of the FCS HSAs with EHAs. Moreover, the efforts made to design a FCS needing a two hydraulic lines power supply are not bringing any advantage unless the LGS is electrified as well. Additionally, comparing the SAA 21 in Figure 5.3 and SAA E in Figure 5.4, it can be noted how the introduction of the EMA technology for the fulfillment of the landing gear functions is leading to a reduction 1.5 times bigger than the one obtained by fully electrifying the FCS. As a consequence, it's clear that the LGS plays a key role in reducing the scheduled MMH and its electrification should be prioritized.

5.3.2 Pneumatic system

The sensitivity analysis on the pneumatic system has been carried out by creating different configurations where the IPS, the ECS and the starting system were gradually electrified in a random order. As a consequence, three steps have been created, where firstly one system out of three is electrified, then two out of three and finally three out of three. All the possible choices for the electrification order have been analysed and are compared in Figure 5.7.

Moreover, one letter has been assigned to each system: the IPS is associated to the letter *I*, the ECS to the letter *E* and the starting system to the letter *S*. The architectures are identified using a three letter code which reflects its systems electrification order. For example, the configuration presenting at first an electric ECS, then also the SGs and finally an electric IPS as well, will be identified by the code *E-S-I*.

By analysing the results shown in Figure 5.7 it can be confirmed that, as one may have expected, no differences occur among the architectures when all three systems are electrified.

On the contrary, the *1 out of 3* and the *2 out of 3* cases are more interesting to analyse. The former suggests that if just one system can be electrified, it should not be the ECS. This choice, in fact, is expecting to lead to an increase in MMH and it's not even allowing the partial removal of pneumatic lines. Instead, if the IPS is the first one to be electrified then a little MMH reduction can be obtained but, again, no pneumatic lines are removed. It's evident that the best choice in

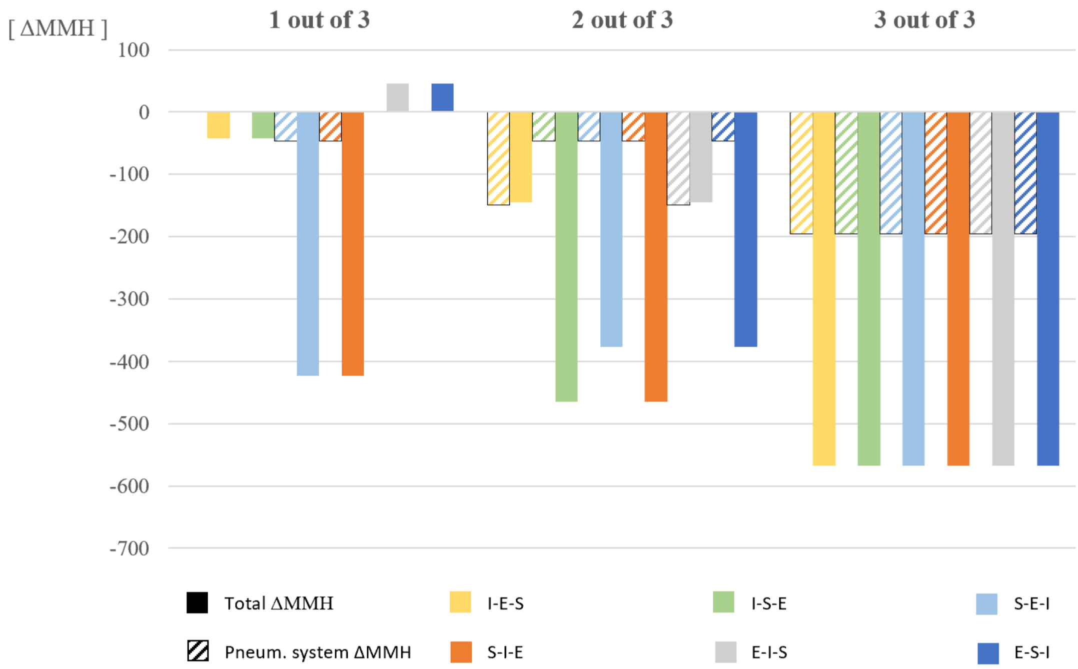


Figure 5.7: MMHER outputs in terms of ΔMMH

this scenario is to electrify the starting system first. This way the greatest MMH saving can be achieved and part of the pneumatic lines can be removed as well.

By looking at the *2 out of 3* scenario, it can be observed that combining the SGs and the IPS electrification leads to the biggest benefits. A similar outcome, even if with a smaller MMH reduction, can also be obtained by installing the SGs and an electric ECS. Contrarily to what it may be expected, in both cases the savings coming from the pneumatic system are way smaller to those introduced by the electrification of either the IPS and the ECS. In that case, in fact, the pneumatic systems MMH reduction is maximized, but it isn't as great as the one obtained in the other configurations.

In conclusion, the introduction of the SG technology should be the first thing to look for in order to maximize the MMH saving. If this technology is not installed at first, it should be integrated immediately afterwards, even if this would mean renouncing to the removal of the engine bleed pneumatic lines.

Chapter 6

Conclusion

Since More Electric Aircraft (MEA) and All Electric Aircraft (AEA) concepts constitute a big innovation from the On-Board Systems (OBS) point of view, conventional cost estimating relationships are no more applicable. The ability to accurately evaluate operating cost, and in particular maintenance costs, in the early design phase can determine the success or the failure of an aeronautical program. Thus, the necessity of new estimating tools arises, but few methods are publicly available and none of them is recent enough to provide reliable results.

The present study aims to contribute to the filling of this scientific gap by studying the effect of MEA and AEA OBS architectures on maintenance. In particular, this thesis is looking to address the OBS architectural consequences on maintenance in the early design stages, where major decisions have to be taken but little information is known. More specifically, the main objective is to understand which are the systems whose electrification has a major impact on the scheduled maintenance, measuring it in quantitative terms. Moreover, the result of partially electrifying some OBS, such as the Flight Control System (FCS) or the Landing Gear System (LGS), has deep implication on maintenance and such hybrid MEA architectures are worthy to be investigated as well.

To accomplish these objectives, a Maintenance Man Hour Estimating Relationship (MMHER) has been build, so that it could estimate scheduled Maintenance Man Hours (MMH) for MEA and AEA OBS architectures. This has been achieved by choosing one reference aircraft, the Airbus A320, and following two approaches.

The former is document-based and focuses on the study of the A320 Maintenance Planning Document (MPD). From the analysis of the MPD it has been possible to link the maintenance tasks to the OBS they were referred to, so that an estimate of the total MMH required for each system could be carried out. Then, a set of three MEA and one AEA architectures with different levels of OBS electrification have been chosen as a basis to understand the MMH variations resulting from different technologies and architectural decisions. In fact, from the MPD analysis it has been possible to identify the maintenance tasks that were deleted as a result of the replacement of components or systems when going from conventional OBS architectures to more electric ones. The second approach that has been followed is instead experience-based. Following the MPD study, a series of interviews to maintenance and OBS experts has been conducted. Basing on their knowledge and their valuable experience, they were asked to evaluate the MMH variations for the same system architectures analysed with the first method. This way it has been possible to determine that the results obtained with both approaches are consistent with each other.

Once the MMHER was built, it has been firstly applied on the architecture presenting the greatest MMH variation. In particular, this configuration is indeed adopted by an AEA where both the HPS and the pneumatic system were removed. The other important aspect to note is that contrarily to the initial expectations, the introduction of Li-Ion batteries has been avoided. This technology is expected to raise the MMH for the electric power system due to safety and reliability issues. From the analysis of this architecture it can be observed that a total saving of nearly 1500 MMH has been achieved, corresponding to a 14.8% reduction in total OBS maintenance with respect to the conventional A320 architecture. More specifically, among all the OBS, the Hydraulic Power System (HPS) and the LGS are the ones where the biggest amount of MMH have been reduced. Regarding the power distribution systems, the removal of the hydraulic lines is expected to lead to higher reductions than the removal of the pneumatic ones. This is due to the characteristics of the former system, which requires several time consuming functional checks and inspections to detect signals of leakages and corrosion.

To better understand the effect of the electrification of each OBS, four more MEA architectures have been generated. At the same time, in order to further investigate the consequences of having hybrid systems on maintenance, two sensitivity analysis, one on the HPS and the other on the pneumatic system, have been performed. The MMH variations provided by the MMHER for each configuration have then been compared and a few aspects are worthy to be pointed out.

Talking about the HPS, the first finding is that a very large spread in saved MMH exists between architectures where just one hydraulic line is removed, instead of all three. In particular, the removal of one line leads to a 23% reduction of HPS MMH, which is smaller than the 33% one may have expected. Secondly, for architectures adopting a hybrid FCS, major MMH savings occur only after the LGS electrification. Before the installation of a more electric LGS, the choice between adopting two or three hydraulic lines to supply the FCS is not affecting the MMH estimation, since all three lines must be retained in every case for safety issues.

For what concerns the pneumatic system, since the engine bleed lines need more numerous and more recurrent tasks than the auxiliary power unit ones, it's more convenient to remove the former than the latter. However, the introduction of the

SG is by far globally reducing more MMH than the combined electrification of IPS and ECS, thus resulting to be the most convenient architectural choice in this case. Moreover, in every case the electrification of the ECS alone is negative and it is expected to lead to a MMH raise, without bringing any significant benefit to the pneumatic system.

The current work provides valuable insights and a valid tool for MEA and AEA maintenance investigations for A320 OBS architectures. This limits this study to a few use cases. In order to extend this study, a bit more actions and research have to be conducted to further expand the knowledge on the topic. A good starting point could be to include the effect of the aircraft dimension and performances in the MMHER, and to address the consequences of high voltage on the electric power system. By doing so, the applicability of the provided equation could be extended to a wider number of MEA and AEA concepts. Moreover, the MMHER could be refined by including in the expert interviews results the opinions of experienced personnel working for an airline. Their belief could be indeed the result of more direct experience with maintenance programs and could therefore constitute an interesting and valuable enlargement of the experts opinion basis. Additionally, some multiplicative factors accounting for labor rate and material cost can also be included in the MMHER and if a proper model accounting for unscheduled maintenance is developed, it could be integrated as well. The resulting cost estimating relationship would hereby be able to address the direct maintenance cost in its entirety.

Appendix A

A320 OBS ADORE model

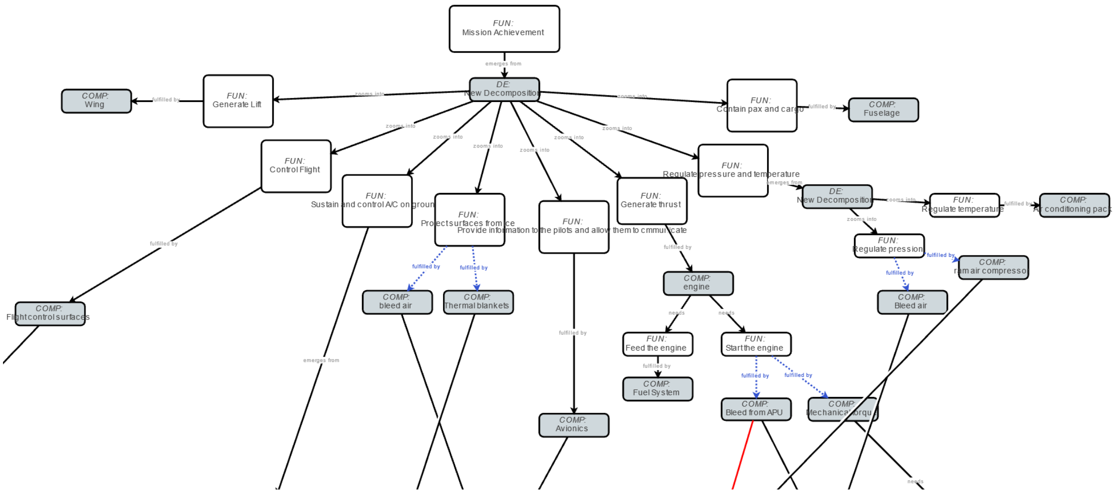


Figure A.1: A320 OBS ADORE design space (top)

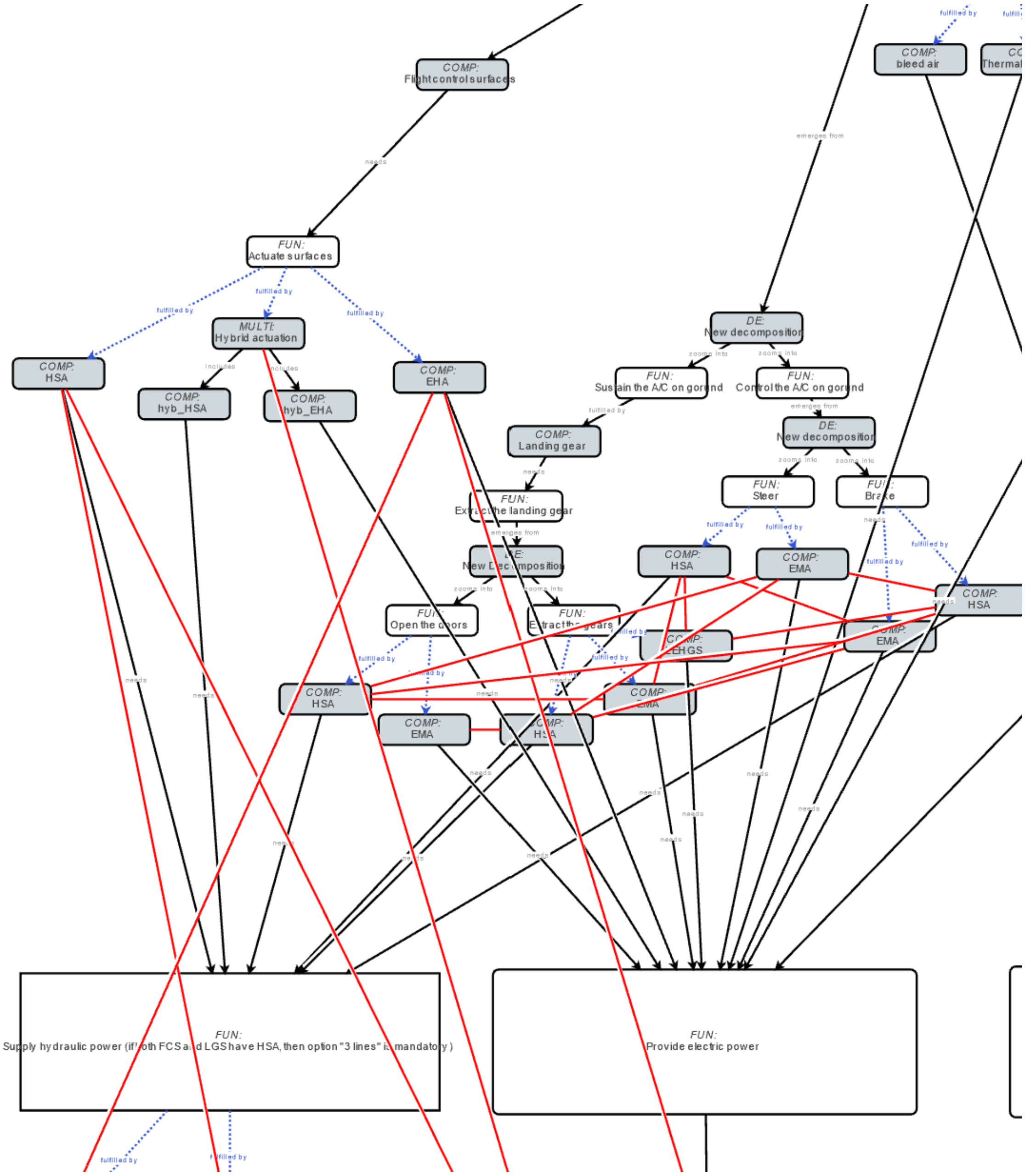


Figure A.2: A320 OBS ADORE design space (mid left)

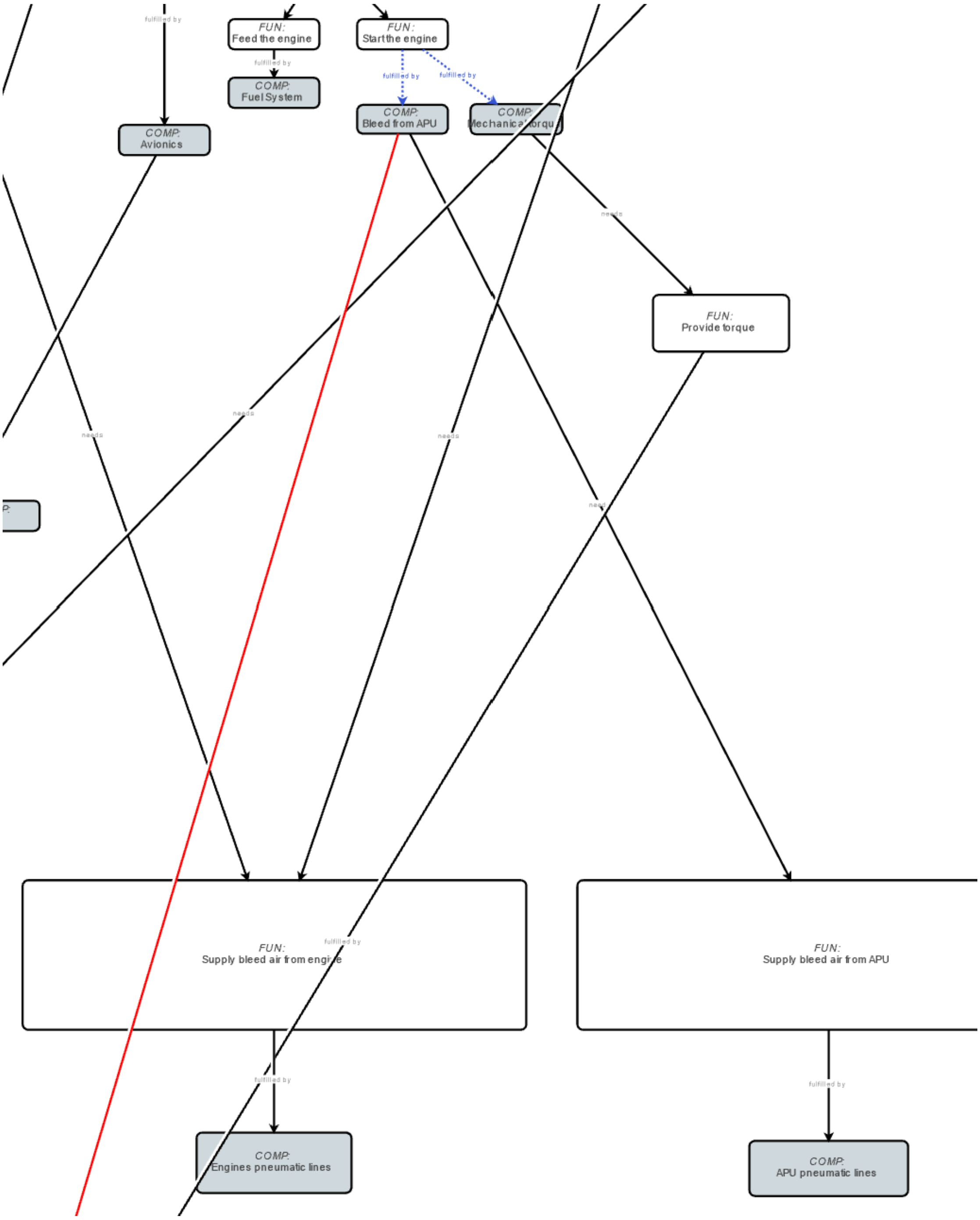


Figure A.3: A320 OBS ADORE design space (mid right)

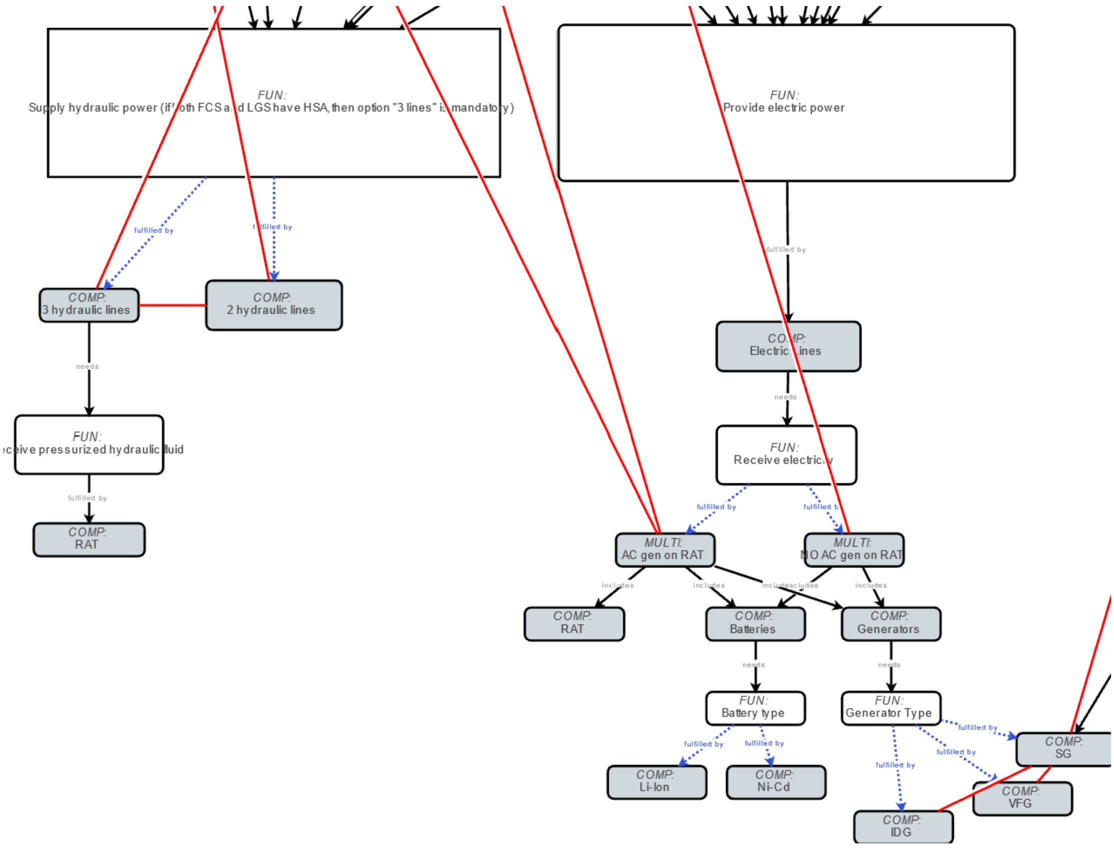


Figure A.4: A320 OBS ADORE design space (bottom left)

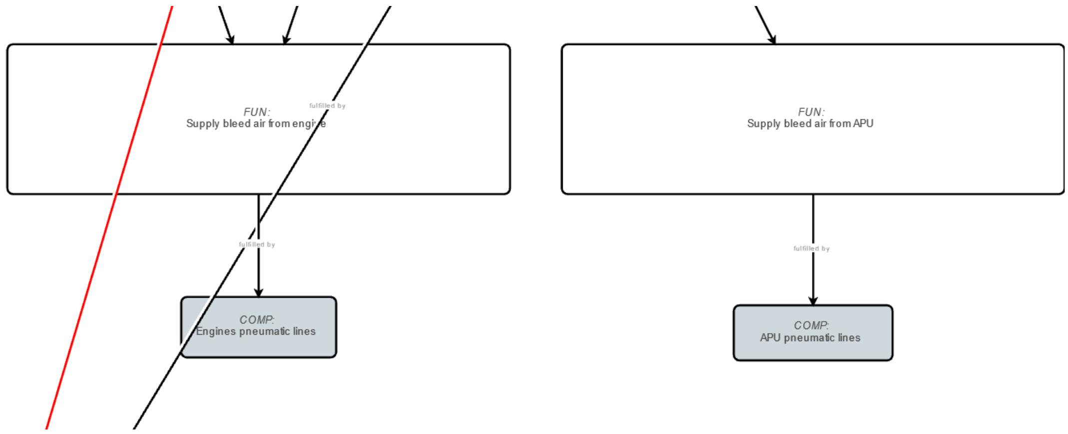


Figure A.5: A320 OBS ADORE design space (bottom right)

Appendix B

Architectures' tasks

Task to be REMOVED:

System	TASK NUMBER	DESCRIPTION	100% INTERVAL	Note	A1 750 FH	A2 1500 FH	A3 2250 FH	A4 3000 FH	C1 18 [Months] 4'200 FH	C2 36 8'400 FH	C3 54 12'600 FH	C4 72 16'800 FH	C5 90 21'000 FH	C6 108 25'200 FH	C7 126 29'400 FH	C8 144 33'600 FH	C9 162 37'800 FH	C10 180 42'000 FH	C11 198 36'200 FH	C12 216 40'400 FH	C13 234 44'600 FH	C14 252 48'800 FH	C15 270 53'000 FH	C16 288 57'200 FH
FCS	271400-03-1	AILERON HYDRAULIC ACTUATION CHECK FLUID RESERVE PISTON POSITION WITH HYDRAULIC RESERVOIR DEPRESSURIZED	180 MO OR 24000 FH	Ailerons									0.48					0.48					0.48	
FCS	272400-01-1	RUDDER HYDRAULIC ACTUATION OPERATIONAL CHECK OF RUDDER SERVOCONTROLS WITH INDIVIDUAL HYDRAULIC SYSTEMS	6 MO OR 750 FH	Rudder	0.1	0.1	0.1	0.1																
FCS	272400-06-1	RUDDER HYDRAULIC ACTUATION LUBRICATION OF RUDDER SERVOCONTROL ROD EYE END BEARING	24 MO OR 10000 FH	Rudder					0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
FCS	273400-03-1	ELEVATOR AND HYDRAULIC ACTUATION CHECK FLUID RESERVE PISTON POSITION WITH HYDRAULIC RESERVOIR DEPRESSURIZED.	180 MO OR 24000 FH	Elevator									0.46					0.46					0.46	
FCS	273400-04-1	ELEVATOR AND HYDRAULIC ACTUATION CHECK OF THE DIFFERENTIAL PRESSURE INDICATOR AND POSITION OF FLUID RESERVE PISTON OF ELEVATOR SERVO CONTROLS	252 MO OR 36000 FH	Elevator												0.46								0.46
FCS	273400-08-1	ELEVATOR AND HYDRAULIC ACTUATION LUBRICATION OF ELEVATOR SERVOCONTROL ROD EYE END BEARING	24 MO OR 10000 FH	Elevator					0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
FCS	274000-02-1	TRIMMABLE HORIZONTAL STABILIZER (THS) OPERATIONAL CHECK OF THS ACTUATOR WITH INDIVIDUAL HYDRAULIC SYSTEMS	750 FH	THS	0.1	0.1	0.1	0.1																
FCS	274400-01-1	THS HYDRAULIC ACTUATION FUNCTIONAL CHECK OF THS ACTUATOR PRESSURE OFF BRAKE (APPLY TORQUE TO MANUAL CRANKING INPUT)	252 MO OR 36000 FH	THS												0.32								0.32
FCS	783100-I1-1	THRUST REVERSER CONTROL & INDICATING OPERATIONAL CHECK OF THRUST REVERSER LOWER ACTUATOR LOCK MECHANISM	216 MO OR 16000 FC OR 24000 FH										1.12					1.12					1.12	
HYDRAULIC	291000-04-1	MAIN HYDRAULIC POWER FUNCTIONAL CHECK OF PTU GREEN TO YELLOW	72 MO OR 24000 FH	No PTU with 2 lines								0.1				0.1				0.1				0.1
HYDRAULIC	291000-06-1	MAIN HYDRAULIC POWER FUNCTIONAL CHECK OF PTU YELLOW TO GREEN	36 MO OR 12000 FH	//						0.1		0.1		0.1		0.1		0.1		0.1		0.1		0.1
HYDRAULIC	291000-08-1	MAIN HYDRAULIC POWER FUNCTIONAL CHECK OF PRIORITY VALVES IN GREEN, BLUE AND YELLOW SYSTEM	144 MO OR 36000 FH	only 2 lines												0.2								0.2
HYDRAULIC	291000-09-1	MAIN HYDRAULIC POWER OPERATIONAL CHECK OF HYDRAULIC FIRE SHUT OFF VALVES AND ASSOCIATED INDICATING SYSTEM.	108 MO OR 12000 FH	//						0.08		0.08		0.08		0.08		0.08		0.08		0.08		0.08
HYDRAULIC	291000-19-1	MAIN/AUXILIARY POWER OPERATIONAL CHECK OF PTU IN-FLIGHT INHIBITION LOGIC	108 MO OR 15000 FH	No PTU with 2 lines							0.81			0.81			0.81			0.81			0.81	
HYDRAULIC	291000-21-1	MAIN/AUXILIARY POWER OPERATIONAL CHECK OF PTU THERMAL INHIBITION LOGIC	108 MO OR 15000 FH	//							4			4			4			4			4	
RAT	292000-06-1	MAIN AND AUXILIARY HYDRAULIC POWER REMOVE RAM AIR TURBINE AGCM AND PUMP FOR IN SHOP FUNCTIONAL CHECK.	144 MO OR 24000 FH										3.08					3.08					3.08	
RAT	292000-12-1	MAIN AND AUXILIARY HYDRAULIC POWER REMOVE RAT (INCLUDING TURBINE, LEG AND PUMP), EJECTION JACK AND AGCM FOR OVERHAUL AND REPLACE WITH NEW OR RECONDITIONED UNITS.	240 MO																		2.91			
EPS	242000-22-1	AC GENERATION - REMOVE AND DISCARD SCAVENGE AND CHARGE FILTER ELEMENTS, - DRAIN AND REPLENISH OIL SYSTEM	6 MO OR 800 FH NOTE		0.88	0.88	0.88	0.88																
EPS	242100-06-1	INTEGRATED DRIVE GENERATOR CHECK TORQUE OF QUICK-ATTACH-DETACH (QAD) TENSION BOLT	24 MO OR 2400 FH				0.91																	
EPS	242100-07-1	INTEGRATED DRIVE GENERATOR CHECK IDG OIL LEVEL AND DIFFERENTIAL PRESSURE INDICATOR	2 MO OR 300 FH NOTE		0.36	0.36	0.36	0.36																
EPS	242100-09-1	INTEGRATED DRIVE GENERATOR OPERATIONAL CHECK OF INTEGRATED DRIVE GENERATOR (IDG)	NOTE	Estimated note interval as the one of task 242100-10-1 (36000FH)												0.6								0.6
EPS	242100-10-1	INTEGRATED DRIVE GENERATOR REMOVE IDG COOLER FOR IN-SHOP CLEANING	252 MO OR 36000 FH NOTE													0.80								0.80
EPS	243800-01-1	DC MAIN GENERATION OPERATIONAL CHECK OF BATTERY CHARGE LIMITER NO 1 AND NO 2 VIA CFDS	12 MO OR 1000 FH		0.10	0.10	0.10	0.10																
EPS	243851-02-1	DC GENERATION REMOVE BATTERY FOR CHECK IN WORKSHOP	CE NOTE	12 MO			0.23																	
				Single A-Check	1.54	1.54	2.68	1.54																
				24y 9mo	35.42	35.42	61.64	35.42	0.88	1.06	5.69	1.16	6.02	5.87	0.88	3.54	5.69	6.2	0.88	5.97	3.79	1.06	10.83	3.54

Total MMH to be removed over 24y 9mo
230.96

Figure B.1: "2H/2E" removed tasks and MMH calculation

Task to be ADDED: (λ ratio)

System	TASK NUMBER	DESCRIPTION	100% INTERVAL		A1 750 FH	A2 1500 FH	A3 2250 FH	A4 3000 FH
FCS	271400-03-1	AILERON HYDRAULIC ACTUATION CHECK FLUID RESERVE PISTON POSITION WITH HYDRAULIC RESERVOIR DEPRESSURIZED	180 MO OR 24000 FH	Ailerons				
FCS	272400-01-1	RUDDER HYDRAULIC ACTUATION OPERATIONAL CHECK OF RUDDER SERVOCONTROLS WITH INDIVIDUAL HYDRAULIC SYSTEMS	6 MO OR 750 FH	Rudder	0.06	0.06	0.06	0.06
FCS	272400-06-1	RUDDER HYDRAULIC ACTUATION LUBRICATION OF RUDDER SERVOCONTROL ROD EYE END BEARING	24 MO OR 10000 FH	Rudder				
FCS	273400-03-1	ELEVATOR AND HYDRAULIC ACTUATION CHECK FLUID RESERVE PISTON POSITION WITH HYDRAULIC RESERVOIR DEPRESSURIZED.	180 MO OR 24000 FH	Elevator				
FCS	273400-04-1	ELEVATOR AND HYDRAULIC ACTUATION CHECK OF THE DIFFERENTIAL PRESSURE INDICATOR AND POSITION OF FLUID RESERVE PISTON OF ELEVATOR SERVO CONTROLS	252 MO OR 36000 FH	Elevator				
FCS	273400-08-1	ELEVATOR AND HYDRAULIC ACTUATION LUBRICATION OF ELEVATOR SERVOCONTROL ROD EYE END BEARING	24 MO OR 10000 FH	Elevator				
FCS	274000-02-1	TRIMMABLE HORIZONTAL STABILIZER (THS) OPERATIONAL CHECK OF THS ACTUATOR WITH INDIVIDUAL HYDRAULIC SYSTEMS	750 FH	THS	0.06	0.06	0.06	0.06
FCS	274400-01-1	THS HYDRAULIC ACTUATION FUNCTIONAL CHECK OF THS ACTUATOR PRESSURE OFF BRAKE (APPLY TORQUE TO MANUAL CRANKING INPUT)	252 MO OR 36000 FH	THS				
FCS	783100-I1-1	THRUST REVERSER CONTROL & INDICATING OPERATIONAL CHECK OF THRUST REVERSER LOWER ACTUATOR LOCK MECHANISM	216 MO OR 16000 FC OR 24000 FH					
RAT	292000-06-1	MAIN AND AUXILIARY HYDRAULIC POWER REMOVE RAM AIR TURBINE AGCM AND PUMP FOR IN SHOP FUNCTIONAL CHECK.	144 MO OR 24000 FH					
RAT	292000-12-1	MAIN AND AUXILIARY HYDRAULIC POWER REMOVE RAT (INCLUDING TURBINE, LEG AND PUMP), EJECTION JACK AND AGCM FOR OVERHAUL AND REPLACE WITH NEW OR RECONDITIONED UNITS.	240 MO					
EPS	242100-06-1	INTEGRATED DRIVE GENERATOR CHECK TORQUE OF QUICK-ATTACH-DETACH (QAD) TENSION BOLT	24 MO OR 2400 FH				0.86	
EPS	242100-09-1	INTEGRATED DRIVE GENERATOR OPERATIONAL CHECK OF INTEGRATED DRIVE GENERATOR (IDG) DISCONNECT AND RECONNECT FUNCTION.	NOTE	Estimated note interval as the one of task 242100-10-1 (36000FH)				
EPS	242100-10-1	INTEGRATED DRIVE GENERATOR REMOVE IDG COOLER FOR IN-SHOP CLEANING	252 MO OR 36000 FH NOTE					
EPS	243800-01-1	DC MAIN GENERATION OPERATIONAL CHECK OF BATTERY CHARGE LIMITER NO 1 AND	12 MO OR 1000 FH		0.22	0.22	0.22	0.22
EPS	243851-02-1	DC GENERATION REMOVE BATTERY FOR CHECK IN WORKSHOP	CE NOTE	12 MO			0.50	
				Single A-Check	0.34	0.34	1.70	0.34
				24y 9mo	7.85	7.85	39.08	7.85

TASK NUMBER	C1 18 4'200 FH	C2 36 8'400 FH	C3 54 12'600 FH	C4 72 16'800 FH	C5 90 21'000 FH	C6 108 25'200 FH	C7 126 29'400 FH	C8 144 33'600 FH	C9 162 37'800 FH	C10 180 42'000 FH	C11 198 36'200 FH	C12 216 40'400 FH	C13 234 44'600 FH	C14 252 48'800 FH	C15 270 53'000 FH	C16 288 57'200 FH
[Months]																
271400-03-1					0.30					0.30					0.30	
272400-01-1																
272400-06-1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.10
273400-03-1					0.29					0.29					0.29	
273400-04-1								0.29								0.29
273400-08-1	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
274000-02-1																
274400-01-1								0.20								0.20
783100-I1-1					0.70					0.70					0.70	
292000-06-1					6.46					6.46					6.46	
292000-12-1													6.11			
242100-06-1																
242100-09-1								0.75								0.75
242100-10-1								0.57								0.57
243800-01-1																
243851-02-1																
24y 9mo	0.55	0.55	0.55	0.55	8.29	0.55	0.55	2.35	0.55	8.29	0.55	0.55	6.65	0.55	8.29	2.35

[MH]_EHA =	**0.62**	· [MH]_HSA
[MH]_VFG =	**0.94**	· [MH]_IDG
[MH]_Li-Ion =	**2.17**	· [MH]_Ni-Cd
[MH]_AC gen =	**2.10**	· [MH]_Hyd pump

Total MMH to be added over 24y 9mo
104.34

Figure B.2: "2H/2E" added tasks and MMH calculation

Task to be REMOVED:

FCS

RAT — See rusults from 2H/2E

EPS

	TASK NUMBER	DESCRIPTION	100% INTERVAL	A1 750 FH	A2 1500 FH	A3 2250 FH	A4 3000 FH	C1 18 [Months] 4'200 FH	C2 36 8'400 FH	C3 54 12'600 FH	C4 72 16'800 FH	C5 90 21'000 FH	C6 108 25'200 FH	C7 126 29'400 FH	C8 144 33'600 FH	C9 162 37'800 FH	C10 180 42'000 FH	C11 198 36'200 FH	C12 216 40'400 FH	C13 234 44'600 FH	C14 252 48'800 FH	C15 270 53'000 FH	C16 288 57'200 FH
HYDRAULIC	290000-03-1	HYDRAULIC POWER CHECK CLOGGING INDICATOR ON ENGINE DRIVEN PUMP (EDP) CASE DRAIN FILTER (POP OUT NOT PROTRUDING)	12 MO OR 1000 FH	0.08	0.08	0.08	0.08																
	290000-05-1	HYDRAULIC POWER CHECK CLOGGING INDICATORS OF THE FOLLOWING FILTERS(POP OUT NOT PROTRUDING) -HIGH PRESSURE DELIVERY -GROUND SERVICING (RESERVOIR FILLING) -RETURN (LOW PRESSURE) -BLUE HYDRAULIC SYSTEM ELECTRICAL PUMP CASE DRAIN -RESERVOIR PRESSURIZATION FILTER -WATER SEPARATOR	24 MO OR 2000 FH		0.16		0.16																
	291000-01-1	MAIN HYDRAULIC POWER CHECK FLUID LEVEL ON RESERVOIR INDICATORS	6 MO OR 750 FH	0.16	0.16	0.16	0.16																
	291000-02-1	MAIN HYDRAULIC POWER CHECK RESERVOIR AIR PRESSURE ON RESERVOIR GAUGE	6 MO OR 750 FH	0.16	0.16	0.16	0.16																
	291000-04-1	MAIN HYDRAULIC POWER FUNCTIONAL CHECK OF PTU GREEN TO YELLOW	72 MO OR 24000 FH								0.1				0.1				0.1				0.1
	291000-05-1	MAIN HYDRAULIC POWER DRAIN WATER SEPARATOR	24 MO OR 2250 FH			0.16																	
	291000-06-1	MAIN HYDRAULIC POWER FUNCTIONAL CHECK OF PTU YELLOW TO GREEN	36 MO OR 12000 FH						0.1		0.1		0.1		0.1		0.1		0.1		0.1		0.1
	291000-08-1	MAIN HYDRAULIC POWER FUNCTIONAL CHECK OF PRIORITY VALVES IN GREEN, BLUE AND YELLOW SYSTEM	144 MO OR 36000 FH												0.6								0.6
	291000-09-1	MAIN HYDRAULIC POWER OPERATIONAL CHECK OF HYDRAULIC FIRE SHUT OFF VALVES AND ASSOCIATED INDICATING SYSTEM.	108 MO OR 12000 FH						0.24		0.24		0.24		0.24		0.24		0.24		0.24		0.24
	291000-10-1	MAIN HYDRAULIC POWER FUNCTIONAL CHECK OF HYDRAULIC FIRE SHUT OFF VALVES	180 MO OR 24000 FH NOTE									0.4					0.4					0.4	
	291000-14-1	MAIN HYDRAULIC POWER CHECK NITROGEN CHARGE PRESSURE ON HYDRAULIC POWER ACCUMULATORS	6 MO OR 600 FH	0.18	0.18	0.18	0.18																
	291000-15-1	MAIN HYDRAULIC POWER ANALYZE HYDRAULIC FLUID	24 MO OR 7500 FH					2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44
	291000-18-1	MAIN HYDRAULIC POWER DRAIN RECOVERY TANK	12 MO OR 1500 FH		0.34		0.34																
	291000-19-1	MAIN/AUXILIARY POWER OPERATIONAL CHECK OF PTU IN-FLIGHT INHIBITION LOGIC	108 MO OR 15000 FH							0.81			0.81			0.81			0.81			0.81	
	291000-20-1	MAIN/AUXILIARY POWER OPERATIONAL CHECK OF EDP DEPESSURIZATION	36 MO OR 12000 FH						0.25		0.25		0.25		0.25		0.25		0.25		0.25		0.25
	291000-21-1	MAIN/AUXILIARY POWER OPERATIONAL CHECK OF PTU THERMAL INHIBITION LOGIC	108 MO OR 15000 FH							4			4			4			4			4	
	291900-02-1	MAIN AND AUXILIARY HYDRAULIC POWER FUNCTIONAL CHECK TO MONITOR INTERNAL LEAK RATE OF BLUE HYDRAULIC SYSTEM	108 MO OR 12000 FH						0.6		0.6		0.6		0.6		0.6		0.6		0.6		0.6
	293100-01-1	HYDRAULIC FLUID QUANTITY INDICATING FUNCTIONAL CHECK OF RESERVOIR LOW LEVEL WARNING	252 MO OR 36000 FH												0.36								0.36
	293400-01-1	RESERVOIR PRESSURIZATION INDICATING OPERATIONAL CHECK OF RESERVOIR LOW AIR PRESSURE WARNING	108 MO OR 12000 FH						0.1		0.1		0.1		0.1		0.1		0.1		0.1		0.1
	ZL-195-01-1	HYDRAULIC COMPARTMENT AND FAIRINGS GENERAL VISUAL INSPECTION OF HYDRAULIC COMPARTMENT AND FAIRINGS (EWIS)	48 MO						0.44		0.44		0.44		0.44		0.44		0.44		0.44		0.44

Figure B.3: "MEA-I" removed tasks and MMH calculation

	TASK NUMBER	DESCRIPTION	100% INTERVAL	750 FH	1500 FH	2250 FH	3000 FH	
LG	324000-15-1	WHEELS AND BRAKES FUNCTIONAL CHECK TO MONITOR INTERNAL LEAK RATE OF BRAKING SYSTEM COMPONENTS. (PARK BRAKE SELECTOR VALVE, PRESSURE RELIEF VALVE AND ALTERNATE BRAKE SELECTOR VALVE)	14800 FH					
LG	324000-17-1	WHEELS AND BRAKES FUNCTIONAL CHECK OF BRAKE ACCUMULATOR SYSTEM.	108 MO OR 8000 FC OR 12000 FH					
LG	324200-02-1	NORMAL BRAKING SYSTEM FUNCTIONAL CHECK OF NORMAL BRAKE ACCUMULATOR BY READING THE CHARGE PRESSURE ON THE ACCUMULATOR GAUGE	6 MO OR 400 FH	0.2	0.2	0.2	0.2	
LG	324411-01-1	BRAKE ACCUMULATOR FUNCTIONAL CHECK OF PARKING/EMERGENCY BRAKE ACCUMULATOR BY READING THE CHARGE PRESSURE ON THE ACCUMULATOR GAUGE	4 MO OR 750 FH	0.06	0.06	0.06	0.06	
LG	324500-02-2	PARKING/ULTIMATE EMERGENCY BRAKING SYSTEM FUNCTIONAL CHECK OF BRAKE ACCUMULATOR SYSTEM WITH THE PARKING BRAKE APPLIED	9000 FH					
				Single A-Check	0.26	0.26	0.26	0.26
				24y 9mo	5.98	5.98	5.98	5.98

[Months]	18	36	54	72	90	108	126	144	162	180	198	216	234	252	270	288	
	4'200 FH	8'400 FH	12'600 FH	16'800 FH	21'000 FH	25'200 FH	29'400 FH	33'600 FH	37'800 FH	42'000 FH	36'200 FH	40'400 FH	44'600 FH	48'800 FH	53'000 FH	57'200 FH	
324000-15-1			1.1			1.1			1.1			1.1			1.1		
324000-17-1		1		1		1		1		1		1		1		1	
324200-02-1																	
324411-01-1																	
324500-02-2		1		1		1		1		1		1		1		1	
		18	38	55.1	74	90	111.1	126	146	163.1	182	198	219.1	234	254	271.1	290

Total MMH to be removed over 24y 9mo
2493.72

Task to be ADDED:

FCS	
RAT	See rusults from 2H/2E
EPS	
HYD	Not replaced
LG	Accumulators not replaced No tasks on LG actuators

Figure B.4: "MEA-I" added tasks and MMH calculation

Task to be REMOVED:

EPS See results from 2H/2E

	TASK NUMBER	DESCRIPTION	100% INTERVAL	A1 750 FH	A2 1500 FH	A3 2250 FH	A4 3000 FH
IPS	301151-01-2	WING ANTI-ICE CONTROL VALVE REPLACE WING ANTI-ICING FILTER	180 MO OR 24000 FH				
PNEUMATIC	361100-01-1	ENGINE BLEED AIR SUPPLY SYSTEM	60 MO				
	361141-04-1	IP BLEED CHECK VALVE CHECK OF IP BLEED CHECK VALVE FOR	108 MO OR 12000 FH				
	361148-01-1	AIR BLEED DUCTS,WING PERFORM LEAK CHECK ON BLEED AIR DUCTING IN WING AREA BETWEEN BLEED AIR PRECOOLER, WING ANTI ICE VALVE AND WING/FUSELAGE CONNECTION	180 MO OR 22000 FH NOTE				
	361200-01-1	AIR BLEED AIR SUPPLY & CROSSBLEED SYST OPERATIONAL CHECK OF CROSSBLEED VALVE IN MANUAL MODE	72 MO				
	753142-I1-1	ACTUATOR - MASTER	12000 FH				
	361143-01-1	THERMOSTAT - FAN AIR VALVE CONTROL	72 MO				
	361200-02-1	APU BLEED AIR SUPPLY & CROSSBLEED SYST PERFORM LEAK CHECK ON APU BLEED AIR DUCTING (UPSTREAM THE APU BLEED CHECK VALVE) NOTE: PLANNING: - TASK MAY BE COMBINED WITH TASKS 361148-01-1 AND 361200-03-1. INTERVAL: - DEPENDING ON OPERATING ENVIRONMENT AND OPERATORS EXPERIENCE, A LESS FREQUENT OR MORE FREQUENT INITIAL INTERVAL MAY BE USED.	180 MO OR 24000 FH NOTE				
	361200-03-1	APU BLEED AIR SUPPLY & CROSSBLEED SYST LEAK CHECK OF BLEED AIR DUCTING IN FUSELAGE AREA BETWEEN APU BLEED CHECK VALVE, AIR CONDITIONING PACK AND WING/FUSELAGE CONNECTION NOTE: PLANNING: - TASK MAY BE COMBINED WITH TASKS 361148-01-1 AND 361200-02-1. INTERVAL: - DEPENDING ON OPERATING ENVIRONMENT AND OPERATORS EXPERIENCE, A LESS FREQUENT OR MORE FREQUENT INITIAL INTERVAL MAY BE USED.	180 MO OR 24000 FH NOTE				
	361251-01-1	APU BLEED CHECK VALVE REMOVE AND CHECK AUXILIARY POWER UNIT BLEED CHECK VALVE FOR CONDITION	180 MO OR 24000 FH				
STARTER	801300-I3-1	ENGINE STARTING SYSTEM DRAIN AND REPLENISH OIL SYSTEM AND INSPECTION OF STARTER MAGNETIC CHIP DETECTOR.	6 MO OR 750 FC OR 600 FH	0.85	0.85	0.85	0.85
	801300-I4-1	ENGINE STARTING SYSTEM CLEAN PNEUMATIC STARTER VALVE FILTER	72 MO OR 5000 FC				
			Single A-Check	0.85	0.85	0.85	0.85
			24y 9mo	19.55	19.55	19.55	19.55

TASK NUMBER	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
	18	36	54	72	90	108	126	144	162	180	198	216	234	252	270	288
	4'200 FH	8'400 FH	12'600 FH	16'800 FH	21'000 FH	25'200 FH	29'400 FH	33'600 FH	37'800 FH	42'000 FH	36'200 FH	40'400 FH	44'600 FH	48'800 FH	53'000 FH	57'200 FH
301151-01-2					1.26					1.26					1.26	
361100-01-1			0.84			0.84			0.84			0.84			0.84	
361141-04-1		1.16		1.16		1.16		1.16		1.16		1.16		1.16		1.16
361148-01-1					2.6					2.6					2.6	
361200-01-1				0.1				0.1				0.1				0.1
753142-I1-1		0.64		0.64		0.64		0.64		0.64		0.64		0.64		0.64
361143-01-1	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44
361200-02-1					2					2					2	
361200-03-1					2.53					2.53					2.53	
361251-01-1					0.65					0.65					0.65	
801300-I3-1																
801300-I4-1			0.68			0.68			0.68			0.68			0.68	
24y 9mo	1.44	3.24	2.96	3.34	10.48	4.76	1.44	3.34	2.96	12.28	1.44	4.86	1.44	3.24	12	3.34

Total MMH to be removed over 24y 9mo
303.06

Figure B.5: "MEA-II" removed tasks and MMH calculation

Task to be ADDED:

	TASK NUMBER	DESCRIPTION	100% INTERVAL		A1	A2	A3	A4	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
									18	36	54	72	90	108	126	144	162	180	198	216	234	252	270	288
					750 FH	1500 FH	2250 FH	3000 FH				16800 FH				33600 FH								
ECS	384142-01-1	AIR FILTER DISCARD SYSTEM FILTER ELEMENT	72 MO OR 24000 FH									0.2				0.2				0.2				0.2
ECS	384241-01-1	AIR SUPPLY DETAILED INSPECTION OF COMPRESSOR INLET FILTER.	144 MO OR 18000 FH NOTE									0.1				0.1				0.1				0.1
ECS	384241-02-1	AIR SUPPLY DISCARD COMPRESSOR INLET FILTER ELEMENT.	108 MO OR 12000 FH							0.3		0.3		0.3		0.3		0.3		0.3		0.3		0.3
ECS	384242-01-1	AIR SUPPLY DISCARD COMPRESSOR OUTLET FILTER ELEMENT.	72 MO OR 24000 FH									0.3				0.3				0.3				0.3
ECS	215000-02-1	AIR COOLING AND TEMPERATURE CONTROL DETAILED INSPECTION OF PACK AIR CHECK VALVES FLAPPERS FOR CONDITION AND OPERATION	144 MO OR 36000 FH													0.81								0.81
IPS	303100-01-1	PROBE ICE PROTECTION FUNCTIONAL CHECK OF THE INSULATION RESISTANCE OF THE PITOT PROBE HEATER	24 MO	x3 (left wing, right wing, tail)					0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
				Single A-Check	0.00	0.00	0.00	0.00																
				24y 9mo	0.00	0.00	0.00	0.00	0.75	1.05	0.75	1.65	0.75	1.05	0.75	2.46	0.75	1.05	0.75	1.65	0.75	1.05	0.75	2.46

Total MMH to be added over 24y 9mo
72.28

Figure B.6: "MEA-II" added tasks and MMH calculation

Task to be REMOVED:

FCS	See results from 2H/3E
EPS	See results from 2H/3E
HYD	See results from MEA-I
RAT	See results from 2H/3E
IPS	See results from MEA-II
ECS	See results from MEA-II
PNEUMATIC	See results from MEA-II
ENG START	See results from MEA-II

	TASK NUMBER	DESCRIPTION	100% INTERVAL	A1	A2	A3	A4
				750 FH	1500 FH	2250 FH	3000 FH
LG	323100-04-1	NORMAL EXTENSION AND RETRACTION OPERATIONAL CHECK TO ENSURE SAFETY VALVE CLOSES AT 260 KNOTS	72 MO OR 15000 FH				
LG	324000-15-1	WHEELS AND BRAKES FUNCTIONAL CHECK TO MONITOR INTERNAL LEAK RATE OF BRAKING SYSTEM COMPONENTS. (PARK BRAKE SELECTOR VALVE, PRESSURE RELIEF VALVE AND ALTERNATE BRAKE SELECTOR VALVE)	14800 FH				
LG	324000-17-1	WHEELS AND BRAKES FUNCTIONAL CHECK OF BRAKE ACCUMULATOR SYSTEM.	108 MO OR 8000 FC OR 12000 FH				
LG	324200-02-1	NORMAL BRAKING SYSTEM FUNCTIONAL CHECK OF NORMAL BRAKE ACCUMULATOR BY READING THE CHARGE PRESSURE ON THE ACCUMULATOR GAUGE	6 MO OR 400 FH	0.2	0.2	0.2	0.2
LG	324411-01-1	BRAKE ACCUMULATOR FUNCTIONAL CHECK OF PARKING/EMERGENCY BRAKE ACCUMULATOR BY READING THE CHARGE PRESSURE ON THE ACCUMULATOR GAUGE	4 MO OR 750 FH	0.06	0.06	0.06	0.06
LG	324500-02-2	PARKING/ULTIMATE EMERGENCY BRAKING SYSTEM FUNCTIONAL CHECK OF BRAKE ACCUMULATOR SYSTEM WITH THE PARKING BRAKE APPLIED	9000 FH				
			Single A-Check	0.26	0.26	0.26	0.26
			24y 9mo	5.98	5.98	5.98	5.98

TASK NUMBER	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
[Months]	18	36	54	72	90	108	126	144	162	180	198	216	234	252	270	288
	4'200 FH	8'400 FH	12'600 FH	16'800 FH	21'000 FH	25'200 FH	29'400 FH	33'600 FH	37'800 FH	42'000 FH	36'200 FH	40'400 FH	44'600 FH	48'800 FH	53'000 FH	57'200 FH
323100-04-1			0.8			0.8			0.8			0.8			0.8	
324000-15-1			1.1			1.1			1.1			1.1			1.1	
324000-17-1		1		1		1		1		1		1		1		1
324200-02-1																
324411-01-1																
324500-02-2		1		1		1		1		1		1		1		1
24y 9mo	0	2	1.9	2	0	3.9	0	2	1.9	2	0	3.9	0	2	1.9	2

Total MMH to be removed over 24y 9mo
49.42

Figure B.7: "AEA" removed tasks and MMH calculation

Appendix C

Architectures' results

	FCS	HYD	RAT	EPS
MMH	-15.24	-26.29	13.35	-98.44
%	-1.74%	-16.43%	7.74%	-58.13%
Total MEA-II MMH	860.91	133.74	185.81	70.90

Sys_tot [MMH]	3381.83
2H/2E_tot [MMH]	-126.62
	-3.744%

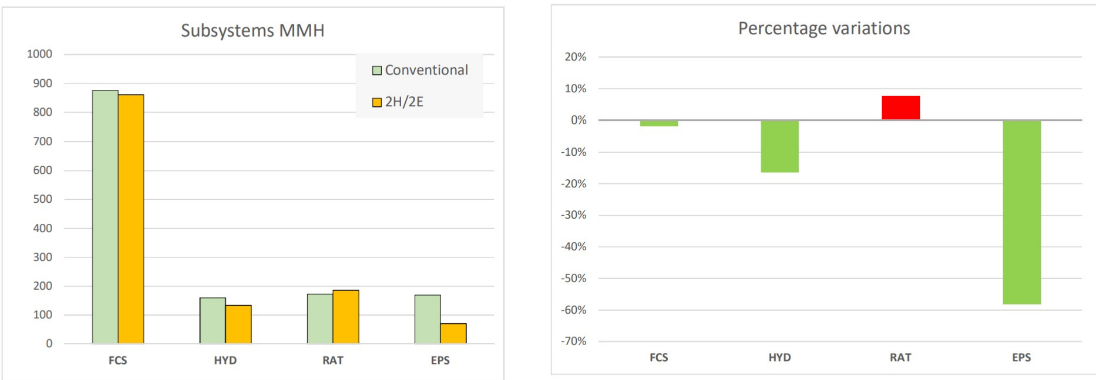


Figure C.1: "2H/2E" MMH variation

	FCS	HYD	RAT	EPS	LGS
MMH	-15.24	-160.03	13.35	-98.44	-45.42
%	-1.74%	-100.00%	7.74%	-58.13%	-3.66%
Total MEA-I MMH	860.91	0.00	185.81	70.90	1194.58

Sys_tot [MMH]	3382
MEA-I_tot [MMH]	-305.78
	-9.04%

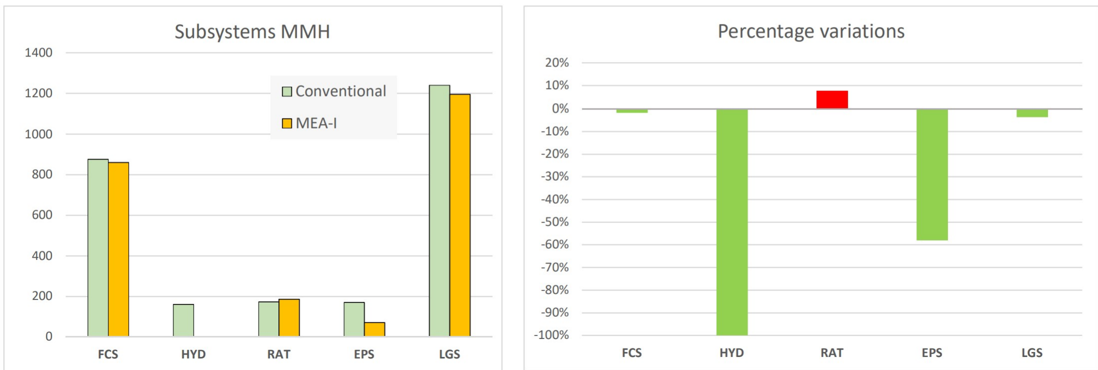
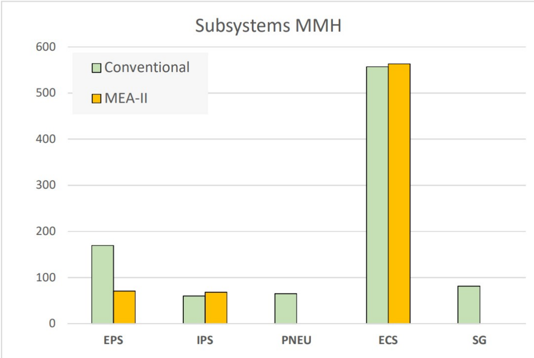


Figure C.2: "MEA-I" MMH variation

	EPS	IPS	PNEU	ECS	SG
MMH	-98.44	8.22	-65.38	6.42	-81.60
%	-58.13%	13.71%	-100.00%	1.15%	-100.00%
Total MEA-II MMH	70.90	68.16	0.00	563.35	0.00

Sys_tot [MH] 3382

MEA-II_tot [MH] -230.78
-6.82%



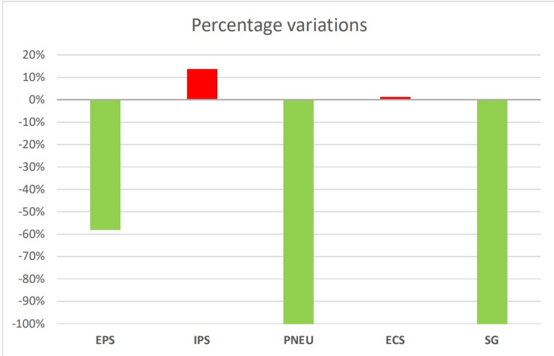


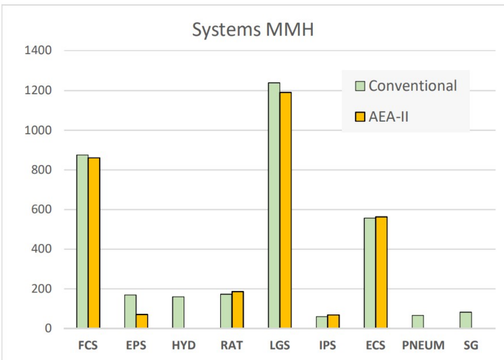
Figure C.3: "MEA-II" MMH variation

AEA - % variations

	FCS	EPS	HYD	RAT	LGS	IPS	ECS	PNEUM	SG
MMH	-15.24	-98.44	-160.03	13.35	-49.42	8.22	6.42	-65.38	-81.60
%	-1.74%	-58.13%	-100.0%	7.74%	-3.99%	13.71%	1.15%	-100.000%	-100.00%
Total AEA MMH	860.91	70.90	0.00	185.81	1190.58	68.16	563.35	0.00	0.00

Sys_tot [MH] 3381.83

AEA_tot [MH] -442.12
-13.07%



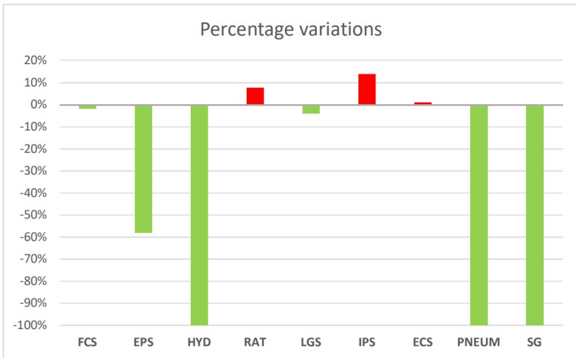


Figure C.4: "AEA" MMH variation

Appendix D

Alternative utilisation scenario

Table D.1: MMH percentage variation per system per architecture in the alternative utilisation scenario

	EPS	**HPS**	**RAT**	**Pneumatic**	**FCS**	**LGS**	**ECS**	**IPS**	**Starting**
1. Conv	-	-	-	-	-	-	-	-	-
2. 2H/2E	-60.40%	-15.59%	+7.10%	-	-1.75%	-	-	-	-
3. MEA-I	-60.40%	-100%	+7.10%	-	-1.75%	-3.95%	-	-	-
4. MEA-II	-60.40%	-	-	-100%	-	-	+1.06%	+13.71%	-100%
5. AEA	-60.40%	-100%	+7.10%	-100%	-1.75%	-4.23%	+1.06%	+13.71%	-100%

Table D.2: Final MMH expected variations in the alternative utilisation scenario

	FCS	**HPS (2 lines)**	**RAT**	**EPS (VFG)**	**HPS (0 lines)**	**LGS (LHEGS)**
%	-2.82%	-18.4%	-8.25%	-34.4%	-100%	-5.30%
ΔMMH	-26	-31	-16	-63	-169	-75

	Pneumatic	**ECS**	**Starting**	**EPS (SG)**	**IPS**	**LGS (EMA)**
%	-100%	+2.72%	-62.0%	-35.2%	-23.2%	-9.20%
Δ MMH	-68	+16	-57	-65	-14	-131

Appendix E

Expert opinions

Scheduled MMH variation for **FCS** in **2H/2E** architecture

	Min	Max	Belief
Exp1_st1	0%	10%	20%
Exp1_st2	10%	20%	80%
Exp2_st1	-30%	-20%	100%
Exp2_st2	-	-	-
Exp3_st1	-0.50%	1%	100%
Exp3_st2	-	-	-
Exp4_st1	-5%	-2.50%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **HPS** in **2H/2E** architecture

	Min	Max	Belief
Exp1_st1	-30%	-10%	50%
Exp1_st2	-10%	0%	50%
Exp2_st1	-35%	-30%	100%
Exp2_st2	-	-	-
Exp3_st1	-5%	5%	100%
Exp3_st2	-	-	-
Exp4_st1	-50%	-30%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **RAT** in **2H/2E** architecture

	Min	Max	Belief
Exp1_st1	-5%	5%	100%
Exp1_st2	-	-	-
Exp2_st1	-50%	-40%	100%
Exp2_st2	-	-	-
Exp3_st1	-50%	-20%	34%
Exp3_st2	-20%	-10%	33%
Exp3_st3	-20%	-5%	33%
Exp4_st1	-5%	5%	100%

Scheduled MMH variation for **EPS** in **2H/2E** architecture

	Min	Max	Belief
Exp1_st1	-10%	0%	50%
Exp1_st2	-5%	0%	50%
Exp2_st1	-35%	-25%	100%
Exp2_st2	-	-	-
Exp3_st1	-5%	5%	100%
Exp3_st2	-	-	-
Exp4_st1	-5%	5%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **HPS** in **MEA-I** architecture

	Min	Max	Belief
Exp1_st1	-75%	-50%	20%
Exp1_st2	-75%	-25%	80%
Exp2_st1	-100%	-95%	100%
Exp2_st2	-	-	-
Exp3_st1	-100%	-75%	100%
Exp3_st2	-	-	-
Exp4_st1	-100%	-75%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **LGS** in **MEA-I** architecture

	Min	Max	Belief
Exp1_st1	-1%	0%	80%
Exp1_st2	-5%	0%	20%
Exp2_st1	-25%	-15%	100%
Exp2_st2	-	-	-
Exp3_st1	0%	1%	50%
Exp3_st2	0%	5%	50%
Exp4_st1	-10%	-5%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **Pneumatic System** in **MEA-II**

	Min	Max	Belief
Exp1_st1	-100%	-75%	100%
Exp1_st2	-	-	-
Exp2_st1	-80%	-70%	100%
Exp2_st2	-	-	-
Exp3_st1	-100%	-75%	100%
Exp3_st2	-	-	-
Exp4_st1	-100%	-75%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **ECS** in **MEA-II** architecture

	Min	Max	Belief
Exp1_st1	-1%	5%	40%
Exp1_st2	0%	5%	40%
Exp1_st3	1%	5.00%	20%
Exp2_st1	10%	20%	100%
Exp2_st2	-	-	-
Exp3_st1	-5%	-0.50%	100%
Exp4_st1	1%	5.00%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **Starting System** in **MEA-II**

	Min	Max	Belief
Exp1_st1	-30%	0%	50%
Exp1_st2	-10%	0%	100%
Exp2_st1	-90%	-80%	100%
Exp2_st2	-	-	-
Exp3_st1	-30%	30%	100%
Exp3_st2	-	-	-
Exp4_st1	-10%	10%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **EPS** in **MEA-II** architecture

	Min	Max	Belief
Exp1_st1	-20%	-10%	40%
Exp1_st2	-20%	-5%	20%
Exp1_st3	-20%	0%	40%
Exp2_st1	-35%	-25%	100%
Exp3_st1	-5%	5%	100%
Exp3_st2	-	-	-
Exp4_st1	-5%	10%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **IPS** in **MEA-II** architecture

	Min	Max	Belief
Exp1_st1	-100%	-80%	100%
Exp1_st2	-	-	-
Exp2_st1	-95%	-85%	100%
Exp2_st2	-	-	-
Exp3_st1	-10%	0%	100%
Exp3_st2	-	-	-
Exp4_st1	-5%	5%	100%
Exp4_st2	-	-	-

Scheduled MMH variation for **LGS** in **AEA** architecture

	Min	Max	Belief
Exp1_st1	-	-	-
Exp1_st2	-	-	-
Exp2_st1	-50%	-40%	100%
Exp2_st2	-	-	-
Exp3_st1	0%	5%	100%
Exp3_st2	-	-	-
Exp4_st1	-1%	1%	100%
Exp4_st2	-	-	-

Figure E.1: Experts interviews' results

Appendix F

MMHER verification

The inputs that have been chosen for the verification example architectures are reported in Table F.1, while the associated MMH variations that have been estimated by the MMHER are reported in Figure F.1.

Starting from the conventional configuration (Architecture 1), one variable at a time is set to one while retaining the previous changes. Firstly, *SG* is set to 1 in Architecture 2, *Gen* is set to 1 in Architecture 3 and *ECS* is set to 1 in Architecture 4. In Architecture 5 *ECS* is set back to 0 and *IPS* is set to 1. Lastly, *ECS* and *IPS* are both set to 1 in Architecture 6.

Table F.1: Verification architectures inputs

	Batt	*Gen*	*SG*	*EHA*	*Lines*	*LGS*	*EMA*	*IPS*	*ECS*
Architecture 1	0	0	0	0	0	0	0	0	0
Architecture 2	0	0	1	0	0	0	0	0	0
Architecture 3	0	1	1	0	0	0	0	0	0
Architecture 4	0	1	1	0	0	0	0	0	1
Architecture 5	0	1	1	0	0	0	0	1	0
Architecture 6	0	1	1	0	0	0	0	1	1

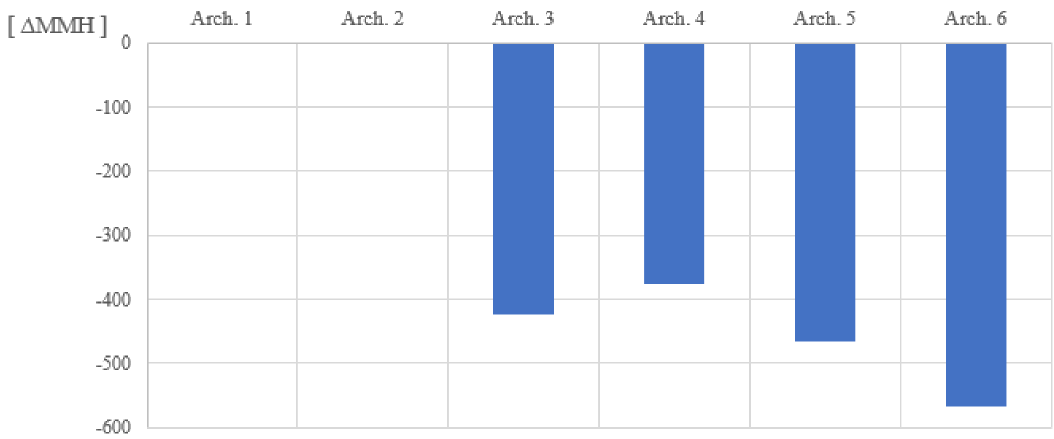


Figure F.1: Total ΔMMH provided by the MMHER for the verification architectures

As can be seen in Figure F.1, no variation occurs between the first and the second architecture. This result verifies that the *SG* variable doesn't affect the estimation when an innovative generator is not installed, that is when the *Gen* variable is set to 0. On the contrary, when both these variables are set to 1, the starter-generators benefits are accordingly provided, as in the case of Architecture 3.

If an electric ECS is also installed, as in the case of Architecture 4, the equation correctly estimates a decrease in the savings, since this technology is expected to require a greater amount of scheduled MMH. On the other hand, an electric IPS and a conventional ECS are adopted in Architecture 5. In this case, it can be seen how the MMHER correctly evaluates an additional MMH reduction due to the electrification of this system.

Lastly, both an electric IPS and an electric ECS have been installed in Architecture 6. In this case, a simple combination of the previous two results would eventually lead to a ΔMMH value close to the one of Architecture 3. However, the electrification of the aforementioned systems leads to the removal of the engine bleed pneumatic lines and an additional reduction in scheduled MMH is expected. As can be appreciated in Figure F.1, the estimating equation is correctly assessing this variation as well, hence indicating Architecture 6 as the one one with the greatest MMH reduction among the ones reported in this example.

Appendix G

Use case architectures

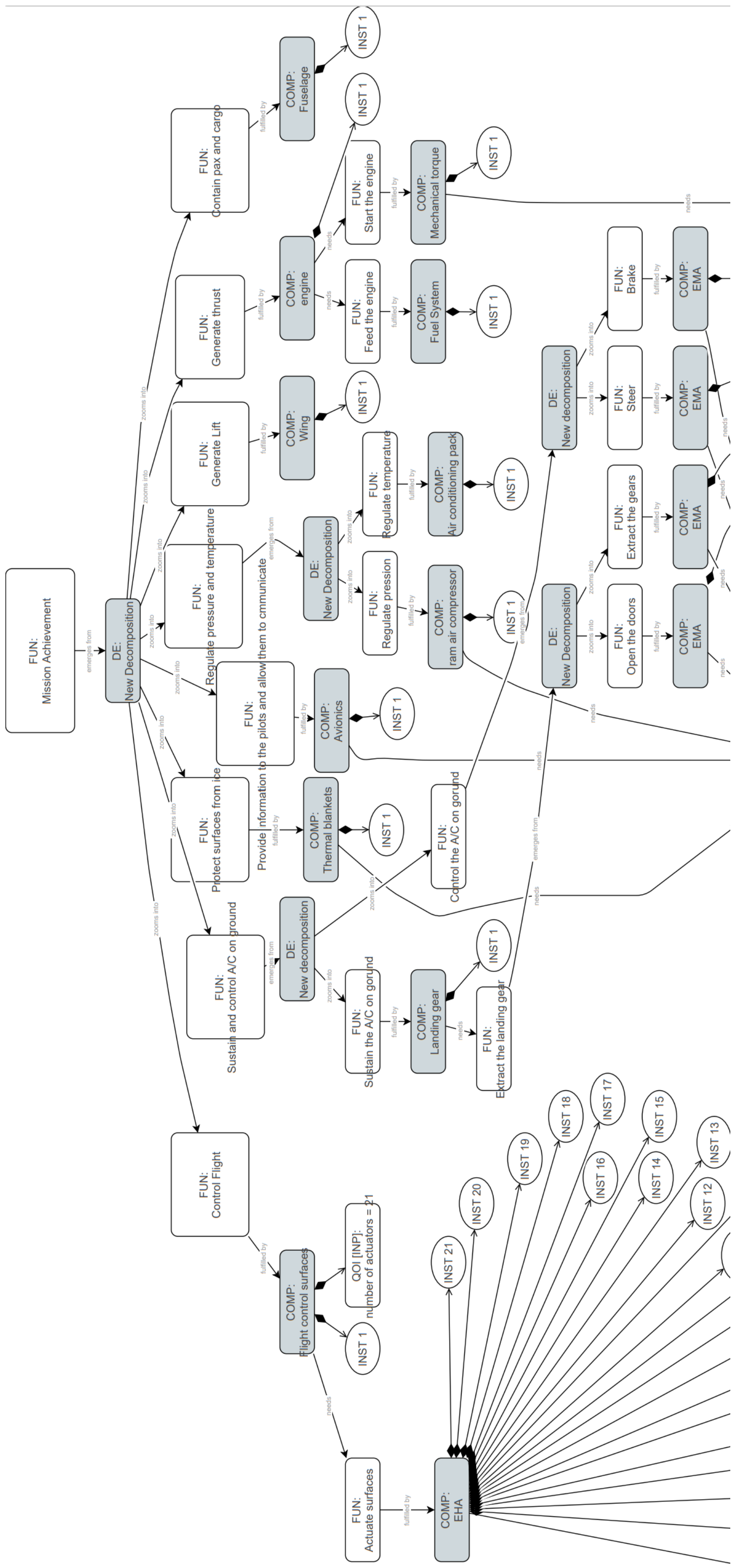


Figure G.1: Use case configuration 1 (part 1)

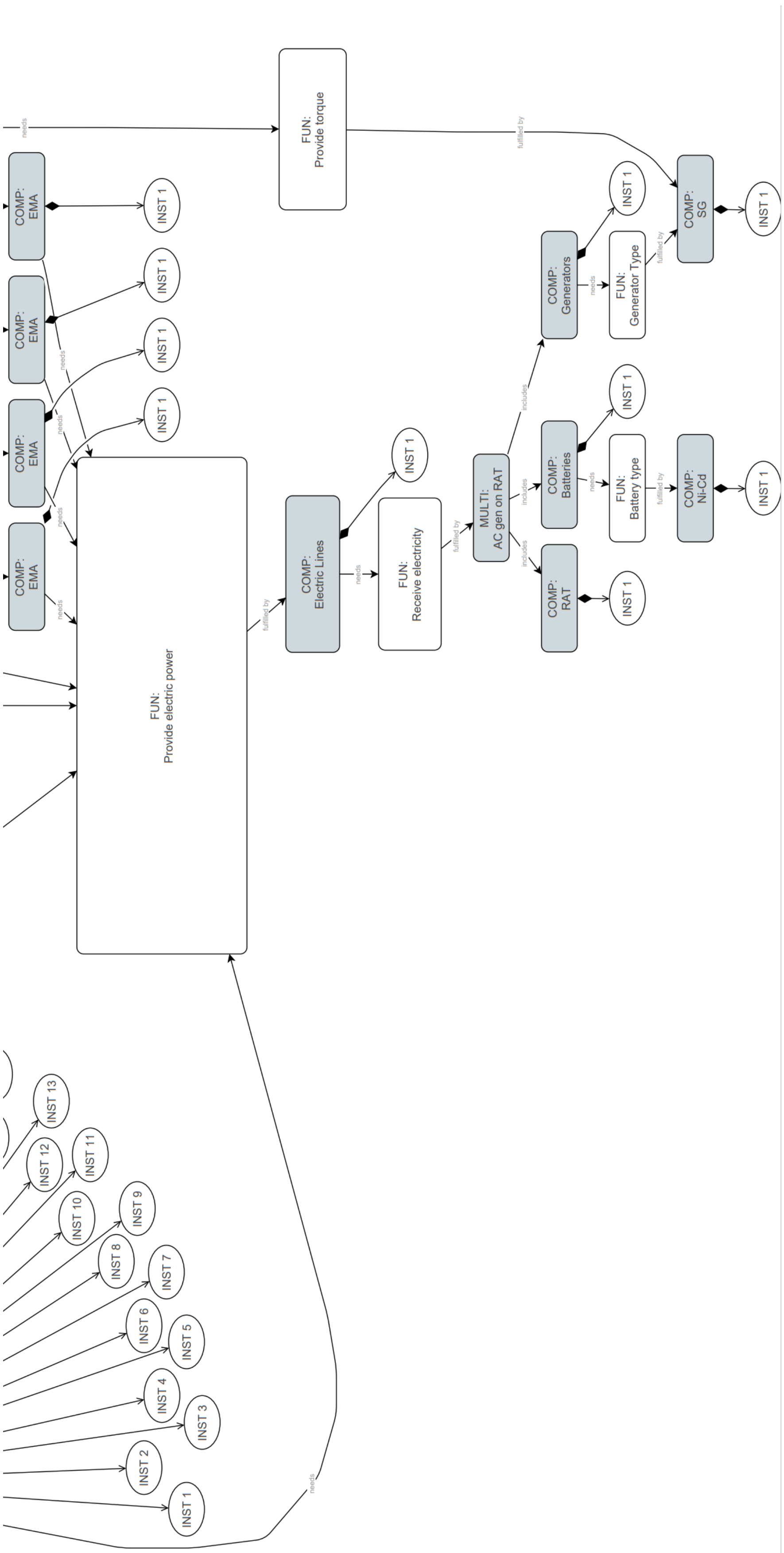


Figure G.2: Use case configuration 1 (part 2)

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