# POLITECNICO DI TORINO

**MASTER's Degree in AEROSPACE ENGINEERING**

**Master's Degree Thesis**

# Concept Development for Maintenance Cost Estimation of More-electric Aircraft On-board System Architectures


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# Summary

Modern aviation is undergoing a transformation driven by innovative aircraft configurations, particularly More-Electric Aircraft, propelled by technological advancements and a pursuit of greater efficiency. This paradigm shift carries significant implications for maintenance costs. Early in the design process, it is essential to estimate future costs, including maintenance cost, to best decide which concepts are the most promising from a cost perspective. As the project progresses and design details become more defined, the impact of potential changes on costs might become substantial. Therefore, having cost estimates available in the early design phases helps mitigate the impact of configuration changes on overall expenses.
However, there is a lack of established methods for estimating the variations in maintenance costs between conventional and more-electric architectures. Therefore, this study aims to systematically estimate the maintenance cost for the difference of More-Electric Aircraft (MEA) compared to conventional architectures, which can be applied during the initial phases of aircraft design when little is finalized, and data are limited.
To address this, a methodology is developed with a primary focus on eliminating maintenance costs associated with existing systems that are either removed or replaced when transitioning from conventional to more-electric configurations. In addition, it establishes a general approach for incorporating maintenance contributions for new components that will replace the conventional ones. This process carefully considers their direct correlation to component reliability. It also relies on reasonable assumptions that allow the use of an analogy-based method that correlates the new systems to existing, similar solutions. By using this approach, the precision and accuracy of the cost estimates associated with the maintenance of innovative aircraft configurations will be significantly improved.
Looking forward, this study's adaptable methodology offers opportunities for future research. It can be further adjusted and extended to estimate maintenance costs based on changes to individual components within any aircraft subsystem, accommodating a wide range of potential design variations. This will provide a more comprehensive understanding of maintenance cost dynamics in innovative aircraft configurations, contributing to the ongoing evolution of the aviation industry.

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# Acronyms

**AC** Alternate Current.

**ADs** Airworthiness Directives.

**AEA** All-Electric Aircraft.

**APU** Auxiliary Power Unit.

**ATA** Air Transport Association.

**ATU** Auto Transformer Unit.

**ATUs** Auto Transformer Units.

**BMS** Battery Management System.

**BPNN** Back-Propagation Neural-Network.

**CBS** Cost Breakdown Structure.

**CEF** Cost Escalation Factor.

**CERs** Cost Estimation Relationships.

**CM** Condition Monitoring.

**CS** Certification Specification.

**CSD** Constant Speed Driver.

**DC** Direct Current.

**DMC** Direct Maintenance Cost.

**DOC** Directive Operating Cost.

**DSS** Decision Support System.

**EBHA** Electric Backup Hydraulic Actuator.

**ECS** Environmental Control System.

**EDP** Engine Driven Pump.

**EDTO** Extended Diversion Time Operation.

**EHA** Electro-Hydraulic Actuator.

**EHAs** Electro-Hydraulic Actuators.

**EMA** Electro-Mechanical Actuator.

**EMP** Electric Motor Pump.

**EOs** Engineering Orders.

**ETOPS** Extended Range Twin-engine OPeration Standards.

**FAA** Federal Aviation Administration.

**FBL** Fly-By-Light.

**FBW** Fly-By-Wire.

**FC** Flight Cycles.

**FCS** Flight Control System.

**FEM** Finite Element Method.

**FH** Flight Hours.

**FMEA** Failure Modes and Effects Analysis.

**FPCC** Flap Power Control Computer.

**FR** Failure Rate.

**FSVM** Fuzzy Support Vector Machine.

**FTA** Fault Tree Analysis.

**HAZOP** HAZard and OPerability.

**HSA** Hydraulic Servo Actuator.

**HSAs** Hydraulic Servo Actuators.

**HT** Hard Time.

**ICAO** International Civil Aviation Organization.

**IDG** Integrated Drive Generator.

**IDGs** Integrated Drive Generators.

**IMC** Indirect Maintenance Cost.

**IPCs** Illustrated Parts Catalogs.

**IPS** Ice Protection System.

**LC** Labor Cost.

**LCC** Life-Cycle Cost.

**LLP** Life-Limited Parts.

**MC** Material Cost.

**MDAO** Multidisciplinary Design Analysis and Optimization.

**MEA** More-Electric Aircraft.

**MMH** Maintenance Man Hours.

**MPD** Maintenance Planning Document.

**MRB** Maintenance Review Board.

**MRBR** Maintenance Review Board Report.

**MRO** Maintenance and Repair Organization.

**MSG** Maintenance Steering Group.

**MTBF** Mean Time Between Failure.

**MTBS** Mean Time Between Substitutions.

**MTOW** Maximum Take-Off Weight.

**MTTF** Mean Time To Failure.

**NN** Neural-Network.

**OBS** On-Board Systems.

**OC** On Condition.

**OOP** Out-Of-Phase.

**PF** Pre-Flight.

**PTU** Power Transfer Unit.

**RAMS** Reliability, Availability, Maintainability and Safety.

**RAT** Ram Air Turbine.

**RCM** Reliability Centered Maintenance.

**RCT** Rear Center Tank.

**SAFE-AFE** Safety Assessment Function and Environment in Aviation.

**SBs** Service Bulletins.

**SMRs** Switched Reluctance Machines.

**SMS** Safety Management System.

**TC** Type Certificate.

**THS** Trimmable Horizontal Stabilizer.

**TOC** Total Operating Cost.

**TR** Transfer Rectifier.

**TRs** Transfer Rectifiers.

**TRU** Transformer-Rectifier Unit.

**TRUs** Transformer-Rectifier Units.

**VFG** Variable Frequency Generator.

**VFGs** Variable Frequency Generators.

**VSCF** Variable Speed Constant Frequency.

# Chapter 1

# Introduction

The aviation industry is currently experiencing a transformative phase characterized by innovative aircraft configurations, particularly More-Electric Aircraft (MEA). This shift is driven by technological advancements and a quest for increased operational efficiency. In this dynamic and evolving landscape, the early estimation of maintenance costs becomes critical in the aircraft design process. Such estimates are essential for assessing the feasibility and economic viability of these innovative concepts that are redefining the aviation industry. Traditional aircraft, with their mechanically and hydraulically driven systems, are being replaced by More-Electric Aircraft (MEA), where electrical systems take center stage. This transition promises to reduce fuel burn and thus greenhouse gas emissions by improving the aircraft performance, making it a key player in the industry's drive toward sustainability. However, this transformation also introduces a set of complexities in terms of system integration and maintenance, creating a critical need for in-depth analysis and accurate cost assessment.

While methods for estimating maintenance costs do exist, their accuracy levels may vary. Greater precision in estimating maintenance costs not only provides a clearer financial path for the aircraft's operational life-cycle, but also increases the adaptability of the design. When maintenance cost estimates are accurate, potential changes and improvements to the aircraft's architecture, especially in the early stages, become more feasible without significant cost impact. This ability to fine-tune and optimize the design during the conceptual phase is critical to ensuring that MEA configurations achieve their full potential in terms of efficiency, sustainability and performance. This research seeks to address the limitations and improve the precision of maintenance cost estimation methods, particularly in the context of emerging MEA configurations.

The primary goal of this thesis is to develop a systematic methodology for estimating maintenance costs associated with two case models, the conventional reference model, and the more-electric case study aircraft, during their initial stages

of design.
By using an analogy method based on the reliability of the various components, represented as failure rates, this approach estimates the potential changes in maintenance costs resulting from the modifications to improve the electric power system (ATA 24), the Flight Control System (FCS) (ATA 27), and the hydraulic system (ATA 29). To assess the impact of these modifications, the study measures the change in Maintenance Man Hours (MMH) by comparing the required maintenance tasks for both the conventional reference case and the more electric case study.

This method can be expanded to calculate maintenance costs based on changes to individual components within any aircraft subsystem. This adaptability allows for a comprehensive understanding of maintenance cost dynamics in innovative aircraft configurations, ultimately contributing to the ongoing evolution of the aviation industry.

The thesis is organized into five main chapters, along with four appendices summarizing the key assumptions of the thesis. Chapter 2 focuses on the literature review, exploring key concepts such as reliability, availability, maintainability and safety in the context of aviation. Aircraft maintenance is also reviewed with a focus on relevant documents and methodologies. Chapter 3 describes the direct maintenance cost estimation method developed during the study. This method is based on analogies between aircraft configurations and includes the estimation of maintenance costs for specific components. Chapter 4 presents the results, including reference data and estimates for the more electric aircraft configuration. Chapter 5 summarizes the conclusions of the work, highlighting the implications of the results. Appendix A, Appendix B, Appendix C and Appendix D summarize the main assumptions formulated throughout the study, along with extensive numerical data that has been excluded from the main thesis to maintain its structural simplicity.

# Chapter 2

# Literature Review

This chapter presents a comprehensive overview of key concepts within the area of aircraft maintenance and reliability. It lays the foundation for the coming research by providing a detailed analysis of existing literature and studies, covering important aspects such as cost estimation, on-board systems, and aircraft configurations.

Section 2.1 examines the main features of Reliability, Availability, Maintainability, and Safety for optimal aircraft performance and safety. Moving onto section 2.2, methodologies for efficient and reliable aircraft operations are analyzed. Section 2.3 discusses techniques for assessing and managing maintenance costs. Section 2.4 investigates Electric Power, Flight Controls, Hydraulic Power, and Landing Gear Systems' role in aircraft functioning. Lastly, section 2.5 compares Conventional, More-Electric, and All-Electric configurations with a focus on the hydraulic and electrical power systems that influence an aircraft's performance and operational characteristics. Literature Science Gaps and Research Questions, where further research is needed, are reported in section 2.6. This section serves to specify where the thesis fits within these gaps, outlining its potential contributions to the field of aircraft maintenance and reliability.

## 2.1 RAMS Concept

The acronym RAMS represents an important concept in the aerospace industry. It stands for Reliability, Availability, Maintainability and Safety and describes a set of principles, practices and analyses required from the early design stages, through the entire life-cycle of an aerospace system to ensure its performance, reliability and safety [1, 2]. The following sections will provide deeper understanding of each of the RAMS characteristics, accompanied by a thorough analysis of risk management. This will contribute to an understanding of how these aspects collectively serve as an essential foundation for any vehicle design project.

### 2.1.1 Reliability

In order to correctly estimate the reliability of a complex system, such as an aircraft, a breakdown to the subsystem level is required. The overall reliability relies not only on the reliability of the components but also on how they are connected to each other. This makes it easy to picture the complexity and the breadth of the reliability assessment. Going into detail, many different parameters can be defined that give a measure of reliability.

Mean Time Between Failure (MTBF), used for repairable parts, it represents the average time between two consecutive failures of a component. It is a measure of the component reliability and is typically expressed in hours or flight cycles.

Mean Time To Failure (MTTF), similarly, it refers to the components that need to be replaced, once they present a failure. It represents the average time it takes a component to fail. This relates to both repairable and non-repairable failures.

$\lambda$ (Failure Rate), which is the most used and it refers to the frequency with which a component fails. It is usually expressed as the number of failures per unit of time, such as failures per hour or failures per flight cycle. Failure rate values might be based on three different types of failures:

- Early "Infant Mortality" Failures
  These represent the malfunctions due to manufacturing defects, such as geometric imperfections. They are more likely to occur in the early stages of the operative life of a component. As they emerge, the defective components are replaced by better manufactured ones, thus the rate of these failures decreases with the operating life.

- Wear Out Failures
  Their probability of occurrence is directly related to the operating life of the components, therefore the chances increase with the age of the system.

- Random Failures
  Unlike the others, this failure mode does not depend on the age of the components. The probability is the same throughout the operating life and can increase as the exposure of the component to its workloads grows, in fact, a component without workloads is only possible if it is outside the system, therefore its probability to have a random failure is zero.

The bath tube curve reported in Figure 2.1, from [3], represents a visualization of the probability of occurrence of each of the failures as a function of service life. Lastly, their combined effect is depicted by the blue-colored curve.
Three main areas can be seen in the figure: the first, on the left side, is characterized by the decreasing failure rate due to defective manufactured components. In the middle lies the nominal operating range, featured by random failures only. The

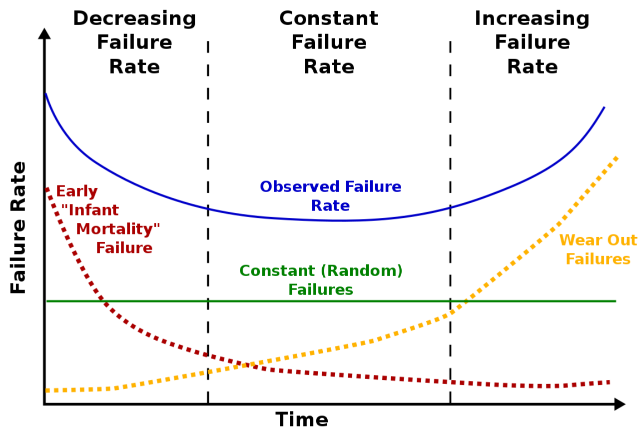



**Figure 2.1:** Bath Tube Curve, from [3]

last area, on the right side, sees an increase in the probability of failure due to the wear-out breakdowns.

### 2.1.2 Availability

This term refers to the ability of the entire aircraft system to be ready to perform its functions whenever required, taking into account downtime for all types of maintenance and repairs. Availability is directly related to both the reliability and the maintainability of a system (lower reliability and higher required maintenance will result in an higher downtime, thus lower vehicle availability) [4].

In the civil aviation industry it is a common practice to measure the availability in terms of Dispatch Reliability, which indicates the percentage of scheduled departures that have not been cancelled, nor heavy delayed, due to technical issues or disruption. Taking all the Certification Specification (CS)-25-certified vehicles as an example, their dispatch reliability results over 99%. As a result, less than 1% of them experienced cancellations or significant delays. This does not imply that the rest of the flights departed as scheduled without any issue, as about 4-5% of them experienced some technical disruption, but thanks to the efficient study and preparation of maintenance interventions, these were resolved in time, allowing the mission to run as planned [4].

### 2.1.3 Maintainability

This concept describes the ability of a complex system to be effectively and efficiently maintained throughout its entire operational life. Maintainability represent a major project driver during all phases of an aircraft life, from the early design to the late

operations it is critical to take any action that could facilitate the ease, speed and cost-effectiveness of maintenance activities [2].
All of the previous RAMS concept depend on the maintainability of the vehicle, in fact, a well designed and maintainable vehicle reduces downtime and increases utilization.

According to [2], the main units of reference for describing maintainability are:

- Maintenance Frequency
  How much time, during a given period of time, a system, or a component, requires maintenance actions to restore its nominal functions.

- Maintenance Time
  The actual time needed to perform the maintenance.

- Maintenance Cost
  In the case of heavy overhauls, the required cost may become significant. It is the most important parameter for the private companies of the sector. However, the search for the most cost-effective solution possible must not forget the key concept of safety, without which the aircraft would not be able to obtain an airworthiness certificate, and thus operate and generate revenue.

A further in-depth analysis on the aircraft maintenance topic is provided in section 2.2.

### 2.1.4 Safety

In the aerospace industry the concept of safety is always associated with risk management, in particular, a state of safety refers to the case in which, during the operation of aircraft and related systems, the risk of harm to personnel, passengers, and the environment is minimized or eliminated.
Within the RAMS framework, safety is typically addressed through various processes and activities [5], including:

- Safety Assessment to identify hazards, evaluate risks, and implement necessary safety measures. This includes techniques Fault Tree Analysis (FTA), HAZard and OPerability (HAZOP) studies, and Failure Modes and Effects Analysis (FMEA).

- Safety Requirements that must be met throughout the aircraft's life-cycle. These requirements encompass design specifications, manufacturing processes, maintenance procedures, and operational guidelines.

- Safety Management System (SMS) to identify and mitigate safety risks. It involves organizational structures, policies, processes, and procedures to manage safety effectively.

- Training and Human Factors: Ensuring that pilots, crew members, and maintenance personnel receive appropriate training on safety procedures and are aware of human factors that can influence safety, such as fatigue, situational awareness, and communication.

- Incident Investigation and Reporting: Establishing a robust system to investigate incidents, accidents, and near-misses, and to analyze the causes. To identify safety improvements and prevent similar occurrences in the future.

- Regulatory Compliance: Adhering to relevant aviation regulations and standards set by national aviation authorities, such as the International Civil Aviation Organization (ICAO).

### 2.1.5 Risk Management

This topic is not a direct part of the RAMS framework, although a safety condition could not be achieved without a proper risk assessment.
To begin with, it is important to define how the concept of risk is not the same for every flying vehicle. In fact, the accepted level of risk depends on the category of aircraft being considered [2].
As shown in Figure 2.2 the tolerable hazard decreases with the dimension and the utilization of the aircraft. Therefore, CS-25 vehicles require the highest level of safety.
To provide a better definition, risk could be seen as result of the multiplication between its severity level and its probability level. Therefore, the Risk Matrix, presented in Figure 2.3 can be introduced.
This type of risk management is used in any kind of industry, including the aerospace one, in fact a description of severity and probability may be found in [6].
Focusing on the worst case, a probability of $10^{-9}$ for the occurrence of a catastrophic event is required to obtain the aircraft type certificate. This number isn't arbitrary, it's the result of the Safety Assessment Function and Environment in Aviation (SAFE-AFE). To understand what a probability of $10^{-9}$ actually means, it can be translated in terms of flight hours:

$$10^{-9} \text{ probability} = 1 \text{ catastrophic event every } 10^{9} \text{ flight hours}$$

Even compared to one of the oldest aircraft families still in service, the A320, this number of flight hours has not yet been reached.

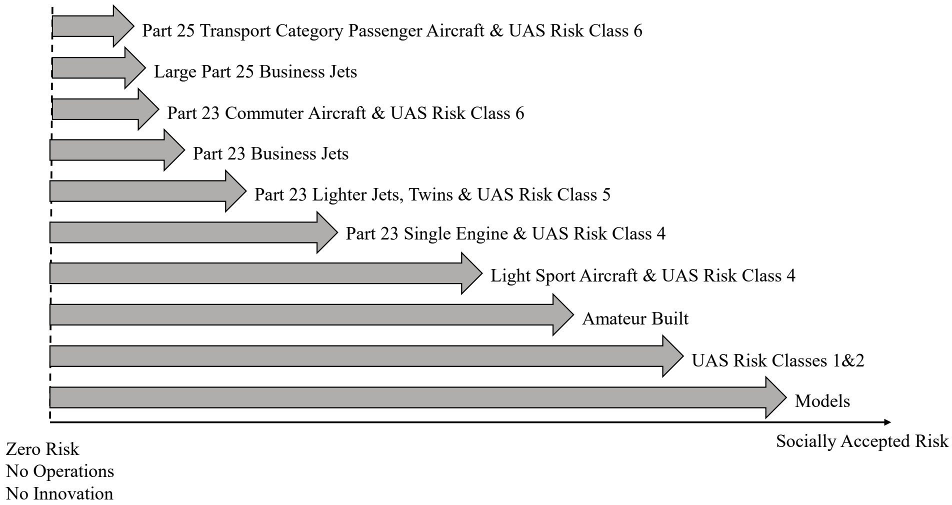



**Figure 2.2:** Safety Continuum made from Federal Aviation Administration (FAA)

| Risk Probability | Risk Severity | | | | |
|---|---|---|---|---|---|
| | Catastrophic A | Hazardous B | Major C | Minor D | Negligible E |
| Frequent 5 | 5A | 5B | 5C | 5D | 5E |
| Occasional 4 | 4A | 4B | 4C | 4D | 4R |
| Remote 3 | 3A | 3B | 3C | 3D | 3E |
| Improbable 2 | 2A | 2B | 2C | 2D | 2E |
| Extremely Improbable 1 | 1A | 1B | 1C | 1D | 1E |

**Figure 2.3:** ICAO Risk Matrix

## 2.2 Aircraft Maintenance

In addition to keeping the aircraft in service, as mentioned above, there are two other key maintenance objectives:

- Value Retention, to preserve the value of the aircraft by preventing its physical deterioration.

- Airworthiness, which can only be achieved when the maintenance program and inspections meet the regulatory requirements established by the aviation authorities. Specifically, certified personnel must perform all tasks within approved facilities using approved equipment.

This section focuses on the specifics of aircraft maintenance. The Maintenance Steering Group (MSG) (2.2.1), Maintenance Review Board Report (MRBR) (2.2.2), Maintenance Planning Document (MPD) (2.2.3), Reliability Centered Maintenance (RCM) (2.2.4), and Maintenance Program Definition (2.2.5) are examined in detail, showcasing the structured methodologies used in aircraft maintenance processes.

### 2.2.1 Maintenance Steering Group (MSG)

The description of the history behind the development of various aircraft maintenance program philosophies was based on the information provided by [7]. The first maintenance process in the aviation industry dates back to the 1950s, when the first large jet aircraft began to populate our skies. This process was referred to as Hard Time (HT), in which each component was taken out of service when it reached a predefined operational age (flight hours, number of flights, calendar time, etc). The retired parts were then zero-timed in the overhaul shops.

In the 1960s a first task force of FAA and airline representatives defined a new approach to maintenance, that would have been more cost- and time-efficient than the previous one. It was called On Condition (OC) and required a periodic inspection of a system to determine whether it could continue to operate (i.e. brake indicator pins).

In 1968 the first Maintenance Steering Group (MSG) was formed to define the scheduled maintenance requirements for new aircraft. In the same year, the MSG-1 programme was developed and applied to the Boeing 747. As shown in Figure 2.4, from [7], it comprised both hard-time and on condition maintenance.

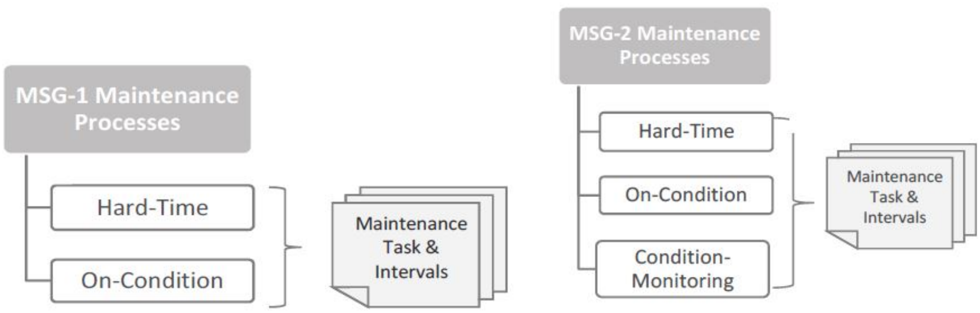



**Figure 2.4:** MSG - Maintenance Evaluation and Program Development, from [7]

Two years later an updated version of MSG-1, the MSG-2 was released (Figure 2.4), which introduced a new maintenance philosophy called Condition Monitoring

(CM). The main feature was the absence of any inspection to check for integrity, the method was not a preventive process, rather the information on items from the overall mechanical performance were collected, analyzed and interpreted to implement corrective actions. All the most complex electrical or mechanical units are usually part of the CM process. As a result, this type of solution allows failures to occur, but the failure modes would not effect on the safety of the aircraft.

Over time, a new update to the MSG-2 became necessary, mainly to deal with the impressive growth in size and complexity of the new aircraft models. Furthermore, the MSG-2 program did not differentiate between safety related and economic related maintenance, at a time when the economic side of the industry was becoming more and more important.

The MSG-3 was defined, a new task-oriented approach with the main focus on the separation between safety related from economy related items, and the appropriate treatment of hidden failures.

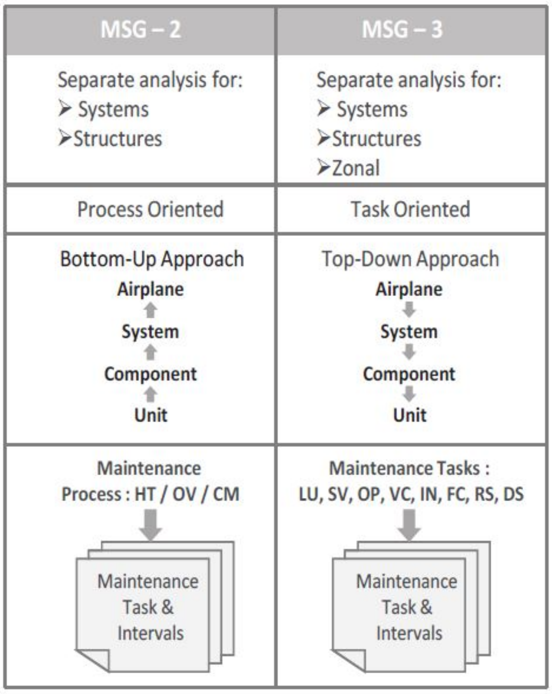



**Figure 2.5:** MSG-2 vs MSG-3 Task Process, from [7]

In essence, the new method emphasised the fact that routine maintenance is not mandatory for functional failures that have no impact on operational safety or economic of operations.

This approach results in fewer maintenance tasks being carried out on the aircraft, which reduces the impact of over-maintenance, such as induced incidents resulting from preventive maintenance. For the time being, the MSG-3 remains the chosen solution by the airlines to best structure the scheduled maintenance of an aircraft.

The MSG-3 maintenance tasks reported in Figure 2.5, from [7] refer to:

- Lubrication/Servicing (LU/SV)
  The first is the act of adding oil, grease or other substances to maintain inherent design capabilities through friction reduction and/or heat dissipation. The second addresses the basic needs of components and/or systems to maintain their inherent design capability.
- Operational/Visual Check (OP/VC)
  The first determines whether an item fulfils its intended purpose. The second involves observing to determine if an item is performing as it intended. This is a failure finding task. Both are failure detection tasks and do not require quantitative tolerances or special equipment.
- Functional Check/Inspection (FC/IN)
  Used to determine if one or more function of an item perform within specific limits. There are three level of inspection: General Visual, Detailed and Special Detailed.
- Restoration (RS)
  These tasks ensure that the item is returned to a specified operating standard
- Discard (DS)
  This indicates the removal from service of an item at a specified life limit.

### 2.2.2 Maintenance Review Board Report (MRBR)

The Maintenance Review Board Report (MRBR) is an important document, containing the initial minimum scheduled maintenance requirements for a new type of aircraft [8]. This document should be provided by the Type Certificate (TC) holder of the vehicle. Once it has been issued, the document must be approved by the local regulatory authorities.

The process used by TC holders provides for the establishment of:

- Maintenance Review Board (MRB)
  They give the final approval to the initial scheduled maintenance tasks in the MRBR. It consists of airline operators, manufacturers members and components from the Regulatory Authorities.
- Industry Steering Committee (ISC).
  Formed by different operators and aircraft manufacturers, they provide the policy, the initial goals for scheduled maintenance check intervals.

- Maintenance Working Group (MWG)
  Formed by maintenance specialists from operators, manufacturers and authorities. Their purpose is to develop both maintenance tasks and intervals for an aircraft type.

### 2.2.3 Maintenance Planning Document (MPD)

The Maintenance Planning Document (MPD) comes directly from the MRBR. As shown in Figure 2.6 there are two additions to the MRBR to compose the MPD:

- Certification Maintenance Requirements (CMR)
  Defined during the design certification of the airplane, to mitigate the potential effects of catastrophic, or hazardous failure conditions.

- Airworthiness Limitations (AL)
  Maintenance tasks defined by the regulatory authorities to prevent any problems for specific safety-related components.


**Figure 2.6:** Maintenance Planning Document (MPD) Definition, from [7]

It is important to emphasise that each airline can decide which task to perform and when to do them, except for CMR and AL which can not be modified.

The Maintenance Planning Document does not represent the entire maintenance plan used by an aircraft operator, however it could be used to develop a maintenance program that describes the individual preventive maintenance tasks for the aircraft and their planned timing [9].

### 2.2.4 Reliability Centered Maintenance (RCM)

The MSG-3 process was introduced to cope with the scale of the maintenance program for the new super jumbos, like the B747. This solution, also known as Reliability Centered Maintenance (RCM) led to significant reduction in labor, material and inventor costs, thereby turning the operation of this large machines profitable.

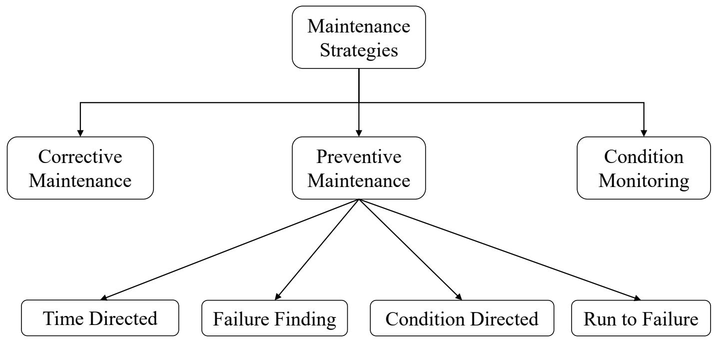



**Figure 2.7:** Maintenance Strategies

RCM is a combination of corrective, preventive and predictive maintenance, it uses methods and tools to help determine the minimum set of preventive maintenance tasks, to guarantee the service reliability of a component. *Asgarpoor et al.* [10] highlight the principles and the benefits of this approach in their study.
The main advantages are the preservation of system functions, the identification of dominant failure modes, the budget focusing with preservation of most critical functions and selection of only effective tasks. The benefits of using the RCM are, reduction of corrective actions with a task frequency optimisation, less intrusive tasks that can induce components failures and creation of documented technical bases for maintenance programs.

### 2.2.5 Maintenance Program Definition

An aircraft only generates revenue when it is in service, and the best way for operators to avoid an impact from material waste is to make the best use of available resources. Therefore, the development of the maintenance program involves the grouping of the tasks in periodic checks (A-, B-, C- checks) in order to optimize the process.

Using the A320 MPD task breakdown analysis from [11] as a reference, it is possible to define the intervals for these tasks. Both the Flight Hours (FH) and monthly values are given, and depending on the aircraft utilization, the first one to be reached defines the task interval.

**Table 2.1:** Letter-Checks Definition, from [11]

| **Check Type** | **Interval** | **Description** |
|---|---|---|
| A-Check | 750 FH<br>750 Flight Cycles (FC)<br>4 mo | The main activities are visual checks, pressure checks of the various systems, filter changes and lubrication of critical parts (e.g. carriage actuators).With a normal A320 utilization, an operator will perform 3/4 A-Checks per year. |
| B-Check | -<br>-<br>6/8 mo | It included more detailed tasks. Today, however, this level is no longer officially recognised, and over time its activities have been gradually integrated partly into the A-Checks and partly into the C-Checks. |
| C-Check | 7500 FH<br>7500 FC<br>24 mo | Most systems and components are properly tested, along with operational and functional checks. An entire C-Check cycle includes six type C checks, thus this has a global interval of 45000 FH, or 12 years. |
| D-Check | -<br>-<br>6-12 yrs | Also referred to as Heavy Structural Inspection (HSI), or C4 Check, it focuses mainly on zonal and structural inspections. Exterior paint is often stripped and many of the outer panels are removed, to allow detailed inspections of most structurally significant items. This heavy inspection is often referred to as the completion of a maintenance cycle. |
| Out-Of-Phase (OOP) | | Those tasks that fall between the main task group intervals |

In the traditional maintenance program configuration, shown in Table 2.1 made from [11], outside the overnight checks, any other line and ramp maintenance components, such as pre-flight, transit, daily and weekly checks, rarely became involved in scheduled servicing. The use of MSG-3 programs makes it more difficult for airlines to adapt their maintenance to their operational needs. Figure 2.8, from [8] illustrates 4 alternatives to the traditional check partitioning to better organize the tasks schedule.

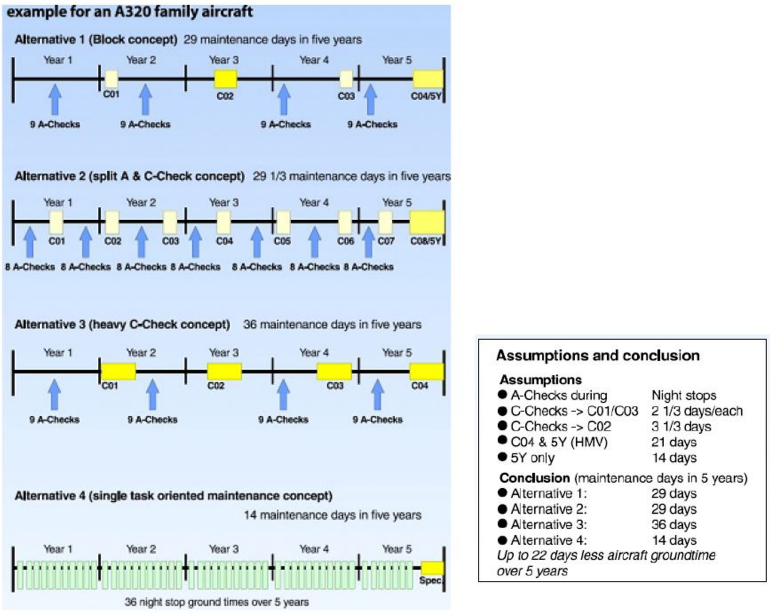



**Figure 2.8:** Different maintenance intervals solution, from [8]

- Alternative 1 (Block check): a traditional C-Check over a 5 years period, that guarantees a total downtime of 29 days. It focuses on the principle of grouping tasks that require frequent repetition under a letter check (see Figure 2.9, from [12]).[12]

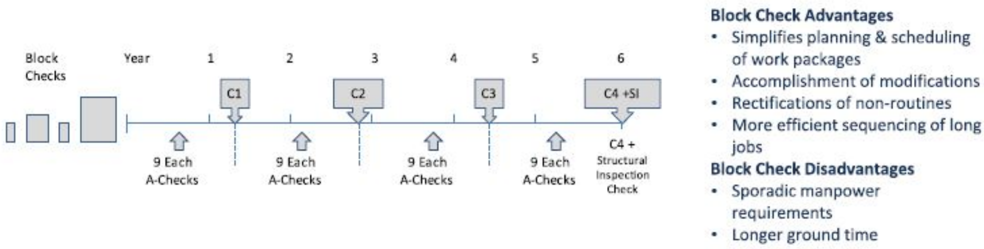



**Figure 2.9:** Block maintenance check packaging, from [12]

- Alternative 2: it divides both A and C check. Over the same time period requires 29 days of downtime as well.

- Alternative 3 (Phased check): heavier checks are divided in smaller packages, with tasks that may be accomplished more frequently than the packages in a block check (see Figure 2.10, from [12]). This solution sees a downtime of 36 days in a five years period. The objective is to level the maintenance workload over time and shorten the length of each period of downtime.

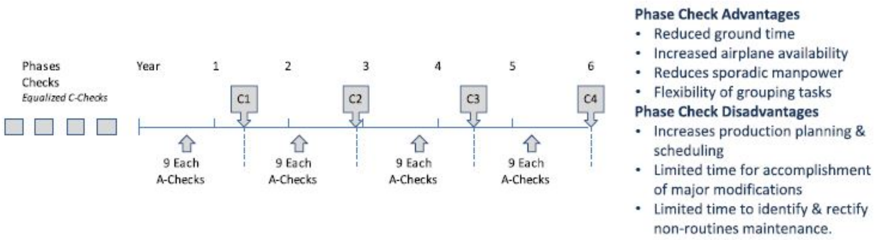



**Figure 2.10:** Phase maintenance check packaging, from [12]

- Alternative 4: a single task-oriented maintenance concept that consumes just 14 days of downtime. This solution fits best to new aircraft, as the non-routine maintenance increases with systems age, thus it is more difficult to schedule this program.

**Table 2.2:** Line Maintenance Checks, values from [13]

| Line Check | Performed in a year |
|---:|---|
| Pre-Flight (PF) | 355 |
| Transit (TR) | 1480 |
| Daily | 250 |
| Weekly | 60 |
| A-Check | 6/7<br>(one every 450FH) |

In 2005 there has been the 28th revision of the MPD for the A320 family [14]. This was a major change, where the tasks went from being grouped together in checks, to being treated individually, thus blurring the line that define group checks.
Nowadays, the most used subdivision for maintenance tasks is between (see Figure 2.11, from [12]):

- Line Maintenance
  It includes the simplest tasks, such as: ramp checks (pre-flight and transit

tasks), daily and weekly checks and A-Checks. Most of them may be postponed until the aircraft returns to the main base, where more tools, spared and qualified manpower are available [15]. Table 2.2 shows the number of line checks performed in a calendar year for an averagely used A320.
Line maintenance can account for 10 to 15 percent of the total Direct Maintenance Cost (DMC).

- Base Maintenance.
  It comprises in-depth inspections known as system checks and structural checks and sometimes includes substantial rectification of non-routine tasks. [12]. Time intervals are defined in the MPD for each aircraft. According with [15], base maintenance is composed of some A, C and heavy checks: the first would be performed every 400FH, the second every 15 to 24 months and the third every 5 to 6 years. To minimize the ground time, these tasks can be grouped into packages.

- Shop Maintenance.
  This represents the maintenance of components after they have been removed from the vehicle. Of all the systems, engines are the most maintenance required, due to their complexity and the strong presence of many Life-Limited Parts (LLP) (spools, shafts, disks,etc), that must be removed when their specified life limits have been reached.
  For this reason, powerplant maintenance alone can account for up to 35-40% of the entire DMC (Figure 2.13, from [12]).

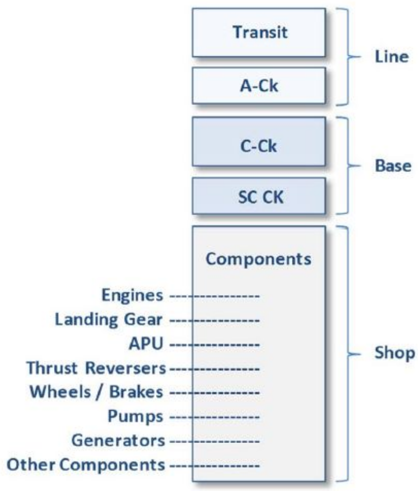



**Figure 2.11:** Maintenance event categories, from [12]

## 2.3 Maintenance Cost Evaluation

This section examines in detail the literature regarding the estimation of maintenance cost. It provides a description of the Cost Breakdown Structure (2.3.1) and different techniques used for product cost estimation (2.3.2), focusing on qualitative and quantitative approaches. Lastly, it shows the Direct Maintenance Cost Estimation Methods (2.3.3) employed to assess and manage maintenance expenses effectively.

### 2.3.1 Cost Breakdown Structure

As stated in [16], a Cost Breakdown Structure (CBS) represents the classification of the total Life-Cycle Cost (LCC) of an aircraft into its most relevant cost components.

A visualisation of the CBS concept has been reported in Figure 2.12, where the first major subdivision of the LCC identifies the acquisition cost, which refers to the initial purchase price of the aircraft and all additions to make it operational (customisation and modifications, acceptance costs, legal and administrative fees, etc), and the operating costs. The latter take into account the entire remaining life of the aircraft, and therefore, it can be subdivided in Total Operating Cost (TOC) and the cost of decommissioning the vehicle once it has reached the end of its operational life. It is possible to further divide the TOCs in Direct and Indirect Operating Costs. Generally, Directive Operating Cost (DOC) can be broken down into 4 groups: crew cost, fuel and oil cost, navigation and landing fees and the DMC. On the other hand, there are the indirect operating costs, which represent the expenses incurred during the operation of an aircraft that can not directly attributed to a specific flight or maintenance event.

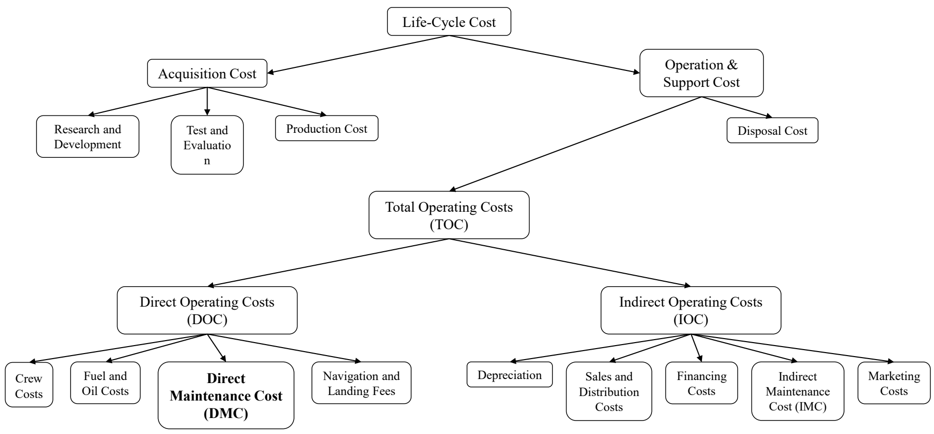



**Figure 2.12:** Cost Breakdown Structure

According to [15], the maintenance costs may be broken into:

- Direct Maintenance Costs (DMC) in Figure 2.13, from [12], which include labor and material costs associated with the repair of airframe, engines and components. They are divided into four groups: line maintenance, base maintenance, component maintenance and engine overhaul.

- Indirect Maintenance Cost (IMC), which include overheads, administration, tools, test equipment and facilities.

The latter are highly dependent on the airline organisation and are, therefore, considered as a percentage of the DMC, usually in a range between 50% and 200%

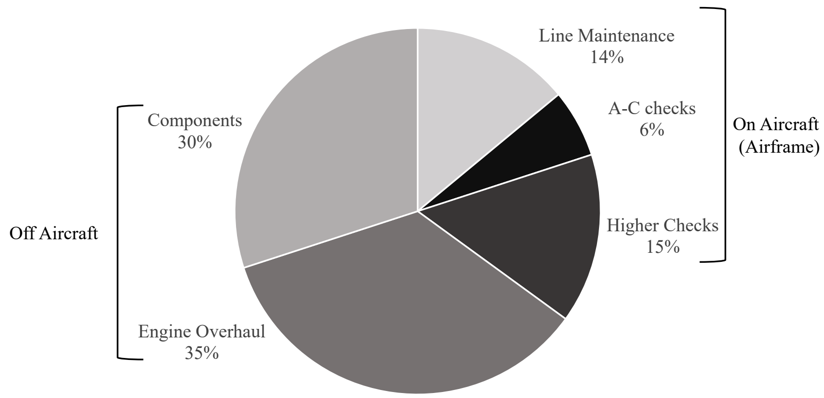



**Figure 2.13:** DMCs breakdown made from [15]

### 2.3.2 Product Cost Estimation

All of the above cost categories play a fundamental role in defining the cost of an aircraft family program.
By carefully studying and planning the entire life-cycle of an aircraft, from the early design to end-of-life, it is possible for an airline to minimise operating costs to the benefit of revenue. Because of this crucial role, significant research efforts have been made to explore all design implications, and new techniques to achieve the maximum customer satisfaction for a low cost, high quality and on-time product delivery.

Niazi et al.[17] proposes a detailed analysis of the various cost estimation method for a product (Figure 2.14, from [17]).
The aforementioned classification has been accepted by the majority of researchers, categorising the techniques according to their common characteristics. The first

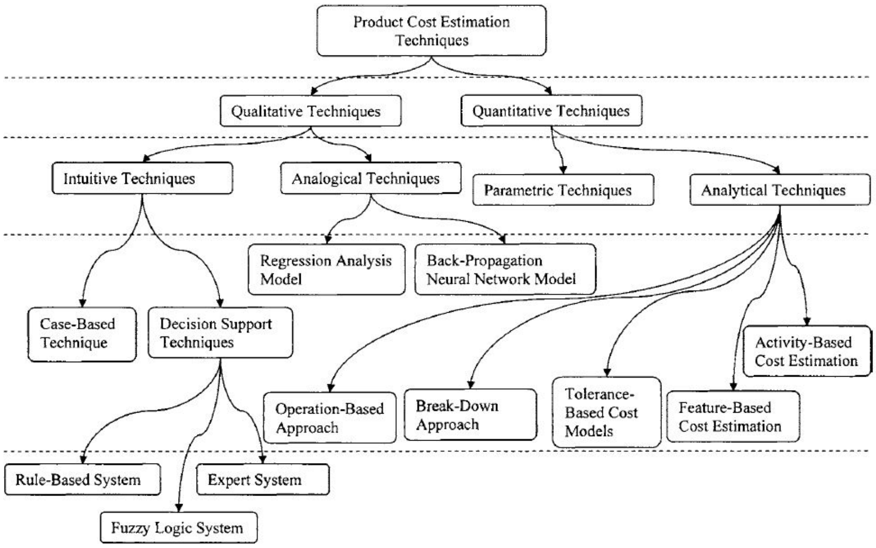



**Figure 2.14:** Product Cost Estimation Techniques [17]

major difference can be seen between qualitative and quantitative techniques. The former are based on similarities between products; a database of components already in service could be used as a reference to obtain cost estimates for new products. Whilst the latter correlates with the analysis of component characteristics and manufacturing processes.
The following sections provide a more detailed analysis of the techniques just mentioned.

### Qualitative Techniques

Usually a new program is not completely new. Most of them evolve from existing programs to which new features have been added, or are simply a combination of existing design. These methods are often referred to as Analogy Methods and they use actual costs from a similar program with adjustments to account for differences between the requirements of the existing and new systems [17].

The main advantages are the ease of application before a detailed program requirements are known, and the minimum cost required to perform this kind of analysis. Analogies might also have some disadvantages, sometimes they rely on very few data points, hence the estimation could result inaccurate, and they tend to be too subjective about the adjustment factors considered. An analogy could also be used as a cross-check for other methods.

The following classification summarizes the most common qualitative estimation methods featured in [17].

- Intuitive Cost Estimation Techniques [17]
    - Case-Based Methodology
      It uses the information contained in previous design cases by adapting a previous design from a database that closely matches the attributes of a new design.
    - Decision Support System (DSS)
      These systems are designed to help estimators make better judgments and decisions at different levels of the estimation process by leveraging the knowledge held by experts in the field.
      The Rule-Based System obtains a cost estimate from a set of available calculations for the manufacture of a part based on design and/or manufacturing constraints, however optimising the results can be very time-consuming. To get a more reliable estimate the Fuzzy-Logic Approach can be used. Thanks to the definition of the system rules and the indication of the relationships between the input and the output, the uncertainty of the cost estimation could be handled.
      The last solution is the Expert Systems, based on storing the knowledge in a database and manipulating it with the help of an automated logical reasoning approach, to emulate the human expert thought process.
- Analogical Cost Estimation Techniques [17]
    - Regression Analysis Method
      A linear relationship between the cost of already existing products and the values of certain selected variables are used to predict the cost of a new product.
    - Back-Propagation Neural-Network (BPNN)
      These models use a Neural-Network (NN) that can be trained to knowledge to deduce the answers to questions that they have never seen before.

**Quantitative Techniques**

Unlike previous methods that use similarities between designs, quantitative techniques rely on collecting and analyzing measurable, concrete data. This usually leads to more accurate estimates. However, especially for innovative designs, these methods face the challenge of finding data that is often confidential or simply doesn't exist.

- Parametric Cost Estimation Techniques [17]
  A statistical relationship is developed between historical cost and program, physical, and performance characteristics, all of them known as cost drivers.

Once the statistics have been evaluated, the estimator selects the best Cost Estimation Relationships (CERs), the ones with the least variability and the highest correlation to cost.
This technique is widely used because of its versatility and objectivity; if the data are available a parametric estimate can be derived at any stage of the project. However, the creation of a consistent and reliable database is one of the main problems of this method, mainly due to the excessive required time to acquire and normalise all the data.

- Analytical Cost Estimation Techniques [17]
  These methods build the overall cost estimate by summing the detailed estimates done at lower level (Breakdown Approach). The low level estimation uses industrial engineering principles such as labor hours, material and machinery costs.
  Of course they will result in a very accurate cost estimation, but, it is easy to see how expensive and time consuming it might become. Furthermore, small errors may cause an avalanche effect, leading to completely inaccurate estimations. These methods are:

  - Breakdown Approach, which estimates the total cost as the sum of the costs of its components. Cost can be broken down into direct and indirect costs. Regarding the first one, their main factors are labor, material and subcontracting.
  - Operation-Based, which are usually used during the final stages of design, due to the nature of the data required.
  - Tolerance-Based, which selects process and design variables that minimise the cost function.
  - Featured-Based, which deal with the identification of the cost related features of a product, either design or process oriented.

### 2.3.3 Direct Maintenance Cost Estimation Methods

All of the aforementioned techniques represent the state of the art in product cost estimation, and depending on the features of the product, one method may result more suitable than the others for estimating cost.
Switching back to Direct Maintenance Costs (DMC), several methods have been proposed in the literature to evaluate them in the early stages of design, such as that proposed by *Wu et al.* [18]. Here the main focus is on the definition of a method to reduce the direct maintenance cost for an aircraft. This method falls into the quantitative category, specifically it is a breakdown approach estimation technique, where the total DMC gets evaluated by adding up the costs for each subsystem.
To achieve this, the authors first define how the maintenance cost can be estimated, using straightforward inputs such as Maintenance Man Hours (MMH), Labor Cost (LC) and Material Cost (MC).

In the same cost estimation category lies the work of *Salamanca et al.* [19], who have taken a step forward regarding the required inputs to their method. The methodology relies on commercial reliability software to define failure, inspection and repair rates, which constitute the most significant maintenance cost drivers. However, the approach focuses only on the aircraft airframe, and its applicability may prove difficult because of the need for in-depth knowledge of Finite Element Method (FEM) software, together with a lack of information that could make reliability inputs very difficult to find.

A more recent study conducted by *Wang et al.* [20] uses a different technique, to estimate the costs. The paper relies on a decision support system, the Fuzzy Support Vector Machine (FSVM), a machine learning algorithm that generates a quantitative forecast of direct maintenance cost during the design stage.
As with the previous one (*Salamanca et al.*[19]), the cost drivers are embodied in reliability parameters of the components (MTBF, Mean Time Between Substitutions (MTBS), Failure Rate (FR), etc). Another reason that makes it difficult to apply the results of this method is the limited age of the aircraft considered, in fact a fleet of 12 B737s aged between 4 and 6 years has been considered. Hence, the analysis does not take into account any heavy checks, nor problems related to the long utilization of the vehicle.

Within the quantitative techniques, parametric methods provide significant results. This is the case of *Mofokeng et al.* [21], which trace the first step towards a complete cost estimation, indeed their aim is to define which are the most influential maintenance cost drivers. To this end, the drivers that contribute to at least 80% of the maintenance cost have been selected through a Pareto analysis. The initial set of data from which the drivers are chosen are: maintenance-related (component age, false removal rate, frequency of check intervals and lack of spares parts) and general information (aircraft age, dry thrust, utilization, etc).

A more detailed look at a parametric model has been given by *Ben et al.* [22]. DMCs are calculated from the aircraft airframe and powerplant design parameters, such as airframe dry weight, block time, net thrust, and man-hour labor cost.
By applying the equations provided by NASA-95 Method [23], very general results have been obtained for maintenance cost and material cost, in addition an interesting sensitivity analysis has been carried out by the authors on the impact of aircraft empty weight, thrust and block hour on maintenance costs.
However, it should be considered that the outcomes relates to a 1995 methodology and the aircraft is only superficially divided into airframe and engines. As a result, the level of precision in the results proves insufficient to provide information about individual systems or even more detailed individual components..

*Fioriti et al.* conducted two different studies [24] [25], both of which exploit a regression analysis, as an analogical estimation technique.
The primary characteristics of the initial [24] model lie in its straightforward input requirements, which include basic aircraft details such as fleet size, utilization, acquisition cost, and Maximum Take-Off Weight (MTOW), and in the outcome costs provided for each of the ATA100 chapters. For these reasons, the method is easy to use in the early stages of aircraft design (2.4.2). The study takes the CERs given by [26] and proceeds towards their refinement, through a regression analysis.

The second research [25] uses the same inputs, but it defines the CERs without a starting reference by performing a completely new regression analysis. Significant is the collinearity test conducted by the authors, which excludes cost drivers that are highly correlated with each other. As a result, the cost relationships are defined as functions of MTOW, seat capacity and FH/FC ratio. These results allow the user to easily estimate the line and base maintenance in the very early stages of aircraft design.

Along with these studies, which have been developed using data from the previous generations of aircraft, newer solutions are being exploited, in order to comprehend how the maintenance will be affected by the new generations of aircraft. The major differences that will need to be taken into account are: the increasing electrification of the vehicles towards the goal of an all-electric aircraft, and the component reliability due to technology growth over time.

This is the case of *Selim et al.* [27], who estimated the ease of maintenance of an aircraft using a Multidisciplinary Design Analysis and Optimization (MDAO) framework. This different point of view, where the ease of maintenance is considered as a cost driver, allows to evaluate the cost of any type of aircraft by its design parameters only (size and access panels location, type of connections, etc), decoupling the analysis from any age-related data.
However, due to the tight correlation between aircraft utilization and required maintenance, the method could give a rough result, that would only be acceptable

in the early stages of design.
The study is a step towards a full maintenance cost estimate, as mentioned before, it only assesses the ease of this process, furthermore the results are very sensitive to any design changes, which will completely invalidate the conclusions, thus requiring a complete new analysis.

Another work worth mentioning is the the one from *Fioriti et al.* [28], which differs from all the others as it uses an intuitive case-based technique to estimate both the direct and indirect operating costs of the aircraft. In addition to the same inputs as [24], the more electric aircraft models shown in [29] are used as reference, in order to estimate the saving in DOC, due to the reduction in maintenance cost.

The aforementioned methods show the state of the art of the maintenance cost estimation for an airplane. As for the older models there are plenty of methods to evaluate the cost to a very high level of detail, for the new generation only qualitative techniques are described, which gives global results.

The aim of this thesis is precisely to fill this gap, by attempting to define a new estimation model capable of defining the savings in maintenance costs between different aircraft configurations (from conventional, through more electric, to all electric), while reaching component and on-board systems level.

## 2.4 On-Board Systems (OBS)

This section provides an in-depth examination of the On-Board Systems (OBS), delving into the network of integrated technologies and components that collectively support and allow an aircraft to function optimally throughout its operational life. Subsection 2.4.1 explores the historical background of the aircraft, providing context for understanding its development and maintenance needs. Then, in 2.4.2, a description of the Air Transport Association (ATA100) Chapters is reported, along with the systems that make up the OBS, such as the Electric Power System (ATA 24) (2.4.3), Flight Control System (ATA 27) (2.4.4) and Hydraulic Power System (ATA 29) (2.4.5)

### 2.4.1 Aircraft History

The evolution of aircraft from their early days in aviation has been driven by two main objectives: the constant pursuit of more efficient systems for improved safety and economics, and the adoption of environmentally friendly solutions to reduce aviation's impact on the planet. A significant milestone in this history was the introduction of jet propulsion with Boeing's Dash-80 prototype, which marked the birth of modern commercial aviation. The subsequent development of the 707 and DC-8 brought faster travel and reduced cabin noise but increased fuel consumption. The introduction of the Auxiliary Power Unit (APU) with the B727 in 1963 [30], followed by the wide-body era in the late-1960s, brought about significant changes in aircraft design.

The Boeing 747's inaugural flight in 1969 and Airbus' A300 in 1972 signaled the onset of the wide-body era. Safety regulations, such as Extended Range Twin-engine OPeration Standards (ETOPS) [31], initially favored four-engine aircraft due to their reliability. However, advancements in technology led to the introduction of Extended Diversion Time Operation (EDTO) in 2012, making twin-engine planes safer and more efficient. As a result, airlines began investing in twin-engine wide-bodies like the Airbus A350, A330, Boeing B787, and B777 families, leading to the retirement of four-engine aircraft like the A380 and B747.

The global commercial fleet is now dominated by single-aisle and twin-aisle aircraft, with the former covering short and medium-haul routes, and the latter used for longer routes including oceanic and desert flights. Regional jets, accommodating up to 100 passengers, operate on short regional routes (Figure 2.15 from [32]). As technology progresses, aircraft categorization based on route range is becoming less relevant. For instance, the Airbus A321XLR, set to be operational in 2024, is a narrow-body aircraft capable of covering long routes efficiently through advanced engine design and additional fuel storage [33].

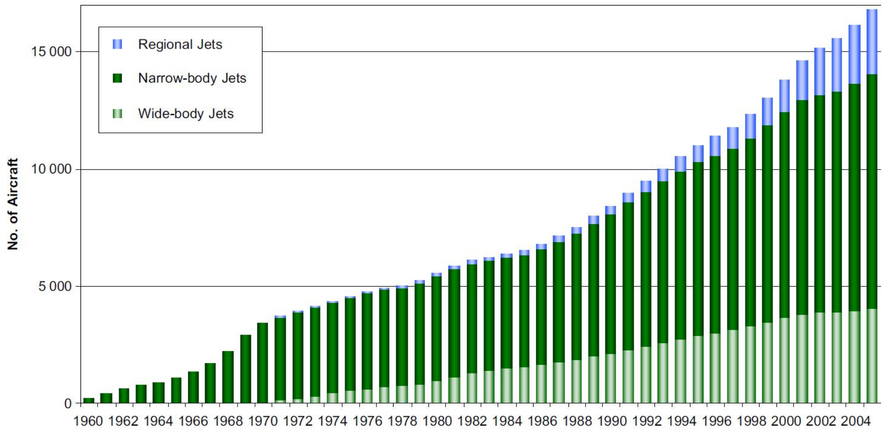



**Figure 2.15:** Global fleet composition from [32]

### 2.4.2 ATA100 Chapters

Regardless of its dimensions, every aircraft represents the cutting-edge of technology, designed with many complex systems working in perfect balance to provide the maximum safety, efficiency and comfort throughout each mission.
Among the main systems are the engines that generate thrust, the structure of the vehicle, the flight controls that allow maneuvering, and the avionics. Each of the these can be further broken down into subsystems, which are composed of various components. An example of breakdown for the propulsion system is reported in Figure 2.16 from [34].

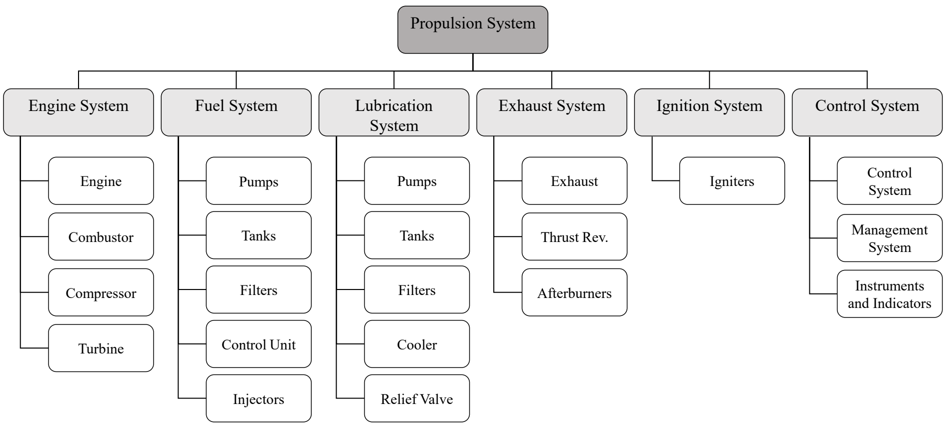



**Figure 2.16:** Propulsion system breakdown, made from [34]

In order to manage and understand the entire systems network on an aircraft,

the Air Transport Association (ATA) published the ATA100 numbering system in June 1956.
The ATA100 chapters provided a categorization solution that divided an aircraft into numbered chapters, each addressing a specific area or system. Although it has been more than 50 years since their introduction, they still represent a common referencing standard used to categorize and organize the various systems and components of an aircraft. The aspect that made this subdivision so widely used is its universality, in fact, regardless the aircraft type, the chapter division will always be the same.
The document covers all different aspects of an aircraft's operation and maintenance, as it provides in-depth descriptions, step-by-step procedures, and a wealth of reference materials for each chapter. Here is a brief description of the ATA chapters [35]:

- Chapters 00 - 19: Aircraft General Information.
  - Chapter 00-09: Technical data, definitions and abbreviations.
  - Chapter 10-19: Systems and components of the aircraft's airframe, including the structure, wings, flight controls and landing gear.
- Chapters 20 - 49: Aircraft Systems.
  - Chapter 20-29: Aircraft's engines and Auxiliary Power Unit (APU), including the fuel system, oil system, and starting system.
  - Chapter 30-39: Aircraft's electrical power system, including the generators, batteries, and wiring.
  - Chapter 40-49: Aircraft's equipment and furnishings, including the cabin systems, seating, and lavatories.
- Chapters 50 - 59: Structure.
- Chapters 60 - 69: Propeller/Rotor.
- Chapters 70 - 90: Power Plant.
  - Chapter 70-79: These chapters provide Illustrated Parts Catalogs (IPCs) that identify and describe the parts used in the aircraft.
  - Chapter 80-89: Damage Flimits and repair practices, including repair techniques and procedures.
- Chapters 91, 97, 115, 116: Miscellaneous topics, including weight and balance, operational limitations, and certification.

- Chapters 92 - 96, 98, 99: Peculiar Military Chapters.

Among all the ATA100 chapters, some systems and avionics are known as OBS. They support aircraft operation, navigation, communication and safety. In the matter of this thesis, the focus will be on four of these on-board systems, the hydraulic power system (ATA 29), the electrical power system (ATA 24), and the flight control system (ATA 27).

### 2.4.3 Electric Power System - ATA 24

Through the years, the amount of electrical power required on board an aircraft has increased significantly, and future aircraft designs aim to increase this demand even further, see Figure 2.17 from [36].

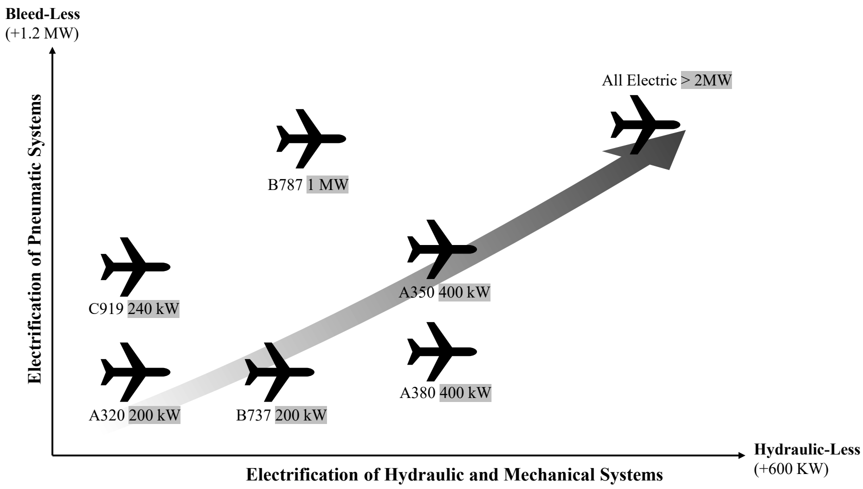



**Figure 2.17:** Increasing on board electrical equipment demand in commercial aviation made from [36]

Electric power saw its first on-board utilization during the World War I, when only a Direct Current (DC) power generation was used. Wind-driven generators were preferred over batteries, which had low reliability and poor energy density [37]. However, as aircraft performance increased, the efficiency of this solution diminished due to the higher drag forces generated, and the earlier 28V DC engine-driven generators started to be used. With the introduction of the more-electric aircraft concept (see Section 2.5.2) in the early 1990s, the focus shifted to Alternate Current (AC) generation. The main benefits of this solution are the smaller size of the AC generators compared to the DC ones, a higher operating voltage, which reduces the weight of the cables, and a higher reliability due to the absence of commutators

inside. On the other hand, there are some challenges due to parallel operation, the need to manage reactive power and the choice of an appropriate frequency. [37]
In this section, only the major components will be described. For a more detailed description of all components, please refer to the other specific works. The main electrical system constituents are [37, 38]:

- **Generators**
  Components that convert mechanical energy into electrical energy.
  Regarding DC generation, the majority of aircraft employ 28Vdc[1] or 120Vdc, and to achieve higher voltage level, reliability, efficiency and fault-tolerance capability. Switched Reluctance Machines (SMRs) are preferred over traditional brushed DC motors, to act as starter and generator.
  As for the AC generation, three-stages wound field synchronous generator represents the most widely used on aircraft due to its inherent safety. The first solutions with this component involved mechanical coupling with the engine through a Constant Speed Driver (CSD), a variable-ratio transmission gearbox. The whole unit was called Integrated Drive Generator (IDG) (Figure 2.18 from [37]).

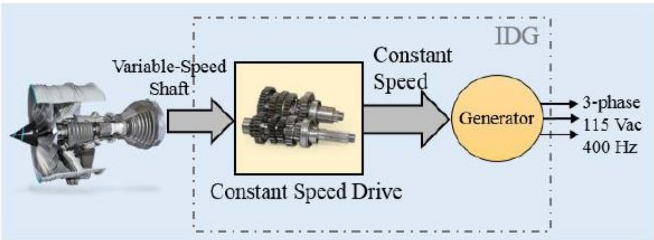



**Figure 2.18:** Integrated Drive Generator (IDG) from [37]

  The introduction of the Variable Speed Constant Frequency (VSCF) generators (Figure 2.19 from [37]) in the 1980s removed the bulky and expensive CSD from the system. However, the frequency converter that supplied the correct power to all the different components was a single point of failure, so VSCFs did not achieve the same level of adoption as IDGs.

  Many of the energy-consuming loads on today's aircraft are frequency-insensitive, allowing them to be powered directly by the Variable Frequency Generators (VFGs) without the need for PECs. Indeed, VFGs represent the main source of electrical power on-board more-electric aircraft [39].

[1] "Volts Direct Current". It refers to electrical voltage that is in the form of direct current (DC)

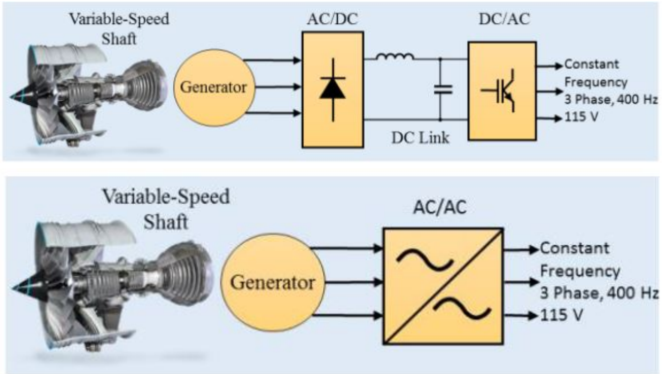



**Figure 2.19:** Two solutions for Variable Speed Constant Frequency generators from [37]

- **Batteries** [40].
  These devices convert the chemical energy generated within their cells into electrical energy. There are several battery technologies, the most commonly used in aviation are lead-acid (Pb-acid), Nickel-Cadmium (Ni-Cd) and Lithium-ion (Li-ion).
  In addition to their size and weight, they are categorized by their specific energy [Wh/kg], volumetric energy density [Wh/L] and specific power [W/kg], see Figure 2.20 from [40].

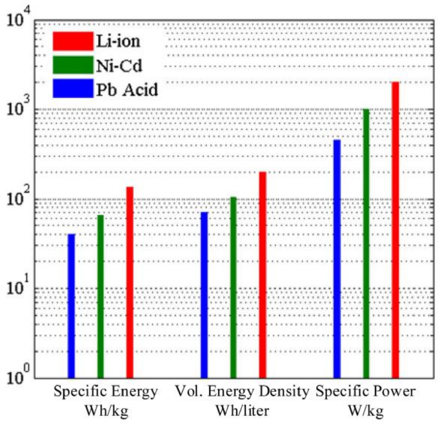



**Figure 2.20:** Different batteries characteristics from [40]

Although most commercial aircraft have used Ni-Cd batteries, the recent trend has been towards Li-Ion batteries. The latter guarantee higher performance with a reduction in weight, as well as a reduction in acquisition and maintenance costs due to their improved reliability.

- **Bus-Bar**.
  These take the output from the generators as input and then distribute it to all of the users connected to the bus. Buses also have the role of redirecting the power towards critical items in the event of an emergency.
  As shown in the Figure 2.21 from [41], it is possible to categorize the buses according to the type of users connected to their power supply:

  - Non-essential services, which are the first to be disconnected from the power line in the event of an emergency. These are called non-essential AC, or DC consumers.
  - Essential services, which are required to ensure a safe landing after an in-flight emergency. Also called AC, or DC essential consumers.
  - Vital services, which are required after an emergency. They are powered by the vital consumers.

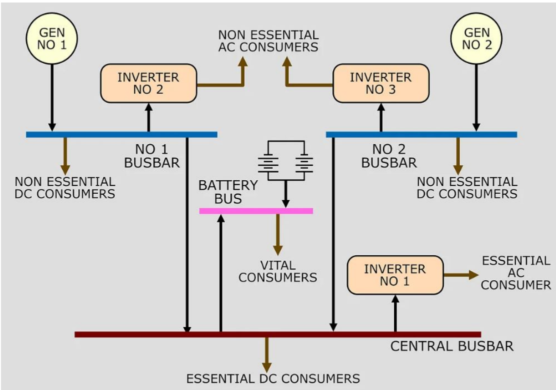



**Figure 2.21:** Power Distribution System from [41]

- **Transfer Rectifiers (TRs)**.
  They are responsible for converting AC power from the aircraft's generators into DC power. This converted DC power is crucial for supplying other systems, usually the batteries.

- **Inverters**.
  Opposite to the TRs, they convert DC energy to AC energy. Rotatory inverters use a DC rotatory motor to drive an AC generator, but their efficiency is lower than static inverters, which use a solid-state square wave generator.

- **Switches**.
  They have the ability to direct current to other precise parts of the circuit and to isolate other parts, depending on the type of switch.

- **Fuses**.
  Fuses are critical safety devices designed to protect electrical circuit from excessive currents. These small components can melt, or break when an overload or a short circuit appears, interrupting the current flow.

- **Circuit Breakers**.
  These are a particular kind or fuses, in fact they may block the current flow in the circuit if an overload is detected, but they do not self-destruct, thus they can be reset and perform the control function again.

Depending on the size and configuration of an aircraft, the electrical system might vary significantly. From smaller general aviation aircraft with simpler electrical setups to large commercial airliners with highly sophisticated electrical architectures, that can require miles of wiring and several of the components listed above. Redundancy also plays a critical role in ensuring that essential electrical functions remain available under any condition.

### 2.4.4 Flight Control System - ATA 27

In the beginning, any aircraft Flight Control System (FCS) was directly controlled by the pilot, whose force was applied to the control stick and then mechanically transmitted to the surface via push rods, cables and pulleys (see Figure 2.22 from [42]).

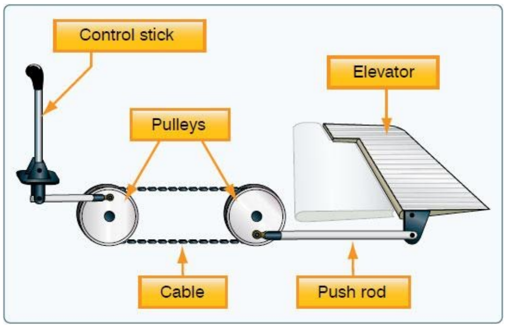



**Figure 2.22:** Elevator mechanical flight control from [42]

The increasing size of the systems and the increase in aircraft performance (e.g. higher top speeds) made it impossible for the pilot alone to control the aircraft. At first, some mechanical devices, such as aerodynamic balances, were introduced to compensate for the higher loads, then, after further growth, in the 1950s, hydraulic solutions were introduced, such as the one illustrated in Figure 2.23 from [43]. This technology employed pressurized fluid to reduce the physical demand on the pilot, and also to guarantee a smoother and more precise input.

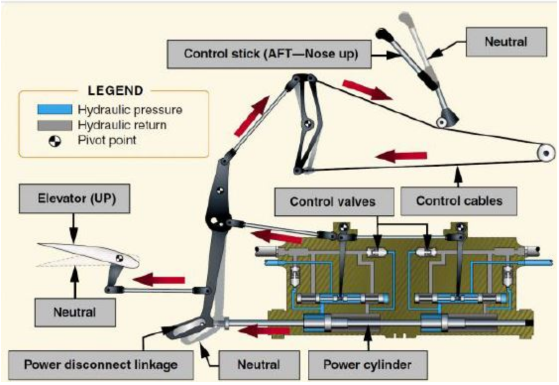



**Figure 2.23:** Hydraulically powered elevator control system from [43]

The hydraulic fluid and mechanical linkages made these systems heavy and complex, adding to the overall weight of the aircraft. This extra weight resulted in higher fuel consumption and reduced overall efficiency.

To address the limitations of hydraulic systems and further enhance aircraft performance and safety, Fly-By-Wire (FBW) technology (Figure 2.24 from [44]) started to replace traditional mechanical and hydraulic controls with electronic systems.

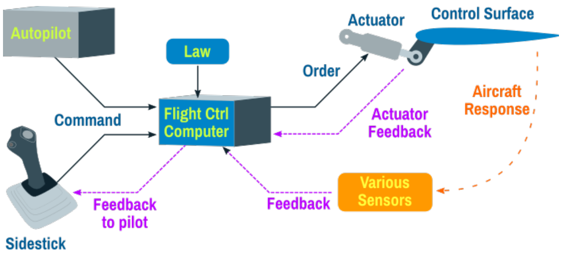



**Figure 2.24:** Fly-By-Wire concept from [44]

Here the control inputs are instead sent to calculators which deliver actual orders to actuators. Each FWB system, in addition to introducing calculators into the pilot-control surface chains, also gets information from sensors to measure the aircraft response to orders (feedback). The main advantage of the calculator is that it monitors the pilot's commands so that the aircraft is never put into an undesirable or dangerous configuration. [43].

To further improve this system, the concept of Fly-By-Light (FBL) is becoming increasingly important. In this advanced architecture, optical fibers serve as the primary medium for transmitting the commands through the system. Its main advantages are a weight reduction with the replace of the copper wiring with the optical fiber, an increase reliability and an immunity to electromagnetic interference.

### Control surfaces

The flight control system has several surfaces and depending on their function they can be categorized into primary and secondary. Figure 2.25 from [45] shows a general FCS configuration for a commercial aircraft.

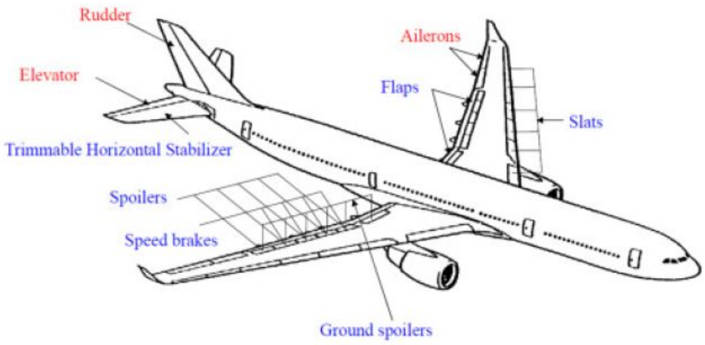



**Figure 2.25:** Flight Control System (FCS) from [45]

Primary surfaces are used to control the attitude of the aircraft around the three control axes: roll, pitch and yaw. They are constantly active during fight and use linear actuators. They are:

- Ailerons.
  Usually mounted on the trailing edge at the end of each wing. By moving asymmetrically, they control the aircraft's roll angle, and/or speed. Pilots can control the ailerons by turning the control cloche clockwise or counterclockwise.

- Elevator.
  This surface is located within the horizontal stabilizer and contemplates two separate elevators, which can move up and down symmetrically. The pilot can control them by pushing, or pulling the cloche.

- Rudder.
  This last primary surface controls the yaw angle of the aircraft. It is located at the trailing edge of the vertical stabilizer and it is controlled by the pilot's pedals. When pressed, the surface moves in the corresponding direction.

The secondary control surfaces are only used in some specific segments of the mission profile (approach, landing, take-off, etc). Their main function is to modify the wing geometry to increase lift and/or drag. They include:

- Flaps and Slats.
  Used to increase lift during take-off and to reduce drag during descend. They

are usually actuated differently from the primary surfaces (see Figure 2.26 from [46]), with each flap and slat connected to an electromechanical rotary actuator. The latter are connected to a common shaft, which is controlled by the Flap Power Control Computer (FPCC). By rotating the shaft, the FPCC can control the extension of all the surfaces. Depending on the maximum lift coefficient required by the wing, different flap and slat configurations are available. The former can be plain, split, slotted, flap Fowler, etc, while the latter can be nose flap, Kruger slat, leading edge drop, etc . [46]

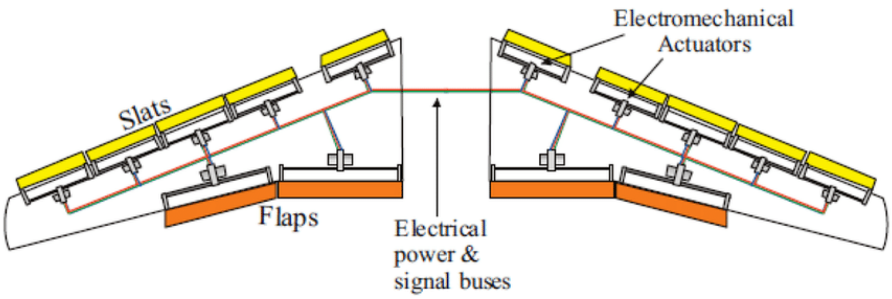



**Figure 2.26:** Flaps and slats actuation from [46]

- Spoilers.
  Also known as lift dumpers, when deployed symmetrically, they perform their primary function of reducing the lift and increasing the drag by disrupting the airflow over the wing. Alternatively, when deployed asymmetrically, they can control the roll of the aircraft. For this second function, spoilers are always used in combination with ailerons.
  Similar to the primary surfaces, each spoiler is directed by a linear actuator.

### Flight Control System Actuators

Flight control system actuators are the components most affected by the change in aircraft architecture. Most airliners feature classical actuation via Hydraulic Servo Actuator (HSA) for all the surfaces, except the Trimmable Horizontal Stabilizer (THS), whose actuation is made by an Electro-Mechanical Actuator (EMA). The new generation aircraft, like the A350, represent the first models to implement a hybrid actuation, consisting of HSAs, but also some Electro-Hydraulic Actuator (EHA) and Electric Backup Hydraulic Actuator (EBHA).
Conventional HSAs are supplied with hydraulic power from hydraulic lines. Generally in a conventional aircraft there are two or three lines, to fulfill safety requirements with the redundancy. The main issue is the weight of the lines and their components (pumps, actuator, filters, etc).

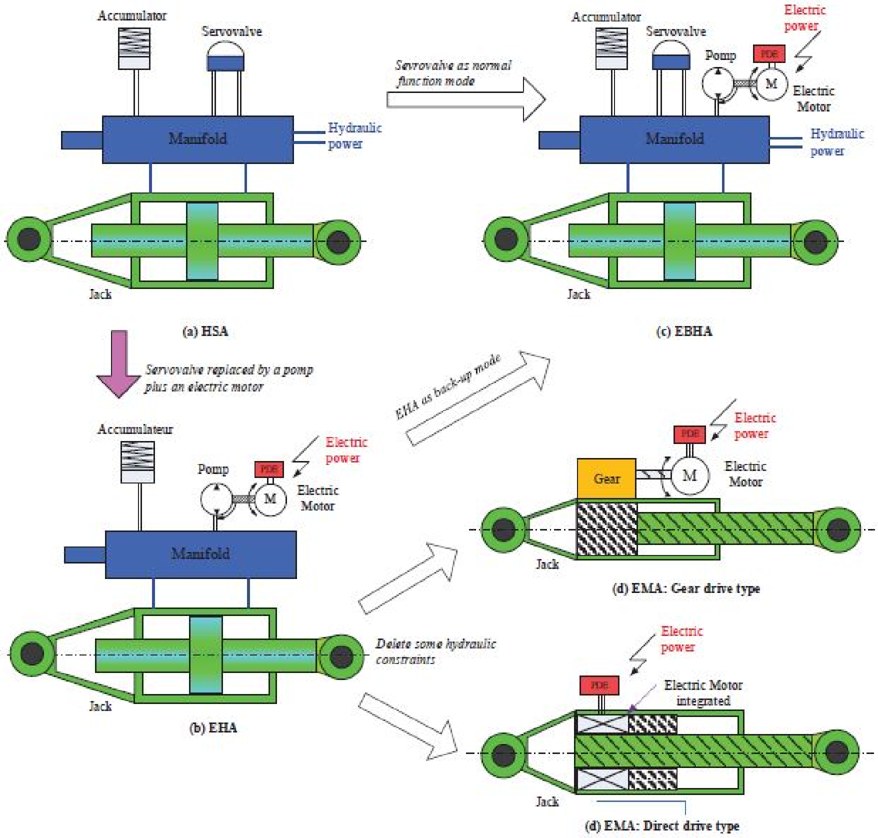



**Figure 2.27:** Schematic of actuator servo-controls from [47]

EHAs represent a solution to this problem. Actuators are always hydraulically powered, but the main difference is in how the power is supplied. While HSAs have a central hydraulic system, each EHA has its own hydraulic circuit powered by an electric motor. This makes the actuators themselves heavier and more complex, but removing all the other hydraulic components makes the overall system lighter and easier to maintain.

Between HSAs and EHAs lie EBHAs. They include both configurations where the actuator is powered by the hydraulic line during normal operation, while in the event of a failure of the hydraulic system, the electrically powered local unit will power the component [45]. The main advantage of this configuration is the reduction of hydraulic supply lines.

Another solution is the EMA, which completely replaces hydraulic power with electromechanical power. They can be seen as a more electric version of the screw-jack actuators, where an electric motor drives the gear assembly. Their actuation is slower, but can handle higher loads.

### 2.4.5 Hydraulic Power System - ATA 29

Until recently, hydraulic system has powered many critical component and subsystem of an aircraft, such as landing gear, flight control surfaces, flaps and brakes. The main advantages in using this solution are high powered densities, ease of installation, minimum maintenance requirements and near 100% efficiency, with only negligible losses due to fluid friction [48].
Several types of hydraulic circuits can be found in the literature, the most widely used in aviation are the the closed-center systems, where the required pressure is instantaneously dispatched once the valve is in position. This feature is critical for any aircraft operation.
The hydraulic system used on large commercial jets is shown in Figure 2.28 from [48].

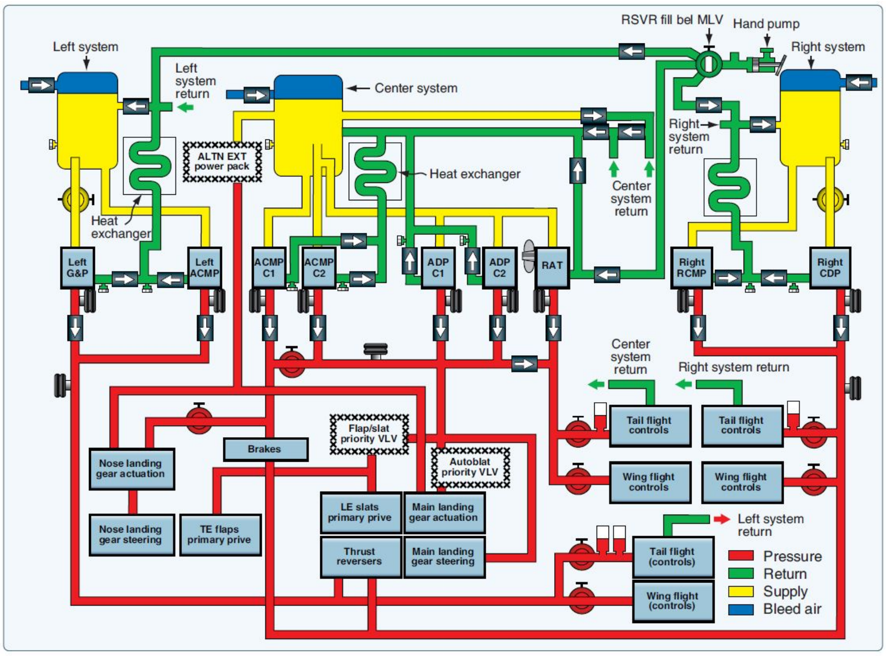



**Figure 2.28:** Large Commercial Aircraft Hydraulic System from [48]

The principal constituents of an hydraulic system are [48]:

- **Hydraulic fluid**.
  Its primarily use is the transmission and distribution forces throughout the system. According to Pascal's Law, due to its incompressibility, pressure applied to any part of the fluid will be transmitted to any other part without losses. Not every liquid can be used as a hydraulic fluid in an aircraft, depending on the particular operating conditions, manufacturers of hydraulic

devices specify the type of fluid best suited for use with their equipment. The most important characteristics to consider in a fluid are viscosity, chemical stability, flash point, and fire point.

- **Reservoirs**.
  These are fluid storage tanks, whose primary function is to supply the operational need of the system, they can also replace the fluid that is lost through leakage and can be used as an overflow tank to store the excess fluid generated by thermal expansion. Reservoirs can be pressurized or non-pressurized, their internal structure presents some fins to avoid the fluid to vortex. Many commercial airplanes use air-pressurized reservoirs, these include a pressure relief valve, that opens to avoid over-pressurization, a glass for visual indication, a sample valve, a drain valve, and a temperature and quantity transmitter.

- **Filters**.
  Devices used to clean the fluid and prevent contaminants from remaining into the system. The reliability and efficiency of the entire hydraulic system depend on them, very small tolerances are required to prevent any component from malfunctioning. To minimize space and facilitate maintenance many modern aircraft use filter modules that can house multiple filters and components.

- **Hydraulic Pumps**.
  To keep the hydraulic lines pressurized, aircraft have different pumping solutions. Modern airplanes have a combination of Engine Driven Pump (EDP), electrically driven pumps, a Power Transfer Unit (PTU) and a Ram Air Turbine (RAT) driven pump. During normal operation for a conventional architecture, the EDPs are the primary source of hydraulic power, while the others are used as an emergency backup to provide power to only the critical system during a non-safety situation with lower pressure and flow than the nominal systems. Therefore these pumps result smaller.
  In addition to the power supply, a pump can be chosen based on its pressure generating mechanism, variable-displacement pumps are the most widely used for aviation purpose; they are directly coupled to the engine and can deliver the correct fluid pressure and flow when needed. To protect the system against excessive pressure, a relief valve is placed within the pump.
  Regarding the PTU, its purpose is to transfer the hydraulic power (not the fluid directly) from one end to the another, by taking hydraulic fluid from one pressurized system and delivering it to the other, usually at a different pressure.

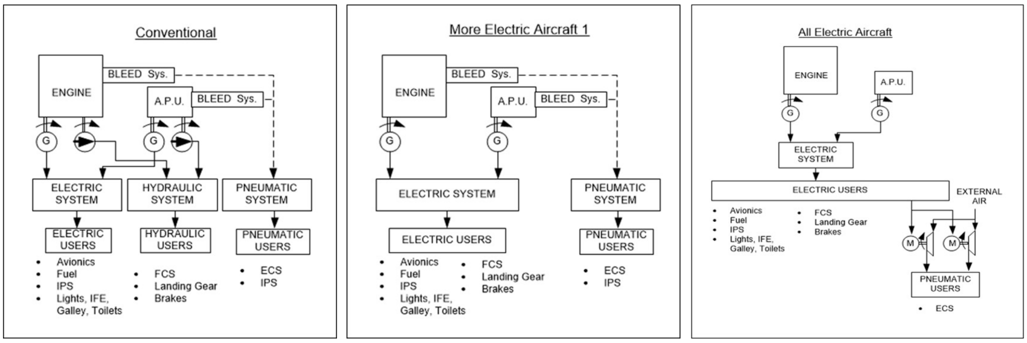
- **Accumulators**.
  Several accumulators may be found on an aircraft, they could be spherical or cylindrical, with two internal chambers separated by a rubber diaphragm; the

upper one contains the fluid at system pressure, while the lower one is filled with pressurized gas (nitrogen or air). Their functions are to compensate for pressure surges in the hydraulic system, to provide additional pressure during intense operations, and to compensate for a small amount of leakage.

- **Valves**. [49]
  By controlling the speed and direction of the fluid, hydraulic valves allow the operation of all the various components in the system. The following are the main flow control valves utilized in a plane:
  - Selector valves control the movement of a hydraulic actuation device.
  - Check valves force the fluid to flow in one direction, preventing movement in the opposite direction.
  - Sequence valves enable one device to automatically activate another component. For example, a sequence valve allows the landing gear and its hatch to move sequentially, since the first cannot start moving when the hatch doors are closed.
  - Priority valves prioritize critical hydraulic subsystems over non-critical ones when system pressure drops below the nominal value.
  - Quick disconnect valves prevent any fluid loss when a component is removed from the line.
  - Pressure control valves. They keep the fluid pressure under control, to ensure safe and efficient operation of components and equipment. They include relief valves, pressure regulators, and pressure reducers.
  - Shuttle valves isolate the normal system from the emergency system, allowing fluid to be diverted through the emergency line to critical components only.

## 2.5 Aircraft Configurations

Taking into account the technological advances described in the previous sections, the different aircraft configurations are described in this sub-chapter. The conventional configuration (2.5.1), which characterizes the historical and current state of aviation, is accompanied by the emerging more-electric configuration (2.5.2), which represents the near future of aircraft design. Finally, there is the all-electric (2.5.3) concept, which represents the ultimate evolution that is expected to replace the more-electric configuration in the more distant future.




(a) Conventional (b) More Electric (c) All Electric

**Figure 2.29:** Aircraft Configurations

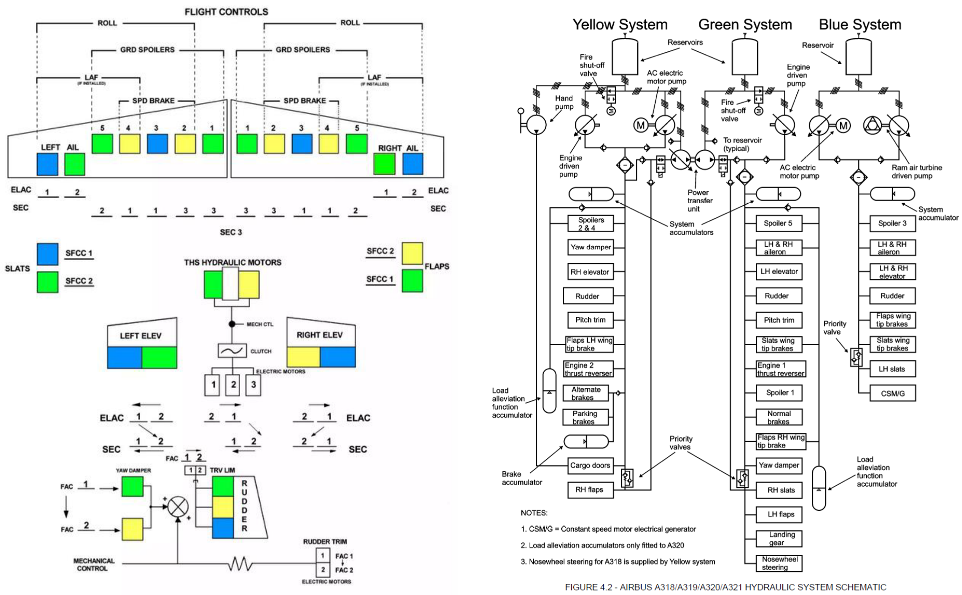
### 2.5.1 Conventional Configuration - A320

As a reference for this category of aircraft the Airbus A320 has been considered. It represents one the most successful vehicle in aviation history. Its operations started in 1988, as for today, more than 10,900 planes have been built, with almost 6,700 others in order [50].
This narrow body is the main protagonist in the coverage of small/medium routes, with most flight between 1.0 and 2.0 FH [14]. Being one of the oldest aircraft, its hydraulic system represents the main power supply for the subsystems.

As shown in Figure 2.29(a), the conventional architecture relies on a combination of hydraulic, electric, and pneumatic systems. However, a major flaw in this setup lies in the bleed system, which extracts compressed hot air from the engine's compressor to maintain the operation of both the hydraulic and pneumatic systems. Unfortunately, this extraction process comes with a significant drawback , the reduction of the engine's potential maximum thrust. As a consequence, achieving a desired level of thrust demands increased fuel consumption, thereby diminishing the engine's overall efficiency.

### Hydraulic Power

The reference aircraft has 3 continuously operating hydraulic lines (see Figure 2.30 from [51]), blue, green and yellow; the nominal working pressure is 3000 PSI, while during an emergency, if the RAT is deployed, the pressure drops to 2500 PSI. [51]




(a) A320 FCS (b) A320 Hydraulic Lines

**Figure 2.30:** A320 Architecture from [51]

Both the green and yellow lines have an autonomous pump, driven by engine 1 and 2 respectively, to pressurize the entire hydraulic lines. In addition, the yellow line has a second electric pump that can also pressurize the line, allowing control of hydraulic consumers when the engines are off (e.g., when the vehicle is on the ground); and a third manual pump to operate the cargo door when electrical power is unavailable. Instead, the blue line is pressurized only by an electric pump and, in the event of an emergency, by a RAT-driven pump that achieves a slightly lower system pressure, 2500PSI instead of 3000PSI. All the components presented in subsection 2.4.5 are integrated into the A320 hydraulic lines. In particular, there are:

- Two engine driven pumps.
- Two electric pumps, one to backup the yellow line and the other one to pressurize the blue line.
- One RAT driven pump, as backup for the blue line.

- One PTU capable of transferring power from the yellow line to the green line and vice versa.
- Three air-pressurized reservoirs, one for each line.
- Three accumulators, one for each line.
- Many filters throughout the systems.
- Three priority and three leak measurement valves, one of each for every line.

For the conventional architecture all the servos will be HSA, both linear and rotatory. Considering the A320 FCS configuration, the model will have 18 surfaces, divided as follows. Two ailerons, one per wing, with two linear actuators each; Two elevators, one per each side of the THS, with two linear actuators each; One rudder, with three linear actuators; Ten spoilers, five per wing, with one linear actuator each; Four main sets of flaps (inner flaps, outer flaps, and two sets of slotted flaps), divided into two tracks, one per wing, with two rotary actuators; Six leading-edge slats with one rotatory actuator on each wing; One THS, with one rotary actuator, powered by two hydraulic motors.

**Electrical Power**

The A320 electrical power system (Figure 2.31 from [52]) consists of a three-phase 115/200V 400 Hz constant-frequency AC system and a 28V DC system. The entire system produces alternating current, some of which is then converted to direct current for specific applications. Each of the three generators can supply power to the entire grid. In the event of a loss of normal AC generation, an emergency generator can provide AC power; if all AC generation is lost, the system can convert DC power from the batteries to AC power. [52]

All the components presented in subsection 2.4.3 are integrated into the A320 hydraulic lines. In particular, there are:

- Two three-phase AC generators. Each of them is connected to the correspondent engine through an integrated drive and it is able to generate up to 90 kVA of power at 115 and 200 V AND 400 Hz.
- One emergency generator that provides 5kVA of three-phase 115/200V, 400 Hz power (1/18 of the nominal output). It is driven by the blue hydraulic line and automatically supplies AC power if all the three main generators fail.
- One static inverter to transforms the DC power from Battery 1 into 1 kVA of single-phase 115V, 400 Hz AC power, which is then supplied to part of the AC essential bus.

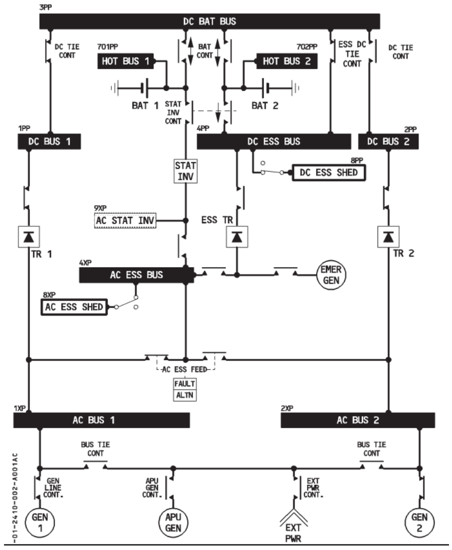


**Figure 2.31:** A320 Electrical System from [52]

- Two transformer rectifier and an emergency one.

- Two batteries, with a capacity of 23 Ah each.

### 2.5.2 More-Electric Configuration - A350

One of the most well-known MEA family is the Airbus A350 family. The innovation of the MEA configuration lies in the gradual abandonment of hydraulic power, while still retaining the pneumatic power system. This strategic shift results in a significant reduction, though not complete elimination, of the bleed system, ultimately leading to enhanced overall aircraft efficiency.
As shown in the Figure 2.29(b), the primary focus of this transformation is on all subsystems that relied on hydraulic power in the traditional configuration, such as FCS and landing gear. With the introduction of advanced electric technologies, these subsystems can now operate with increased efficiency and reliability.
This progressive move towards more electric solutions promises a multitude of benefits, including improved fuel efficiency, reduced maintenance costs, and a decreased environmental footprint. However, because safety has a primary role in the aviation industry, when it comes to introducing major changes, such as completely abandoning the conventional design that has defined aviation history, a gradual approach is essential. This allows us to fully understand the potential and the risks of the new design without compromising the safety of the aircraft. For this reason, hybrid configurations that lean toward a more electric approach, but still rely on the reliability of hydraulic systems, are prevalent.

### Hydraulic Power

The A350 has a 2H/2E (two hydraulic circuits/two electrical circuits) architecture. Both hydraulic lines (yellow and green) operates at an increased pressure of 5000psi, from the standard 3000psi [53]. The hydraulic generation is assigned to:

- Four engine driven pumps, two per engine. One for nominal operation and the other one for backup.
- One Electric Motor Pump (EMP), only used to generate pressure on the ground.
- Two fire shutoff valves per engine.
- A cooling system to avoid any degradation of the hydraulic fluid.

The A350's most significant innovations lie in the flight control system actuators. As illustrated in Figure 2.32, each aircraft side features two ailerons, two elevators, seven spoilers, and one rudder. In particular, the introduction of EHA as redundancy for the inner aileron, elevators, and rudder represents a major advance. In addition, the adoption of EBHA as a backup for one wing spoiler further enhances the aircraft's reliability and performance.

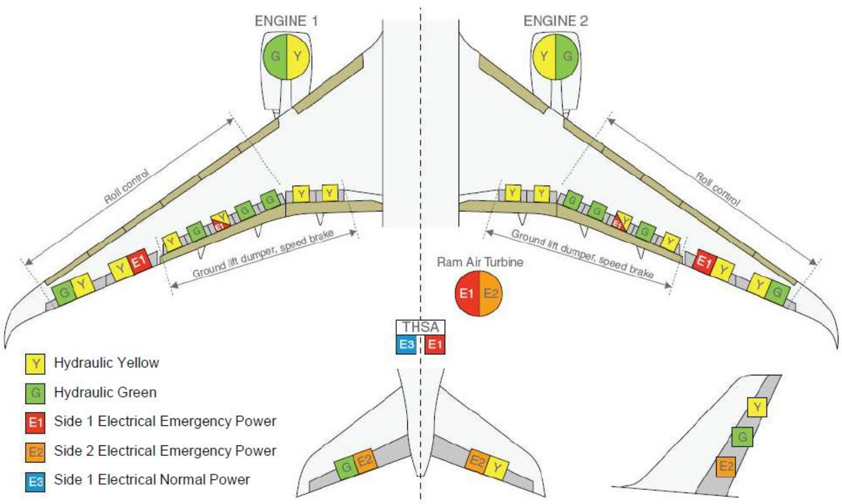



**Figure 2.32:** A350 flight control system from [53]

### Electrical Power

Figure 2.33 illustrates the entire A350 electrical power supply, featuring three distinct networks: a 230V AC line, a 115V AC line, and a 28V DC line. Each network is equipped with both normal and emergency electrical distribution capabilities, ensuring reliability and redundancy in the aircraft's power supply. Thanks to these solutions, the A350 can confidently support ETOPS with a diversion time of up to 350 minutes. [53]

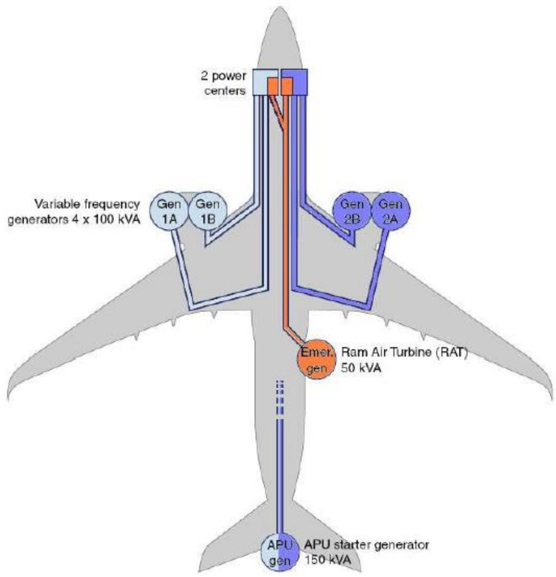



**Figure 2.33:** A350 electrical system from [53]

- AC Power Generation.
  During normal operations, the A350 is equipped with four VFGs, along with one main generator and one backup generator per engine. These generators work in tandem to supply 230V AC at variable frequency to the corresponding electrical line.
  On the ground, the APU generator can power the entire electrical line with 230V AC at a constant frequency. This setup is particularly useful during ground operations, providing a stable power supply for various systems and equipment on the aircraft. Moreover, the APU generator serves as an essential emergency solution during flight.
  Lastly, a drop out RAT drives an AC emergency generator, that can supply essential systems if all the generators fail.

- DC Power Generation.
  The primary source of DC power on the A350 is obtained by converting the 230V AC power. Additionally, the aircraft employs four identical Lithium-Ion batteries directly connected to the 28V DC network. These batteries play a crucial role in ensuring a continuous and uninterrupted supply of DC power.

In the event of any disruption to the AC power supply, the batteries kick in, seamlessly providing DC power to critical systems. This feature is particularly important during ground operations when AC power might not be available or during situations where there could be a temporary loss of AC power.

- Electrical Power Distribution.
  The 230V AC network serves as the supplier for the 115V AC network busbar through the use of Auto Transformer Units (ATUs). These ATUs facilitate the voltage transformation from 230V to 115V, ensuring efficient power distribution between the two AC networks. Furthermore, the 230V AC line also supplies the DC busbars via the use of Transformer-Rectifier Units (TRUs). These TRUs play a crucial role in converting the AC power to DC power, which is essential for providing a stable and continuous power source to the DC systems and equipment on the aircraft.

### 2.5.3 All-Electric Configuration

The concept of All-Electric Aircraft (AEA) represents a significant step towards eliminating conventional fuels and combustion engines. It foresees powering the entire aircraft using electric propulsion and electrical systems, including the elimination of pneumatic power with a bleed-less engine configuration, as depicted in Figure 2.29(c). [54] While the Boeing B787 continues to use conventional aviation fuel, it stands as a milestone by being the first commercial aircraft to adopt a bleed-less engine solution, marking the initial progress in embracing electric propulsion and advancing the AEA vision within the aviation industry.

Furthermore, several prototypes and small-scale electric aircraft have been successfully tested, showcasing the potential of electric motors and batteries to power flight. However, implementing an All-Electric Aircraft for commercial long-range flights is still in its early stages and presents various challenges [54, 55, 56]. These include:

- The need for significantly higher energy density devices (such as batteries, fuel cells, or alternative solutions) to enable energy storage for long-haul flights.
- Extending the flight range without compromising payload capacity.
- Developing completely new infrastructures that can ensure quick turnarounds and efficient charging of electric aircraft.
- Integrating these novel electric solutions into the existing aviation regulatory system, addressing safety, certification, and airworthiness requirements.

In conclusion, the electrification of aircraft is a solution that meets global demands for improved safety, environmental friendliness, and cost-effectiveness.

By adopting electric propulsion and electrical systems, aviation can become more sustainable and people-friendly. The future promises greener, quieter, and more efficient flights, where aircraft operate in harmony with the environment, elevating the air travel experience for passengers while contributing positively to the planet's well-being.

## 2.6 Science Gaps and Research Questions

Newer aircraft configurations, especially more-electric ones, driven by technological advances and the quest for efficiency, have the potential to transform aviation. A key part of this transformation is how these configurations affect maintenance costs. Despite extensive research into the changes these configurations can bring, there's still a gap in understanding their impact on maintenance costs. This gap points to the need for a systematic approach to accurately assess these costs.

This study aims to address this scientific challenge by investigating several key research questions. The primary research question focuses on determining the magnitude of the change in maintenance costs when transitioning from conventional aircraft to innovative more-electric aircraft configurations. In addition, several secondary research questions will be explored to provide a comprehensive understanding of the topic, including identifying which specific on-board systems are most affected by the transition, establishing effective methods for deriving maintenance tasks from the A320 Maintenance Planning Document (MPD) to assess changes in on-board systems, developing a methodology for eliminating the contributions of existing systems from the total maintenance cost estimate for various tasks, and developing a framework for reintegrating the maintenance contributions of new components into the total estimate, taking into account their direct proportionality to component reliability through various failure rates.

An opportunity for future research lies in the adaptability of the method. While this study provides a tool for estimating maintenance costs for a configuration that represents the evolution of the conventional Airbus A320, there's room for expansion to consider a wider range of solutions. Future research could explore how the method can be adjusted and extended to estimate maintenance costs based on changes to individual components within any aircraft subsystem. This way, researchers can create a framework that covers numerous possible design variations, providing a more comprehensive estimate of maintenance costs.

# Chapter 3

# Direct Maintenance Cost Estimation

The primary objective of this chapter is to explore and quantify the maintenance cost variations associated with the transformation from conventional to More-Electric configurations. This result has been obtained as a numerical result of the variation in MMH required between the conventional and the more electric configuration, according to 3.1.

$$\begin{aligned}\text{Maintenance Cost}_{MEA} = {} & f(\text{Conventional Aircraft Overall Maintenance}) \\ & - f(\text{Conventional OBS Maintenance}) \\ & + f(\text{More Electric OBS Maintenance})\end{aligned} \tag{3.1}$$

Here, the first term represents the baseline MMH value for a conventional configuration, while the square brackets represent the delta change in MMH resulting from the selected on-board system changes. These are then combined to estimate what the MMH contribution should be for an aircraft model with the assumed on-board system modifications.

It is important to highlight that all of the following analyses or statements regarding component maintenance refer exclusively to components active during the aircraft's regular operation. This distinction arises from the fact that the maintenance task definitions outlined in the MPD do not include the servicing of redundancies and back-up components.

This third chapter is divided into two sections. The first one, 3.1, outlines all available information, including how it is obtained. This is followed by the definition of potential methods that can be used in its latter part. The second subsection, 3.2, provides an explanation of the selected method, along with a detailed description of the steps required for its proper application.

## 3.1 Preliminary Work for DMC Estimation Method Development

This initial section of the chapter provides the basis for the subsequent descriptions. The common starting point for all considerations is the conventional configuration of the A320. This choice is based on its widespread use and longevity, ensuring easy availability of relevant material.

Moving through the on-board system changes, indicated in 3.1.1, a model of a more electric configuration for this aircraft is defined. The following sections, 3.1.2 and 3.1.3, outline the steps that will be used to gather all the necessary data. Once this information is obtained, 3.1.4 describes the potential methods for defining the desired results, along with an analysis of their applicability.

### 3.1.1 Overview of Conventional and More-Electric On-Board System Architectures

As stated in 2.5.2, More-Electric aircraft configurations represent a departure from conventional design, to achieve greater efficiency, reduced fuel consumption and enhanced environmental sustainability. The main protagonists affected by this transformation are the on-board systems described in 2.4. In this section, we will define these key changes. This is the first step in establishing a method for estimating the variation in maintenance costs between the two chosen configurations. With reference to 2.5.1, Table 3.1 at the end of this section summarizes the important points discussed, helping to clarify the proposed changes to the More Electric model.

#### Hydraulic Systems

The primary driver for this new more electric aircraft model is the relentless search for aircraft weight reduction, a key factor in achieving greater efficiency. At the center of this there is a conscious decision to re-evaluate, and in some cases eliminate, the hydraulic system, as its components (from pipes and accumulators to filters and pumps) have come under the microscope for their excessive weight.

The conventional configuration of the A320 sees the presence of 3 hydraulic power supply lines (3H), each of which consists of the components described in 2.5.1. A middle ground between conventional and more electric is represented by the A350 (2.5.2), which sees the removal of one hydraulic power line (2H configuration), with an increase in the amount of electric power produced on board. In the context of this study, a further step will be taken and a radical change in configuration will be assumed, in which the hydraulic power system is completely eliminated, leaving a 0H configuration.

Once these elements are defined, the next step is to find the maintenance tasks that they require within the MPD. As this system is not being replaced but rather eliminated from the model, its removal will lead to a decrease in the overall maintenance expenses.

### Flight Control Systems

The situation is slightly different for the FCS. In conventional configurations, this on-board system works in tandem with the hydraulic system, which provides the necessary pressure to actuate the controls. Since the model to be developed does not include a hydraulic power system, and since actuators are currently the only means of controlling movable surfaces, it is necessary to replace them with electrically powered alternatives. Following the path already taken by aircraft such as the A350 and A380 (2.5.2), the choice fell on Electro-Hydraulic Actuators (EHAs) (2.4.4).

It's important to note that this logic applies only to surfaces controlled by hydraulic linear actuators, such as ailerons, elevators, spoilers, and the rudder (2.5.1). Flaps and slats are connected to a transmission shaft that is moved by a rotary Electro-Mechanical Actuator (EMA). Therefore, their configuration remains unchanged for the purpose of defining the model aircraft. In this case, the overall impact on maintenance costs will initially be a reduction due to the elimination of tasks required by traditional Hydraulic Servo Actuators (HSAs). Subsequently, maintenance costs will increase due to the introduction of the new components into the system.

### Electrical Systems

As far as the electrical system is concerned, several sources are available to define its components in relation to the reference aircraft (A320). On the other hand, there is a lack of detailed information regarding new technologies used on board the most recent aircraft. For this reason, a more general approach was necessary to evaluate the system changes from the conventional architecture to the more electric one. In particular, two categories of components can be distinguished:

- The first one includes elements that have a considerable impact on maintenance costs during the transition between architectures. These include generators and batteries. For the former, traditional Integrated Drive Generators (IDGs) are replaced by the more reliable Variable Frequency Generators (VFGs) (2.4.3), while the latter undergo a change in their internal chemical composition (2.4.3), moving from the old Ni-Cd batteries to the newer Li-Ion batteries that are notably lighter and offer a higher energy density, providing more power for a given weight [57].

- The second category includes components that will remain unchanged during the transition. Their core technology will remain the same; the only expected variation is in their numbers, with some potentially increasing while others may decrease, as indicated in [37]. The main changes will affect the loads connected to the system; many of them will become "frequency insensitive" (i.e. communication system, lighting system, etc), so they can be connected directly to the generator without the need for transformers or converters. The maintenance contribution of these components is negligible when considered individually; in fact, some of them, such as Transformer-Rectifier Units (TRUs), are designed to operate without requiring any maintenance [58]. For this reason, this second group is treated as a collective entity and an overall result is generated that takes into account the sum of the individual small contributions of the various components.

**Table 3.1:** More Electric Model Changes Overview

| On-Board System | More Electric Model Changes |
|---|---|
| Hydraulic System | Complete elimination of hydraulic lines and consequently of all the components identified in 2.4.5. |
| Flight Control System | Replacement of linear hydraulic actuators for spoilers, ailerons, elevators, and rudders with Electro-Hydraulic ones.<br>Slats and flaps, as reported in 2.4.4, are already driven by a linear ball-screw actuators powered by rotating shafts connected to central distribution units. |
| Electrical System 1 | As mentioned above, this first group includes the assumed changes for batteries and electrical generators. The former will change from Ni-Cd technology to the newer, more powerful Li-Ion technology. The latter will see the replacement of IDGs with the more reliable VFGs. |
| Electrical System 2 | This group includes all other electrical power line components (2.4.3). Its change is estimated by the variation of the failure rate of the whole subsystem in the transition from conventional to more electric power. |

### 3.1.2 Reference Estimation Method

Before going into which maintenance tasks will actually be changed (replaced or removed) in the more electrical architecture model, an intermediate step is required to define a cost model as the foundation for developing the rest of the analysis. Given that the objective of this thesis is to build a maintenance cost estimation technique for an aircraft still in its early design phases, the reference point must rely on fairly generic inputs that can be derived at any stage of the project's development.

Among the various studies available in the literature, many require inputs that can only be defined in more advanced project stages (i.e. [27]). On the other hand, some methods are based on more general parameters, but not all are applicable, such as the NASA method [26], which, due to its age, may provide less reliable results for modern aircraft. Within the latter, the *Fioriti et al.* model [24] stands out for its feature of providing detailed CERs for various subsystems, providing a comprehensive level of analysis and view into the cost estimating process.

**Table 3.2:** Cost Estimation Relationships (CERs) from [24]

| ATA | Constant | Fleet Size | Utilization [h/day] | FH/FC | Fuselage Length [ft] | Aircraft Cost [$ $\cdot$ $10^6$] | Aircraft Age [mo] | Number of seats | Average age [yrs] | Number of tires | Number of engines | Thrust [lbf] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Line maintenance | 193.16 | 0.0107 | -18.694 | 14.537 | 0 | 0.8842 | 0.1193 | 0 | -1.972 | 0 | 0 | 0 |
| Base Maintenance | 144.87 | 0.008 | -14.02 | 10.903 | 0 | 0.6632 | 0.0894 | 0 | -1.479 | 0 | 0 | 0 |
| Electrical | 7.0216 | 0 | -0.3866 | 0 | 0 | 0.0423 | 0 | 0.0003 | 0 | 0 | 0 | 0 |
| FCS | 9.7101 | 0 | -0.7535 | 0.499 | 0 | 0.0503 | 0.0017 | -0.0004 | 0 | 0 | 0 | 0 |
| Hydraulic | 3.4695 | 0 | 0 | 0.638 | 0 | 0 | -0.0042 | 0.0127 | 0 | 0 | 0 | 0 |

The regression coefficients used within this study, from all those identified by the study of *Fioriti et al.* are shown in the Table 3.2. The outputs of the method are listed in the first column of the table and are related to the inputs (listed in the first row) through different numerical coefficients, according to the equation:

$$MaintenanceCost = Constant + \sum_i (CER_i \cdot Input_i) \tag{3.2}$$

To better understand how these results serve as a starting point for the cost estimating method, an initial description of them is necessary. With reference to subsection 2.3.1, all of the results fall into the category of scheduled maintenance. Therefore, any unscheduled repair outside of the maintenance program is not included in the overall calculation of these results.

Moreover, the results can be further categorized into on-aircraft and off-aircraft maintenance, as shown in Figure 2.13. Each category includes both labor and material costs incurred during repairs. The first one comprises the results for Line and Base Maintenance, which correspond to the old Ramp and A-Checks, and C-Checks, respectively (2.2.5). The second category includes all the other ATA chapter results, along with engine overhauls.

### 3.1.3 MPD Analysis

As previously mentioned, defining the methodology for estimating maintenance cost variation starts with identifying the components present in the conventional configuration that will change during the transition. To do this, it's necessary to identify the maintenance tasks related to the On-Board Systems (OBS) in order to isolate those that need to be removed or modified. An analysis of the A320 MPD provides the best solution for defining these tasks. As described in subsection 2.2.3, this document contains all the minimum scheduled maintenance requirements for an aircraft.

Locating the desired task within the document has been made possible thanks to the "Task Data Description" (see Figure 3.1), which contains a lot of information. The first two digits of the numeric code assigned to each task represent the ATA chapter reference. By looking for codes beginning with 24, 27, and 32, it was possible to isolate those related to the electrical system, the FCS, and the hydraulic system, respectively. While for the first and third of these subsystems all tasks were considered, the second one required further refinement to isolate only those related to the control of surface actuation systems, excluding any structural checks of moving surfaces or control system checks, etc.

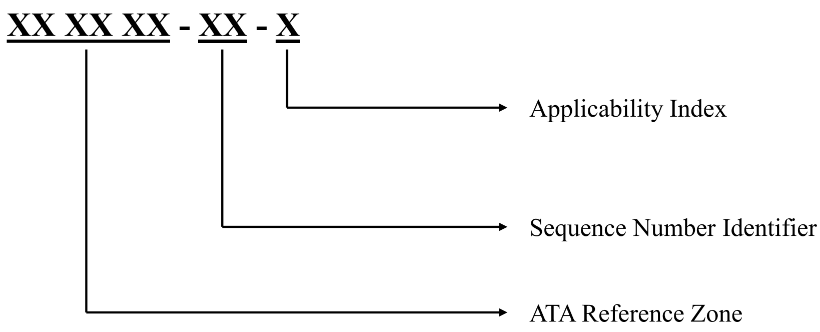



**Figure 3.1:** Task Data Description from [59]

For all of these tasks, with reference to Figure 3.2 the useful information obtained from the MPD includes:

- The description of the maintenance task (column H), which allows it to be attributed to the corresponding component at a later stage.

- The maintenance interval (column N) and, where applicable, the first threshold (column M) for the task. This allows to estimate how many times the specific action has been performed over the course of the aircraft's operational life, considered as input. This can be expressed in different units (months, FH, or FC). Based on the usage of the model, the threshold that is reached first is taken into account.

- The number of Maintenance Man Hours (MMH) required (per individual worker) to perform the check (column T), along with the number of MMH required to access and prepare the component prior to the intervention (column U and V) (e.g., flaps must be extended before any maintenance can be performed).
- The number of workers required to complete the check (column S), which scales the required labor hours. If only one worker is required, the MMH won't change; if two workers are required, the MMH will double, and so on.

It is important to emphasize that the MMH value specified in the MPD represents the ideal scenario where no problems or complications arise during maintenance. In the real world, such a scenario is highly unlikely, especially when dealing with such complex systems. According to *Aircraft Commerce*, the prediction of maintenance requirements may involve using a multiplicative factor, typically ranging from 2 to 4, depending on the specific case [60]. In order to maintain a general approach, the average of these factors has been selected. Therefore, the values extracted from the document were multiplied by three in order to adapt them to a more realistic scenario.

| A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|
| REV CODE | SECTIO N | TASK NUMBER | SOURCE TASK REFERENCE | ACCESS | PREPARATION | ZONE | DESCRIPTION | SKILL CODE | TASK CODE |
| | 2-29 | 290000-01-1 | MRB 29.10.00/06 | 195BB 196BB 197CB 197FB 734 | | 100 | HYDRAULIC POWER<br><br>CHECK CLOGGING INDICATORS OF THE FOLLOWING FILTERS ( POP OUT NOT PROTRUDING )<br>- HIGH PRESSURE DELIVERY<br>- GROUND SERVICING ( RESERVOIR FILLING )<br>- RETURN ( LOW PRESSURE )<br>- BLUE HYD SYS ELECTRICAL PUMP CASE DRAIN<br>- HIGH PRESSURE BLEED AIR<br>- LOW PRESSURE BLEED AIR | AF | VCK |

| K | L | M | N | O | P | Q | R | S | T | U | V | W |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE THRESHOLD | SAMPLE INTERVAL | 100% THRESHOLD | 100% INTERVAL | SOURCE | TCI | TPS | REFERENCE | MEN | TASK M.H. | ACCESS M.H. | PREP.M. H. | APPLICABILITY |
| | | | 12 MO<br>OR<br>1000 FH | LUR<br>MRB 9 | | | 291000-200-004 | 1 | 0.06 | 0.10 | | A320<br>PRE 25365<br>(29-1076)<br>OR<br>A321<br>PRE 25365<br>(29-1076) |

**Figure 3.2:** MPD Task Sample from [59]

After obtaining the necessary information, a final choice had to be made, this time regarding the configuration of the aircraft on which the component needs to be maintained, since the manual contains data for all aircraft in the A318, A319, A320 and A321 families, and each individual aircraft may have different modifications. Initially, all repairs not related to the A320 reference model were discarded, i.e. those with designations in the last column W different from "ALL" or "A320". As for the various modifications, it's important to first specify their purpose. According to ICAO, these modifications are issued for four main reasons [61]:

- Mandatory requirement (e.g. AD or operational regulations).
- Specific type of aircraft operation.
- Improvement of component reliability (based on data from aircraft operating experience).
- Operator specific installation requirements.

From the above, it is clear that these modifications are mostly corrections to improve system safety. In combination with the lack of detailed information on individual modifications, it was assumed that from this point on only tasks with the label "POST + [modification number]" in the applicability cell (column w) of the MPD rows would be considered, indicating modifications already implemented on the aircraft.

### 3.1.4 Methodology Selection

Having obtained the necessary initial information, it was possible to proceed with the definition of the methodology to identify the missing details required to achieve the desired result.

Starting with on-aircraft maintenance, as shown in Figure 3.3, the reference method [24] provided the total contribution for line and base maintenance, defined as the sum of Labor Cost (LC) and Material Cost (MC). The first component could be extracted from the MPD analysis, while the second one is a highly variable element, especially depending on the type of maintenance performed.
Table 3.3 provides an overview of the two primary approaches to achieving the desired results, along with the definition of their advantages and disadvantages, resulting in the ease of application based on the data at hand.
The first approach uses a breakdown method, where the estimation of maintenance cost variation relies on analyzing differences within the individual components that compose the DMC, followed by their combination.
On the other hand, the second approach offers a less detailed solution compared to the first one, using an analogy-based principle. As explained in subsection 2.3.2, this method uses similarities between systems and/or components to derive a reasonably accurate estimate of maintenance costs.

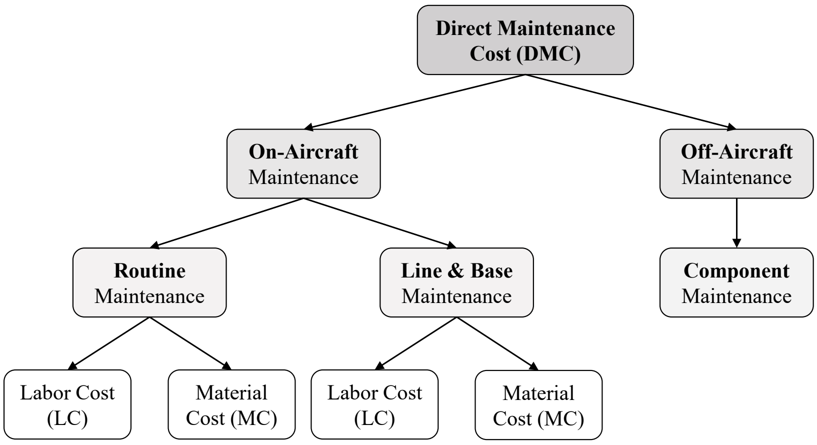



**Figure 3.3:** Scheduled DMC Breakdown

**Table 3.3:** Methodologies Overview

| Method | Advantages | Disadvantages | Applicability for this case |
|---|---|---|---|
| Breakdown Approach | High results accuracy, employing a bottom-up approach | Demands a comprehensive database for all components | Difficult, due to the lack of data |
| Analogy Approach | Requires information about similar existing solutions | The result are less detailed than the breakdown | Aligns with available data |

It's worth noting that the first approach requires access to an extensive database, which can be challenging. Due to the relatively young age of the technologies used (e.g. Electro-Hydraulic Actuators (EHAs), generators or next generation batteries), information with a level of detail comparable to that described in an MPD is often not publicly available and remains restricted to the companies operating the component.

If a solution to this first obstacle had been found, two other issues would have had to be addressed. The first related to the on-aircraft maintenance MC, the variation of which should be evaluated in parallel with LC. Unfortunately, no recent method was found in the literature that could provide material costs for individual subsystems. The only solution that came close was the [62], however, when attempting to validate it using input data associated with the conventional architecture with an appropriate Cost Escalation Factor (CEF), inconsistent results were obtained, with MC even exceeding LC.

The second obstacle would be the definition of changes related to off-aircraft maintenance. Since these interventions are carried out in specialized workshops, their contribution is not integrated in an MPD. For this reason, the allocation of off-aircraft maintenance costs between LC and MC is challenging both for conventional aircraft such as the A320, for which there is sufficient material available, and even more so for state-of-the-art components installed on next-generation aircraft.

Due to the inability to obtain the necessary data in the early stages of the project, the breakdown method was not applicable. Consequently, the second method was chosen for this study, which sacrifices some degree of precision in the results, but remains sufficiently valid for estimating maintenance costs during the initial aircraft design phases.

## 3.2 Analogy Method for DMC estimation

In the context of this study, the analogy used refers to the reliability of individual components, in particular the estimated values of their failure rates.

This second section of the chapter outlines the actual steps taken with the data derived from the previous section to arrive at an estimate of the variation in maintenance costs between the two aircraft configurations. 3.2.1 provides a general overview of the elements necessary to obtain a complete estimate, which will be detailed in the following sections. Specifically, 3.2.2 presents the core of this research, detailing the steps for estimating LC and MC for line and base maintenance. The research framework is then completed in 3.2.3 with ramp inspections and the evaluation of costs for off-aircraft component maintenance.

### 3.2.1 General Overview

The ultimate goal is to obtain an estimate of the MMH variation based on parameters that are independent of the progress of the design project.
The decision to perform the Labor Cost (LC) estimation in terms of man-hours rather than actual maintenance costs was made primarily to decouple the results from the variation in labor rates over the years. Therefore, to obtain actual maintenance LC in dollars, the results obtained would simply have to be multiplied by the current labor rate in the aerospace industry.

As is well known, an aircraft is a complex system made up of numerous subsystems, components and parts that work in synergy. Over the years, the search for greater aircraft efficiency has led to the development of various potential solutions that are gradually finding their place in new aircraft configurations. These solutions include the use of lighter and more reliable composite materials for structures, increasingly efficient and powerful engines, and the incorporation of EHAs, among others. The subsystems selection in this thesis is the result of a process that involved choosing from among these new solutions. In order to narrow down the focus, composite materials and new propulsion solutions were excluded due to their extensive scope, which would require dedicated studies. Instead, the focus was placed on those subsystems (highlighted in 3.1.1) that drive innovation and have a significant impact on these emerging configurations.

### 3.2.2 Line and Base Maintenance

Before discussing the process steps for evaluating maintenance changes related to line and base maintenance, it is important to introduce the final part of the required inputs. This piece, in conjunction with the results from the reference model (3.1.2) and the analysis of the MPD (3.1.3), forms a critical part of the analogy analysis.

For the reference aircraft, the A320, due to its tremendous success and longevity, there is a wealth of literature describing every minute detail, including its maintenance program. Given the importance of this program to the study, the *Aircraft Commerce* website [63] was used as a reference point for the material needed. This editorial, through interviews with aviation professionals (executives, lessors, Maintenance and Repair Organization (MRO) organizations), provides real-world data on operational performance and information on the majority of existing aircraft. Specifically, the articles ([11, 13, 14]) report actual costs associated with A and C checks observed over the years. These values are provided for the individual checks that make up each of the total maintenance cycles. In detail:

- An A-check cycle is performed every 3000FH and consists of four smaller A-checks (A1, A2, A3 and A4), each performed every 750FH. These checks include routine and non-routine inspections, corrections, administration, interior cleaning, Airworthiness Directives (ADs), Service Bulletins (SBs) and Engineering Orders (EOs) [14].

- Similarly, a base C-check cycle is performed every 144 months (12 years) and consists of eight minor checks (C1, C2, C3, C4, C5, C6, C7, C8), which, like the previous ones, are performed at irregular intervals. According to *TAP Maintenance & Engineering* from [14], their intervals are as indicated in Table 3.4.

**Table 3.4:** Base C-Check Intervals from [14]

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
|---|---|---|---|---|---|---|---|---|
| **Interval** | 20 months | 40 months | 60 months | 72 months | 100 months | 120 months | 140 months | 144 months |

Table 3.5 contains the collected data from the previous sections. They will be used to derive the desired results.

**Table 3.5:** Data Overview

| **Source** | **Data Description** |
|---|---|
| *Aircraft Commerce* | The cost of each component of the Line (A-Check) and Base (C-Check) cycles is known. This provides the relative weight, in terms of cost, of each of these components in their respective complete cycle. |
| A320 MPD Analysis (3.1.3) | Characteristics of the tasks that will be removed in the transition from conventional to more electric. |
| *Fioriti*'s Method (3.1.2) | Line and Base maintenance cost per FH over a specified time frame. |

### Labor Cost

The flowchart presented in Figure 3.4 illustrates the various steps of the method described herein. It serves as a reference point, providing a clear structure for the explanations that follow.
Using the maintenance interval specific to each task, the corresponding MMH contribution can be assigned to its corresponding check. It should also be noted that Out-Of-Phase (OOP) tasks do not exactly align with the intervals defined for minor checks. In order to avoid missing the deadlines set by the authorities, these tasks have been assigned to the closest prior maintenance check.
By combining this with the MMH requirements for each check derived from ([11, 13, 14]), the percentage impact of removing these systems (and their tasks) from the aircraft can be quantified.

To complete the picture, new components were introduced into the system along with their resulting impact on maintenance. This was accomplished by considering the failure rates per flight hour for both old and new components, obtained from [64]. Given the lack of more comprehensive data, it was assumed that, holding all other factors constant (such as system structure, component redundancy, maintenance effectiveness, etc.), a component with a higher failure rate will necessitate more maintenance over the same time span than a component with greater reliability. Specifically, a linear relationship between reliability values and MMH requirements was used, as described by 3.3 and 3.4.

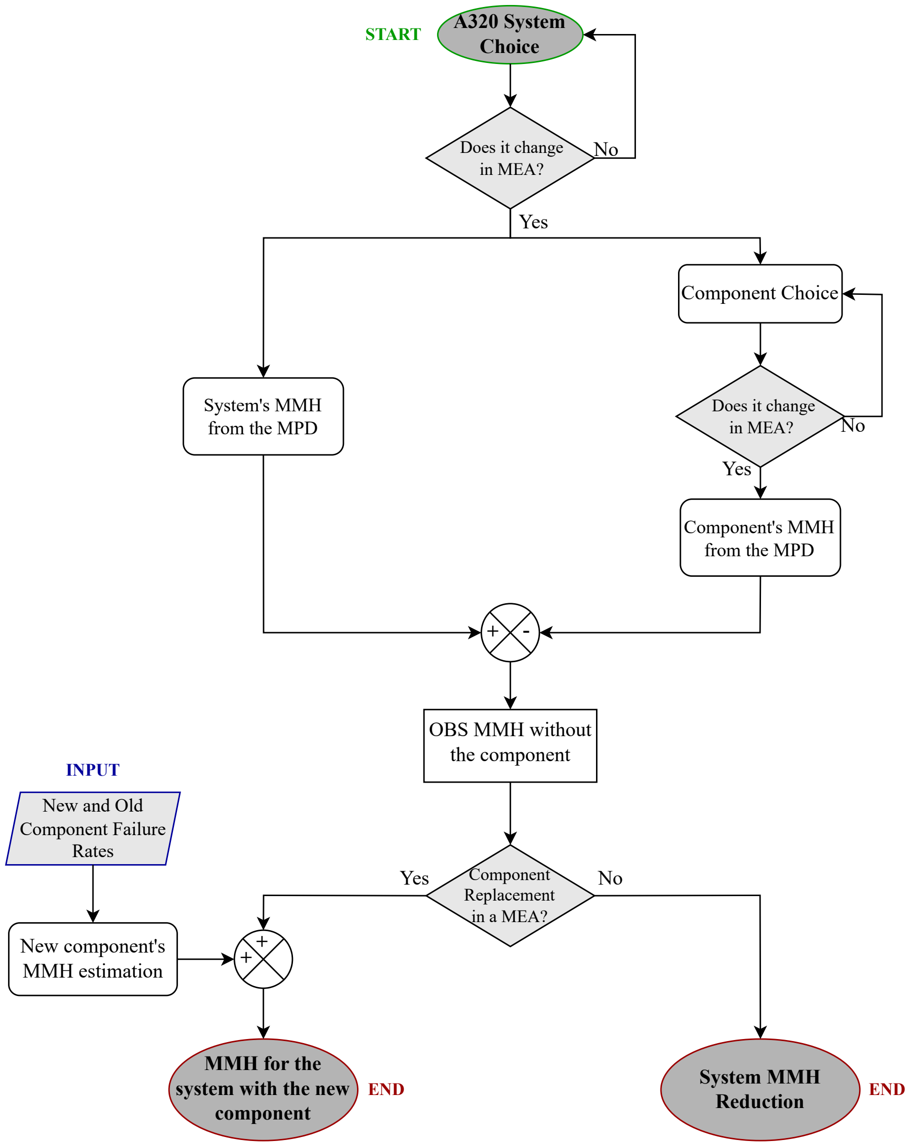



**Figure 3.4:** Labor Cost Methodology Map

$$\left(\frac{\lambda}{[\text{MMH}]}\right)_{Old\ Component} = \left(\frac{\lambda}{[\text{MMH}]}\right)_{New\ Component} \tag{3.3}$$

$$[\text{MMH}]_{\text{New}} = \frac{\lambda_{\text{New}}}{\lambda_{\text{Old}}} \cdot [\text{MMH}]_{\text{Old}} \tag{3.4}$$

Following these assessments, the maintenance contribution of these new components was integrated into the previous model, which had removed the old on-board systems. Subsequently, the variation in maintenance labor for the changes outlined in 3.1.1 was estimated.
Finally, knowing the cost per FH for line and base maintenance from 3.1.2, and having obtained an understanding of the percentage change in MMH required by the new configuration, the two results were combined and multiplied by the labor rate to determine the actual cost in $\left[\frac{\$}{FH}\right]$ for the two types of maintenance.

## Material Cost

The steps presented so far refer to the labor costs involved in on-aircraft maintenance. However, as shown in the Figure 3.3, there's another aspect to consider: the cost of materials required to carry out these activities, which cannot be overlooked. Unlike labor costs, the results in this case were derived in terms of actual costs in U.S. dollars.

In the case of the hydraulic system, the new configuration requires its complete removal. Consequently, the cost of materials for this system will be zero. To define the reduction in MC, it was assumed that the relative weight of the hydraulic system on both LC and MC was the same, so that the same percentage change derived for work could be adopted, obtaining the desired result.
Similarly, for FCS, the effect on MC was assumed to be the same as for LC.
Therefore, by taking what was previously derived, and knowing the material costs for the checks performed in Line and Base Maintenance through the values from ([11, 13, 14]), it was possible to estimate the MC variation due to the modification of the hydraulic and electrical systems.

The situation is different for the electrical system. Even in the conventional configuration, this subsystem doesn't require large quantities of materials for maintenance, such as grease, oil, pipes, filters and other components commonly used in hydraulic systems. In addition, the changes mentioned in 3.1.1 are not expected to significantly alter the overall system structure. For these reasons, the material costs for maintaining the electrical system can be considered relatively constant, at least as a first approximation.

### 3.2.3 Routine and Component Maintenance

As emphasized in the first pages of [59], where all facets are explained in detail for better interpretation, this document does not include maintenance tasks with intervals shorter than 750 FH (typical of the A-check). This means that there is no contribution from ramp maintenance (Pre-Flight (PF), transfer, daily and weekly checks). Therefore, in the absence of detailed data, as in the previous cases of line and base maintenance, the focus has shifted to the search for more general information on more electric aircraft, such as the B787 and the A350. Among the various articles in the *Aircraft Commerce* database [63], the article [65] was considered. Figure 3.5 below summarizes what is reported in the reference.

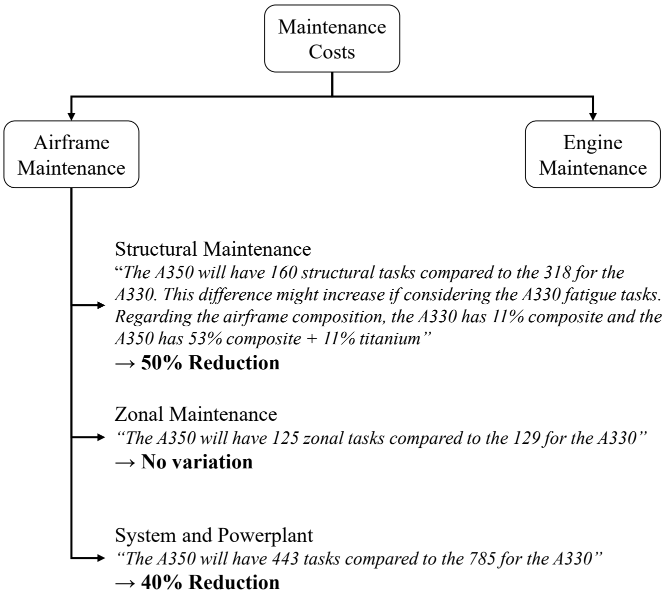



**Figure 3.5:** Maintenance Costs Breakdown from [65]

The article compares the maintenance requirements of the next generation aircraft with those of the previous one, dividing the tasks into two major categories: Airframe and Engine maintenance, and provides a detailed characterization of each. Since the point of interest are the OBS from 3.1.1, only the first group is considered. This is further subdivided into:

- Structural Tasks, which include the activities necessary to maintain the integrity of an aircraft's structure. With the increasing use of composite materials in modern aircraft, a significant reduction in these tasks is expected. In fact, an A350 requires 50% less maintenance than a conventional A330.

- Zonal Tasks.They involve maintenance activities that focus on specific zones or areas within an aircraft rather than individual components. The A350 is expected to have the same amount of zonal tasks as an A330.

- Systems and Powerplant Tasks, which include maintenance activities related to aircraft systems and powerplant components. This category of maintenance includes the inspection, repair, and maintenance of various systems such as avionics, hydraulics, electronics, and powerplant components such as engines and associated equipment. By incorporating more reliable components, the A350 expects to reduce the required maintenance by 40%.

Considering the percentage allocated to systems, this relates to the improvement of six specific subsystems: hydraulics, flight controls, landing gear, bleed, electrical and fuel. Assuming that this reduction is evenly distributed among these subsystems, it will be only applied to the daily and weekly checks, as the inspections required in the pre-flight and transit checks should remain the same due to their importance in ensuring safe operations.
The contribution for each of the subsystems is equal to the value obtained in Equation 3.5.

$$\frac{40\% \text{ Reduction}}{6 \text{ Subsystems}} = 6.67\% \text{ Reduction per System} \tag{3.5}$$

By multiplying this result by the number of subsystems changing from the conventional to the more electric model, in this case three, it is possible to define the percentage change in maintenance costs associated with the OBS selected for routine maintenance.

The final contribution to be considered to complete the framework of scheduled maintenance relates to off-aircraft repairs, also known as component in-shop maintenance. As specified in 2.2.5, once a component is removed from the aircraft, it undergoes the required maintenance in a dedicated workshop (hence the term "off-aircraft"). Again, the MPD refers only to the scheduled maintenance performed on the aircraft (whether on the ramp or in a dedicated hangar) and does not include any information about the maintenance activities required for a component once it is removed from the aircraft.
However, unlike the previous case of ramp maintenance, the results provided by [24] are useful for this category of controls. In fact, the results (outside Line and Base Maintenance and Engine Overhaul) refer to the maintenance costs related to the workshop maintenance of the corresponding ATA systems.

The simplest case, the hydraulic system, can be taken as a starting point. As it has been repeated several times in this context, the desired model does not include its presence, so in this case its cost outside the aircraft will be zero.

The electrical system and the FCS require different solutions. Regarding the former, since there is no much precise information about the changes in the various lines (except for generators and batteries), as presented in 3.1.1, a shift to a global approach was made. To achieve this, consideration was given to the change in the failure rate as indicated in [66] for the entire electrical system.
In the second case, assuming that the percentage change in off-aircraft maintenance is the same as the percentage change in on-aircraft maintenance. In this case, three separate values were calculated, each representing a different contribution: one for the lines, one for the first base cycle, and one for the second base cycle. Each of these values was weighted according to the relative amount of maintenance hours required for each of the controls, thus calculating a weighted average value, which was then used to obtain the change in MC for each of the systems.

# Chapter 4

# Thesis Results

After detailing the steps to be followed in applying the method in the previous chapter, this section reports the main stages of their application. It is divided into two subsections: the first one (4.1) defines the starting data required by the methodology, while the second (4.2) reports all the results obtained from that data.

This study focuses on delineating the maintenance cost differences between two aircraft architectures: the conventional model represented by the reference case of an A320 and the more electric architecture. The latter is the study case and is based on an A320 but incorporates the modifications outlined in Table 3.1. By estimating the differences in terms of MMH required for maintenance activities in both architectures, the results presented in this chapter have been derived.
Both models are based on 24-year-old aircraft. This choice was made because it represents the time frame in which two complete base maintenance cycles are performed (one every 144 months or 12 years). This approach partially represents an aging factor for the results, since the second cycle of base maintenance requires more in terms of both LC and MC, due to the higher age of the vehicle. Furthermore, all costs obtained were scaled to the year 2018 using appropriate scaling coefficients. This adjustment was made to align the costs to the same publication year as the A320 MPD from which the maintenance tasks were taken.

## 4.1 Reference Values

In this first subchapter, all the numerical data used as a starting point for the application of the methodology are presented. To avoid overloading the paragraphs, several data-filled tables have been included in the appendices at the end of the thesis (Appendix B and C).

First, the reference values derived from *Fioriti et al.* method are presented in 4.1.1, with the corresponding selected inputs, followed by 4.1.2, where the maintenance tasks related to the OBS derived from the MPD are shown. Lastly, the values reported by *Aircraft Commerce*, which represent the actual costs incurred during maintenance operations, are shown in 4.1.3.

### 4.1.1 Results for the Reference Architecture

Starting from what has been explained in 3.1.2, this section describes the different inputs considered and the results obtained with them.

Table 3.2 presents the coefficients needed to calculate maintenance costs for ATA chapters utilizing the Equation 3.1 model. In order to be used effectively, these coefficients are related to the definition of inputs given in the header of the table. The inputs can be divided into two groups:

- The first group includes values that do not depend on the choice of aircraft type (e.g. fleet size, fuselage length, aircraft cost, number of seats, engines and tires, and dry engine thrust). These parameters are taken from the data suggested by *Fioriti et al.* study [24].

- The second group consists of parameters such as annual utilization, FC/FH ratio, aircraft age and Cost Escalation Factor (CEF), shown in Table 4.1. As these parameters are closely connected to the type of operation of the aircraft, they have been chosen to provide consistent results with the overall study. In particular, the first three values were derived from *Aircraft Commerce* references ([11, 13, 14]), thus obtaining results that refer to an aircraft with the same use as the one indicated in these references.
  Lastly, since the results obtained by the method from *Fioriti et al.* are related to the year 2017, it was necessary to introduce a scaling coefficient to bring them to a more appropriate reference. To account for inflation, a CEF of 1.08 was applied to scale the result to 2018. This value was obtained using coefficients from [67] to relate the value of the desired year (2018, in this case) to the initial year (2017). This coefficient is a useful tool since, by modifying its value, it is possible to obtain the cost results for any other year.

All these inputs were used to obtain the $/FH off-aircraft maintenance cost, for the different ATA chapters.
Among all the results obtained from the application of this method, those that have been used for this thesis are included in the Table 4.2.
Here, the second column displays the values of the outcomes obtained through the selected method, while the remaining two columns represent a transformation of these results.
To obtain the annual maintenance cost, it is sufficient to multiply the value in

**Table 4.1:** CERs Inputs

| Inputs | | |
|---|---|---|
| **Utilization** | 7.9 | [h/day] |
| **FH/FC** | 1.5 | |
| **Aircraft Age** | 300 | [months] |
| **Cost Escalation Factor** | 1.08 | |

**Table 4.2:** Maintenance Cost Results

| | Cost per FH | Cost per year | Cost in 24 years |
|---|---|---|---|
| **Electrical System (ATA 24)** | 8.7 $/FH | 24 360 $ | 584 640$ |
| **FCS (ATA 27)** | 5.5 $/FH | 15 400 $ | 369 600 $ |
| **Hydraulic System (ATA 29)** | 10.5 $/FH | 29 400 $ | 705 600 $ |
| **TOT** | 24.7 $/FH | 69 160 $ | 16 959 840 $ |

$\left[\frac{\$}{FH}\right]$ by the utilization in terms of $\left[\frac{FH}{Year}\right]$; then, multiplying this result by 24 gives the total cost related to the operating life of the aircraft. This way, the results are reported over the time interval defined at the beginning of this analysis and can therefore be related and evaluated with all the other values obtained in the following sections.

### 4.1.2 Maintenance Tasks from the A320 MPD

In 3.1.3, the procedure for selecting the appropriate maintenance tasks has been reported. In Appendix B, Table B.1, B.2 and B.3 show all of the task details for each of the OBS.
The last three columns of each table are not directly derived from the MPD reference, but instead provide further interpretation of the data obtained from it. Since many tasks have more than one possible interval (FH, FC, or months), the first step was to identify which one was reached first, based on the chosen aircraft

utilization. To do this all intervals were converted to FH according to Equation 4.1 and 4.2.

$$[\text{months}] \cdot \frac{1}{\left[\frac{\text{months}}{\text{year}}\right]} \cdot \left[\frac{FH}{\text{year}}\right] = [FH] \tag{4.1}$$

$$[FC] \cdot \left[\frac{FH}{FC}\right] = [FH] \tag{4.2}$$

The smallest of these was then selected and documented in the second-to-last column, followed by its conversion into months, which was then entered in the third-to-last column.

The final column displays the overall MMH contribution needed for each task. This contribution, as explained in Equation 4.3, is calculated by summing the MMH contributions required for both task execution and preparation. This sum is then multiplied by the number of personnel required and the correction coefficient of 3 to account for real-world challenges and uncertainties in maintenance planning.

$$\text{Tot MMH} = 3 \cdot (\text{Task MMH} + \text{Access MMH} + \text{Prep MMH}) \cdot \text{Req Men} \tag{4.3}$$

After determining the final contribution and identifying the first possible allocation interval, the MMH required for each task were allocated to the corresponding maintenance check.
Three macro groups can be defined among all tasks:

- Tasks that align precisely with the interval of a maintenance check or are exact multiples of it. In this instance, the MMH contribution was assigned once to each relevant maintenance check. For example, a task with an interval of 750FH would be allocated once to each A-Check.
- OOP tasks with an interval that fell between two maintenance tasks, in this case the decision was made to allocate their MMH contribution to the preceding maintenance check, since according to the regulations the time limits specified in the MPD cannot be exceeded.
- OOP tasks with an interval less than the first available check, for example, a task with an interval of 70FH and $x$ MMH required. In this case, it is assumed that the task will still be performed before the first A-check (750FH), and the sum of the contributions related to the number of times this task will be performed is assigned to the first available check. In the example case:

$$\frac{750\ \text{FH}}{70\ \frac{\text{FH}}{\text{Task}}} = 10.7\ \text{Task} \tag{4.4}$$

Therefore, each type A check is assigned a value of: $(10.7 \cdot x)$ MMH.

By repeating this process for all the selected components, it was possible to define their percentage weight within the different types of maintenance.

### 4.1.3 Aircraft Commerce Values

In the Appendix C, all the numerical values used in this study related to the maintenance cost, both in MMH and in USD, are given for each type of maintenance (Routine, Line, Base 1st and 2nd).
The intervals for Line and Base Maintenance checks, as detailed in 3.2.2, were derived from [14]. Similarly, the intervals related to routine maintenance along with its MMH and its effective cost were obtained from ([14], [13]).
However, different from the intervals and MMH values, the cost data for routine, line and base maintenance had to be scaled in order to the base year of 2018. Two different scaling coefficients were needed. Because the values related to routine maintenance come from the 2006 reference, while for line and base maintenance the reference is more recent, from 2011.

Another point to consider is the labor rate to which the derived LC values refer. As shown in Table 4.3, line and base maintenance are associated with two different values, the former being higher than the latter.
Since base maintenance is a major operation, it requires aircraft downtime that can stretch for months, so the aircraft needs to be moved to appropriate hangars for these activities. In general, facilities in countries where labor is cheaper are chosen. In contrast, scheduled activities, which do not require much time, are performed near the airport areas where the aircraft operates, eliminating the possibility of moving to less expensive regions.

**Table 4.3:** Cost Values Input from [14]

| **Inputs** | |
|---|---|
| Utilization | 2800 FH/year |
| Labor rate (Routine & Line Maintenance) | 70 $/FH |
| Labor Rate (Base Maintenance) | 50 $/FH |

## 4.2 More Electric Model Results

The next part of this chapter provides an overview of the results obtained by implementing the different steps of the methodology. It begins by examining routine maintenance, which is characterized by the shortest intervals, in 4.2.1. Following this, 4.2.2 discuss the results of LC and MC related to line and base maintenance. Finally, in accordance with the framework depicted in Figure 3.3, 4.2.3 displays the outcomes linked to maintenance performed off the aircraft. After the presentation of all individual contributions, the overall results are summarized in the last part of this subchapter (subsection 4.2.4).

### 4.2.1 Routine Maintenance Variation

In Table 4.4 are shown the results obtained for the routine maintenance. In the first row are the data obtained for the conventional model taken from *Aircraft Commerce* database (Appendix C). While in the second row are the results after applying the reduction percentages defined in 3.2.3.

**Table 4.4:** Routine Maintenance Results

| | Cost per year | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Pre Flight** | **Transit** | **Daily** | **Weekly** | **Total** | **TOT over 24 years** | |
| **Conventional Configuration** | 17 300 $ | 323 950 $ | 259 900 $ | 105 200 $ | 706 350 $ | 16.952M $ | |
| **More Electric Model** | 17 300 $ | 323 950 $ | 207 900 $ | 84 100 $ | 633 250 $ | 15.198M $ | **-10.34%** |

The results indicates that the percentage reduction in maintenance requirements resulting from the adoption of these new technologies is approximately 10%.
This reduction is related to the higher reliability of the new technologies and their lower maintenance requirements. In particular, since routine maintenance tasks consist mainly of component servicing (fluid level checks, fluid and filter changes, component lubrication), removing the hydraulic system and replacing the linear hydraulic actuators leads to the elimination of these tasks.

It's worth noting that this reduction is tied to the limited availability of detailed information for a more comprehensive evaluation. Therefore, assuming an identical variation as observed in the transition from the conventional A330 to the more electric A350 may potentially lead to an overestimation of the results. This is due to two main factors:

- First, the evolution of the configuration affects the various systems differently. However, due to the limited availability of detailed data, it was initially decided to distribute the 40% reduction evenly, with a 6.67% contribution to each system affected by the changes between the two models.
- Second, there are some differences in architecture and dimensions between the models considered in this study (A320 and the more electric model) and the aircraft on which this percentage is based (A330 and A350). These differences also include improvements in all other on-board systems.

### 4.2.2 Line and Base Maintenance Variation

**Labor Cost**

Based on the results obtained for the contributions of each component to the various line and base maintenance checks (shown in the Appendix D D.1, D.2, D.3), it is possible to proceed through the stages outlined in Figure 3.4. First, the contributions are separated from the rest of the maintenance. Then, the components are grouped into the corresponding OBS.
These results describe an aircraft model in which the conventional component MMH contribution has been subtracted from the global computation, resulting in an overall reduction of the required MMH

The following step corresponds to the final decision block shown in the flowchart in Figure 3.4. This step involves identifying the components that will be substituted with new solutions and then reintroducing their required MMH into the overall calculation.

Since the model assumes the complete removal of the hydraulic system, its contribution results in a MMH reduction. Differently for the FCS and electrical system, the MMH contributions linked to their new components must be incorporated into the overall calculation. To do this, it is necessary to know the MMH requirements for these components.
Table 4.5 presents the selected failure rate values and their corresponding ratios, which serve as the scaling coefficient used to derive the new MMH contribution based on the requirements of the conventional components.

**Table 4.5:** Components Failure Rates from [64] and [66]

| System | Component | Value [failures/FH] | Ratio |
|---|---|---|---|
| **Flight Control System** | HSA | 9.50E-05 | $\frac{\lambda_{EHA}}{\lambda_{HSA}} = 0.62$ |
| | EHA | 5.90E-05 | |
| **Electrical 1** | IDG | 8.25E-06 | $\frac{\lambda_{VFG}}{\lambda_{IDG}} = 0.94$ |
| | VFG | 7.78E-06 | |
| | Ni-Cd | 4.29E-06 | $\frac{\lambda_{Li-Ion}}{\lambda_{Ni-Cd}} = 2.17$ |
| | Li-Ion | 9.32E-06 | |
| **Electrical 2** | Conventional Architecture | 2.10E-03 | $\frac{\lambda_{MEA}}{\lambda_{Conv.}} = 1.57$ |
| | More Electric Architecture | 3.30E-03 | |

Lastly, Figure 4.1, Figure 4.2 and Figure 4.3 serve as comprehensive summaries of all the values obtained thus far.

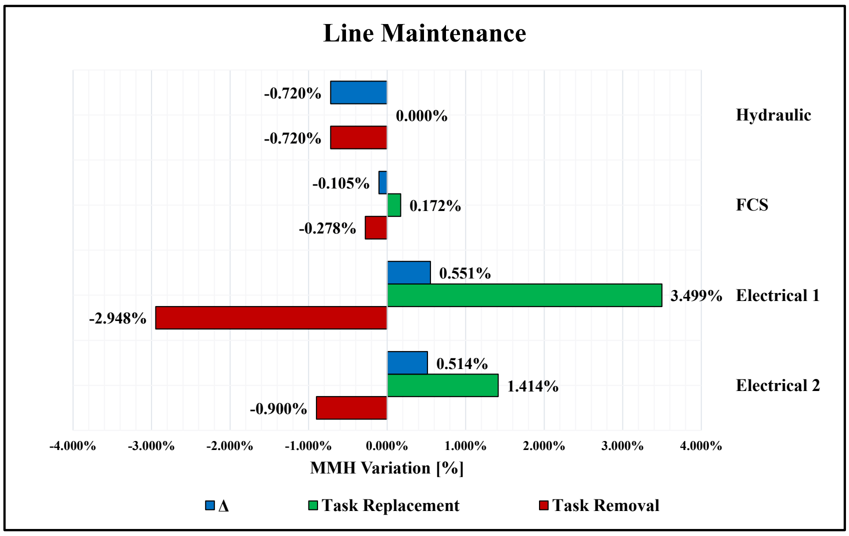



**Figure 4.1:** Line Maintenance MMH Percentage Variation

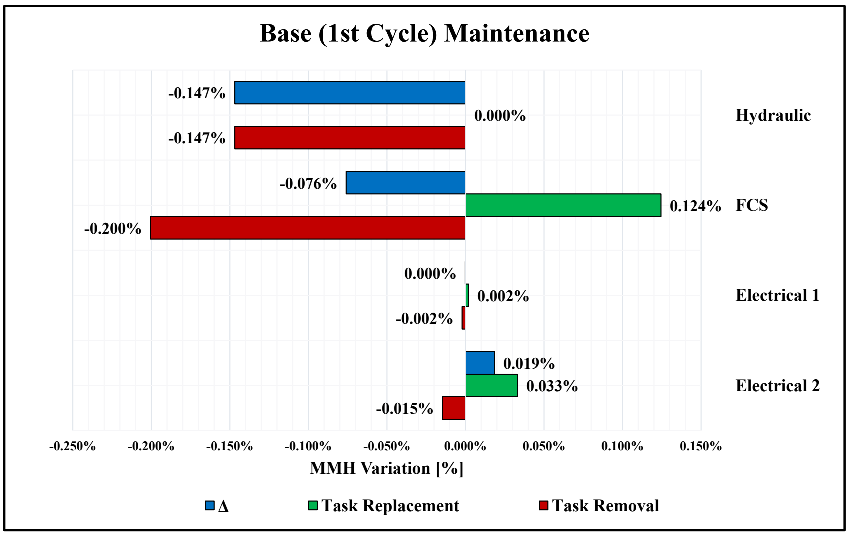



**Figure 4.2:** Base (1st Cycle) Maintenance MMH Percentage Variation

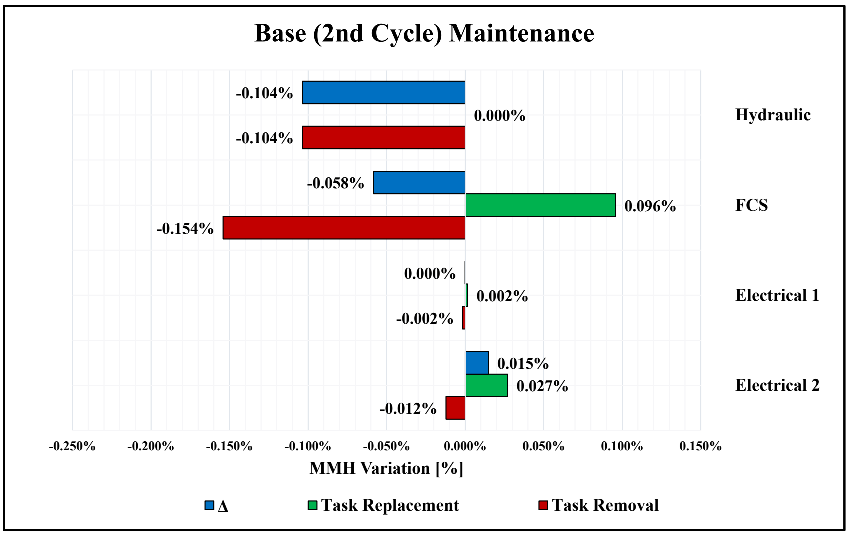



**Figure 4.3:** Base (2nd Cycle) Maintenance MMH Percentage Variation

Three different types of bars are shown in each graph. The red bars represent the percentage reduction in MMH associated with the removal of tasks related to the components of the conventional OBS. The green bars represent the percentage increases associated with the estimated MMH for the new components. Finally, the blue bars show the net percentage change resulting from the combination of the two contributions just mentioned. These last bars represent the desired results for line and base maintenance for the study case.

As can be seen from the graphs, especially the one on line maintenance (Figure 4.1), the contribution of the Electrical 1 element, which includes generators and batteries, has an overall positive percentage impact (blue bar). Although the transition from IDG to Variable Frequency Generator (VFG) leads to a reduction in MMH due to an increase in their reliability, the change in batteries due to changes in failure rates (Table 4.5) has a greater positive effect than the benefit related to generators.
This effect is related to lithium-ion cells having the main advantage in their higher performance compared to the old Ni-Cd batteries. The actual contribution of the cells to maintenance doesn't vary significantly; instead, the Battery Management System (BMS) plays a crucial role. The BMS is responsible for both protecting the cells from external factors that could compromise their safety (such as strong shocks, extreme temperatures, and perforation) and preventing any malfunctions from affecting other components [68]. This justifies the higher MMH required by new technologies to ensure their safe operation.

The resulting percentage increase in MMH for the electrical system. can be explained by the shift in the model to exclusively electrically powered components after the elimination of hydraulic lines. Consequently, this modification leads to an increase in the demand for electrical power to successfully carry out the mission. This, in turn, necessitates an enlargement and enhanced capacity of the electrical system.

### Material Costs

The considerations employed to determine this cost component were described in 3.2.2. Table 4.6 offers a comprehensive summary of the percentage impacts linked to alterations in each system.

**Table 4.6:** Material Cost Variation

| | Hydraulic | FCS | Electrical | Tot |
|---|---|---|---|---|
| **Line A-Check Maintenance** | - 0.720% | - 0.105% | + 0.000% | - 0.826% |
| **1$^{st}$ Base Maintenance Cycle** | - 0.147% | - 0.076% | + 0.000% | - 0.220% |
| **2$^{nd}$ Base Maintenance Cycle** | - 0.104% | - 0.058% | + 0.000% | - 0.160% |

The complete elimination of hydraulic system maintenance tasks results in a zero material cost required for these tasks. The values shown in the corresponding column of the table are based on the assumption that the relative weight of these tasks is the same for both LC and MC, and therefore their percentage impact estimated for the former can be used for the latter. The same logic applies to the FCS. As for the electrical system, it can be seen that it doesn't lead to a relative change in MC, since it is assumed that its variation in the case study leads to a negligible increase in the material required for maintenance.

### 4.2.3 Components Maintenance Variation

After establishing the coefficients of variation for the hydraulic and electrical systems (with the former at -100% for complete removal and the latter at +57% following modification), the focus now shifts to determining the impact related to the FCS.
As defined at the end of 3.2.3, a weighted average was calculated between the changes related to the line, 1st base and 2nd base maintenance labor costs. This was then used to obtain the change in MC for the systems. Based on the MMH values obtained from *Aircraft Commerce* (presented in Appendix C), the aircraft's operation over 24 years will have accumulated:

$$\text{Line Maint.} \Rightarrow 1600\ \frac{\text{MMH}}{\text{A-Check Cycle}} \cdot 2800\ \frac{\text{FH}}{\text{Year}} \cdot 24\ \text{Years} = 37334\ \text{MMH} \tag{4.5}$$

$$\text{Base Maint.} \Rightarrow 56500\ \text{MMH} + 73450\ = 129950\ \text{MMH} \tag{4.6}$$

The results obtained from Equation 4.5 and 4.6 clearly indicate that line maintenance constitutes 22% of the total MMH,while the remaining 78% is attributed to base maintenance.

**Table 4.7:** Off-Aircraft Maintenance Variation

| | Hydraulic | FCS | Electrical | Other Systems | Total |
|---|---|---|---|---|---|
| **Starting Values** | 5.5 $/FH | 10.5 $/FH | 8.7 $/FH | 532.2 $/FH | 556.9 $/FH |
| **Conventional Configuration** | $ 369 600 | $ 707 616 | $ 584 640 | $ 35 766 600 | $ 37 425 800 |
| **More Electric Model** | 0 | $ 707 049 | $ 918 720 | $ 35 766 600 | $ 37 392 400 |
| **Δ** | - 100% | - 0.08% | + 57.14% | - | **- 0.09%** |

Table 4.7 illustrates the percentage results concerning off-aircraft maintenance. The baseline values for the latter are derived from the application of *Fioriti et al.* method to the chosen aircraft model. The "Other Systems" category represents the sum of the values derived for all other ATA chapters that, together with the hydraulic, electrical and flight control systems, make up the entire aircraft.
The relative impact among the systems themselves reflects a reduction of about 2%, highlighting how the impact associated with the complete removal of the hydraulic system is nearly offset by the increase associated with the evolution of the electrical system.
In contrast, the impact of the changes on total aircraft maintenance is less than the relative impact due to the contribution of all other systems that do not change between models. The percentage reduction is similar to that observed for line and base maintenance, except that for this maintenance category the change is applied to the highest cost value among all others over 24 years.

### 4.2.4 Global Results

In this concluding section, all the calculated percentage changes have been implemented on the real costs associated with the different types of maintenance obtained in 4.1.1 and 4.1.3.

After already delineating the contributions of routine and component maintenance over a 24-year duration, and taking into account that both the first major maintenance cycle (occurring after the initial 12 years) and the second major maintenance cycle (following the subsequent 12 years) will occur within this time frame, the only remaining factor to ascertain is the contribution of line maintenance over the same period.

$$\frac{1 \text{ Check}}{3000 \text{ FH}} \cdot \left[\frac{\$}{\text{Check}}\right] \cdot \left[\frac{\text{FH}}{\text{Year}}\right] \cdot 24 \text{ Years} = \text{Maintenance Cost } [\$] \tag{4.7}$$

Following what Equation 4.7 outlined, the results derived were summarized in Table 4.8.

**Table 4.8:** Line Maintenance Cost in 24 Years

| | Complete A-Check Cost (3000 FH) | | | |
|---|---|---|---|---|
| | **Labor** | **Material** | **Tot** | **Tot in 24 Years** |
| **Line A-Check Maintenance** | 105 200 $ | 42 400 | 147 600 $ | 3 306 500 $ |

To conclude this thesis, Table 4.9 presents all the different forms of maintenance for the conventional A320, together with their respective changes resulting from the procedures described in this study.

**Table 4.9:** Overall Results

| | Cost over 24 Years | | | | |
|---|---|---|---|---|---|
| | **Routine** | **Line** | **Base** | **Component** | **TOT** |
| **A320 Conventional** | 16.95M $ | 3.306M $ | 10.283M $ | 37.423M $ | 67.692M $ |
| **More Electric Model** | 15.198M $ | 3.304M $ | 10.269M $ | 37.387M $ | 67.158M $ |
| | - 10.3% | - 0.66% | - 0.137% | - 0.096% | - 2.65% |

With reference to Table 4.9, it can be seen that the overall result is a 6.64% reduction of required maintenance when moving from the conventional reference case to the more electric study case.

Taking the most frequent type of maintenance as a starting point, a reduction of 10.3% (equal to \$1.752M in the 24 years time span) was achieved for both LC and MC combined. This reduction is attributed to changes in the daily and weekly checks, while between-rounds operations remained unaffected. For line and base maintenance, the changes made to the maintenance tasks from the MPD resulted in reductions of 0.66% and 0.137% in line and base maintenance costs, respectively, compared to the baseline values associated with the conventional reference case. Furthermore, savings were achieved in the area of off-aircraft maintenance, with a reduction of \$372 000, representing a 22.4% reduction in total costs over 24 years of operation.

The most significant relative percentage reduction is in Routine maintenance. It has a significant impact on the overall maintenance cost. As observed, its cost over 24 years exceeds that of base maintenance (\$16.9M compared to \$10.2M). Although the cost of each check is relatively low, what significantly increases their total cost is the number of required interventions (355 pre-flight, 1480 transit, 250 daily and 60 weekly checks per year, as reported in Table C.1).

Then comes the component maintenance, which, as explained in subsection 4.2.3, experiences a slight decrease due to the actuator change in the FCS (- 0.08%), a significant increase in required MMH related to the growth and expansion of the electrical system (+ 57%), and the contribution related to the complete elimination of maintenance tasks related to the hydraulic system (- 100%).
Despite this relatively small percentage change, component maintenance has the

largest impact on total aircraft maintenance costs because the cost required for component maintenance ($37M) are the highest among the others ($3.3M for line maintenance, and $10.2M and $16.9M for base and routine maintenance, respectively.

Finally, there are the results related to line and base maintenance, with lower relative percentage reductions than the previous ones. For base maintenance in particular, the limited impact of the assumed changes of the case study is due to the extensive nature of these maintenance checks. These inspections cover all parts of the aircraft (interior refurbishment, repainting, structural and engine checks, subsystem checks, etc.). Given the large number of components that make up the entire aircraft, it is easy to understand that the three OBS analyzed in this thesis (electrical, flight control and hydraulic) represent only a small part of the whole. Therefore, the impact of their variation is more limited.

There are a few limitations to consider when analyzing the results. First, the accuracy of the routine maintenance values is limited by the assumption of an equal distribution of maintenance task reductions from the A330 to the A350. This limitation is primarily due to a lack of detailed data and further refinement is required to improve the accuracy of these values.
Secondly, there is potential to improve the results related to line and base maintenance. This is through establishing more precise relationships beyond the linear correlations with failure rates, which could lead to a more accurate assessment of these types of maintenance.
In addition, the estimation of increased off-aircraft maintenance requirements due to the improve electrical system lacks detail, primarily due to the absence of detailed information regarding the system changes in the transition. This information gap limits the accuracy of the estimate and highlights the need for more comprehensive data to refine these assessments.
Finally, it is important to note that the analysis did not include an assessment of the landing gear, which is part of the hydraulic system. In the absence of electrified landing gear, complete removal of the hydraulic system is not feasible and only a reduction from three to two lines is possible. Therefore, in the case of a fully electrified landing gear, a more substantial reduction, similar to that achieved with FCS, could be expected along with the complete elimination of the hydraulic system. These limitations are an integral part of the research findings and should be acknowledged to provide a full understanding of the results.

# Chapter 5

# Conclusions

More-Electric Aircraft (MEA) are driven by technological advancements and efficiency goals. It emphasizes the importance of estimating maintenance costs early in the design process to make cost-effective decisions.
The primary objective of this study is to estimate aircraft maintenance costs during the initial design phases. To accomplish this, a methodology for estimating maintenance cost changes resulting from the removal or replacement of systems when transitioning from the reference conventional case to the more electric study case was developed, in addition to considering the contribution of new components. This comprehensive approach considers component reliability and uses analogy-based methods to draw correlations between the new and existing systems. In particular, this analogical approach estimates potential changes in maintenance costs associated with changes to the On-Board Systems (OBS). These variations include the complete elimination of the hydraulic system, the replacement of all Hydraulic Servo Actuator (HSA) with Electro-Hydraulic Actuator (EHA), improvements in electrical generation through Variable Frequency Generators (VFGs), the replacement of Integrated Drive Generators (IDGs) and Ni-Cd batteries with Li-Ion batteries, and general improvements in the electrical system. To assess the impact of these solutions, the study quantifies the variation in Maintenance Man Hours (MMH) required by comparing maintenance tasks between the conventional reference case and the more electric case study.
The analysis shows that improvements in line and base maintenance are achievable. These improvements can be attributed to the component-level data obtained from the Maintenance Planning Document (MPD) of the aircraft. The data then were linearly scaled with failure rates, which serve as an initial estimation approach given the limited detailed information and the evolving status of these emerging technologies. Routine maintenance is the most expensive segment, mainly because it has the highest task frequency among all the other types, resulting in an overall reduction of 10.3%. Furthermore, off-aircraft maintenance presents a higher cost

profile compared to line and base maintenance. The cost of this maintenance category is mainly determined by the projected removal of the hydraulic system maintenance tasks, which, according to the results of the reference method, stands out as the most resource-intensive system in terms of maintenance requirements, particularly due to its extensive and complex design. This type of maintenance is reduced by -0.096% as a result of the modification. This research seeks to provide an initial estimate of maintenance costs using the limited data available in the early stages of aircraft design, and the results herein serve as a valuable starting point. The accuracy of this method can be further refined through future research, which may also increase its versatility by making it responsive to different parameters capable of simulating a wide range of aircraft configurations. As a part of future work, this methodology can be extended to assess new OBS, including but not limited to Environmental Control System (ECS), Ice Protection System (IPS), and fuel systems. Furthermore, this analysis can serve as a foundational framework for evaluating other types of vehicles, such as those with hybrid electric propulsion or hydrogen-based systems, which stand to benefit from these innovative technologies.

# Appendix A

# Assumptions Summary

Throughout this study, numerous assumptions have been central to shaping the methodology, analysis, and conclusions presented in this thesis. This appendix provides readers with a comprehensive overview of these.

**Methodology Assumptions**

- On-Board Systems Changes: In 3.1.1, the modifications that the studied more electric model will have to incorporate are considered exclusively on a mathematical level. The purpose of the study is to estimate their potential influence on the overall MMH calculation for the systems without considering the physical integration of these new components into the model.

- On-Board Systems Changes: Not all surface actuators are replaced with EHAs. Rather, only the hydraulic linear actuators that control the aileron, rudder, elevators, and spoilers are substituted, While flaps and slats are currently controlled using linear ball-screw actuators powered by rotating shafts connected to central distribution units.

- MPD Tasks: All maintenance tasks under consideration relate to active components only during a mission.

- MPD Tasks: Only the task with the label "POST" + [modification number] in the applicability cell of the MPD are considered in the analysis (subsection 3.1.3).

- MPD Tasks: As indicated in subsection 3.1.3, the MMH value for each task taken from the MPD was multiplied by a factor of 3 to provide a more realistic scenario [60].

- Line and Base Labor Cost (3.2.2): Given the lack of more comprehensive data, it was assumed that, holding all other factors constant (such as system structure, component redundancy, maintenance effectiveness, etc.), a component with a higher failure rate will necessitate more maintenance over the same time span than a component with greater reliability. Obtaining Equation 3.3 and Equation 3.4

**Maintenance Types Assumptions**

- Line and Base Material Cost (3.2.2): The relative weights of the hydraulic system and the FCS on both LC and MC were the same, so that the same percentage change derived for LC could be adopted.

  Regarding the electrical system, the MC for the conventional configuration are considered negligible. Thus, any system variation's impact on these costs is assumed to be zero, resulting in an unchanged MC.

- Routine Maintenance (3.2.3): The thesis assumes that the maintenance percentage change from A320 to the more electric model is equivalent to that between A330 and A350 systems.

- Routine Maintenance (3.2.3): Only the daily and weekly check are assumed changing between configuration, leaving all of the pre-flight and transit checks unchanged.

- Component Maintenance (3.2.3): The weighted average variation between the results for line, 1st base and 2nd base maintenance has been assumed to estimate the off-aircraft variation for the FCS.

**Results Assumptions**

- Overall Maintenance Cost (4.2.4): Due to their significant size, the total cost results were rounded to the nearest hundred. It is assumed that this level of rounding does not have a substantial impact on costs, which are measured in millions of dollars.

- OOP Tasks: The MPD tasks for the AC emergency generator and for the static inverter have an interval (70FH) lower than the first A-check available (750FH). It is assumed that the task will still be performed before the first A-check, and the sum of the contributions related to the number of times this task will be performed is assigned to the first available check.

- MPD Tasks (4.1.3: The MMH values obtained from the 2011 reference in *Aircraft Commerce* are assumed to remain constant until the reference year of the A320 MPD (2018). This assumption enables a direct comparison between the two datasets.

# Appendix B

# MPD Maintenance Tasks

**Table B.1:** FCS Maintenance Tasks from [59]

| Subsystems | Components | Task Number | Zone | Interval [mo] | Interval [FH] | Task MH | Access MH | Preparation MH | Required Men | First Interval to be reached [MONTHS] | First Interval to be reached [FH] | Required Maintenance Time [MH] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flight Control System Actuators | Ailerons | 271400-01-1 | 210 | 36 MO | 5000 FH | 0.10 | 0.00 | 0.00 | 1 | 21.40 | 4993 | 0.3 |
| | | 271400-02-2 | 575<br>675 | 144 MO | 18000 FH | 1.00<br>1.00 | 0.14<br>0.15 | 0.00 | 2 | 77.10 | 17990 | 13.74 |
| | | 271400-03-1 | 575<br>675 | 180 MO | 24000 FH | 0.20<br>0.20 | 0.03<br>0.05 | 0.00 | 1 | 102.80 | 23986 | 1.44 |
| | | ZL-590-01-1 | 590<br>690 | 48 MO | | 0.10<br>0.10 | 0.08<br>0.07 | 0.00 | 1 | 48 | 11200 | 1.05 |
| | Elevators | 273400-01-1 | 210 | 36 MO | 5000 FH | 0.10 | | 0.00 | 1 | 21.40 | 4993 | 0.3 |
| | | 273400-03-1 | 334<br>344 | 180 MO | 24000 FH | 0.20<br>0.20 | 0.03<br>0.03 | 0.00 | 1 | 102.80 | 23986 | 1.38 |
| | | 273400-04-1 | 334<br>344 | 252 MO | 36000 FH | 0.20<br>0.20 | 0.03<br>0.03 | 0.00 | 1 | 154.20 | 35980 | 1.38 |
| | | 273400-08-1 | 334<br>344 | 24 MO | 10000 FH | 0.33<br>0.33 | 0.03<br>0.03 | 0.00 | 1 | 24.00 | 5600 | 2.16 |
| | | ZL-335-01-1 | 335<br>355 | 72 MO | | 0.20<br>0.20 | 0.28<br>0.28 | 0.00 | 1 | 72 | 16800 | 2.88 |
| | Rudder | 272400-01-1 | 210 | 6 MO | 750 FH | 0.10 | 0.00 | 0.00 | 1 | 3.20 | 746 | 0.3 |
| | | 272400-02-1 | 325 | 144 MO | 18000 FH | 1.00 | 0.08 | 0.00 | 2 | 77.10 | 17990 | 6.48 |
| | | 272400-05-1 | 325 | 24 MO | 10000 FH | 0.10 | 0.04 | 0.00 | 1 | 24.00 | 5600 | 0.42 |
| | | 272400-06-1 | 325 | 24 MO | 10000 FH | 0.10 | 0.06 | 0.00 | 1 | 24.00 | 5600 | 0.48 |
| | Spoilers | 276400-01-1 | 575<br>675 | 24 MO | 2000 FH | 0.25<br>0.25 | 0.00 | 0.04 | 1 | 8.50 | 1983 | 1.62 |
| | | 276400-02-1 | 575<br>675 | 144 MO | 18000 FH | 1.40<br>1.40 | 0.00 | 0.04 | 2 | 77.10 | 17990 | 17.04 |

**Table B.2:** Hydraulic System Maintenance Tasks from [59]

| Subsystems | Components | Task Number | Zone | Interval [mo] | Interval [FH] | Task MH | Access MH | Preparation MH | Required Men | First Interval to be reached [MONTHS] | First Interval to be reached [FH] | Required Maintenance Time [MH] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydraulic System | Hydraulic Fluid | 291000-15-1 | 100 | 24 MO | 7500 FH | 2.40 | 0.04 | 0.00 | 1 | 24.00 | 5600 | 7.32 |
| | EDP | 290000-02-1 | 435<br>445 | 12 MO | 1000 FH | 0.02<br>0.02 | 0.02<br>0.02 | 0.00 | 1 | 4.20 | 980 | 0.24 |
| | | 291000-20-1 | 210 | 36 MO | 12000 FH | 0.25 | 0.00 | 0.00 | 1 | 36.00 | 8400 | 0.75 |
| | RAT | 292000-06-1 | 190 | 144 MO | 24000 FH | 3.00 | 0.08 | 0.00 | 1 | 102.80 | 23986 | 9.24 |
| | PTU | 291000-04-1 | 210 | 72 MO | 24000 FH | 0.10 | 0.00 | 0.00 | 1 | 72.00 | 16800 | 0.3 |
| | | 291000-06-1 | 210 | 36 MO | 12000 FH | 0.10 | 0.00 | 0.00 | 1 | 36.00 | 8400 | 0.3 |
| | Reservoir | 291000-01-1 | 100 | 6 MO | 750 FH | 0.10 | 0.06 | 0.00 | 1 | 3.20 | 746 | 0.48 |
| | | 291000-02-1 | 100 | 6 MO | 750 FH | 0.10 | 0.06 | 0.00 | 1 | 3.20 | 746 | 0.48 |
| | | 293100-01-1 | 190 | 252 MO | 36000 FH | 0.30 | 0.06 | 0.00 | 1 | 154.20 | 35980 | 1.08 |
| | | 293400-01-1 | 210 | 108 MO | 12000 FH | 0.10 | 0.00 | 0.00 | 1 | 51.40 | 11993 | 0.3 |
| | Accumulators | 291000-14-1 | 100 | 6 MO | 600 FH | 0.10 | 0.04 | 0.00 | 1 | 2.50 | 583 | 0.42 |
| | Filters | 290000-05-1 | 100 | 24 MO | 2000 FH | 0.06 | 0.10 | 0.00 | 1 | 8.50 | 1983 | 0.48 |
| | Other | 291000-05-1 | 195 | 24 MO | 2250 FH | 0.10 | 0.02 | 0.00 | 1 | 9.60 | 2240 | 0.36 |
| | | 291000-08-1 | 210 | 144 MO | 36000 FH | 0.30 | 0.00 | 0.00 | 2 | 144.00 | 33600 | 1.8 |
| | | 291000-09-1 | 574<br>674 | 108 MO | 12000 FH | 0.10<br>0.10 | 0.02<br>0.02 | 0.00 | 1 | 51.40 | 11993 | 0.72 |
| | | 291000-18-1 | 148 | 12 MO | 1500 FH | 0.30 | 0.04 | 0.00 | 1 | 6.40 | 1493 | 1.02 |
| | | 291900-02-1 | 210 | 108 MO | 12000 FH | 0.30 | 0.00 | 0.00 | 2 | 51.40 | 11993 | 1.8 |
| | | ZL-195-01-1 | 195<br>196 | 48 MO | | 0.20<br>0.20 | 0.02<br>0.02 | 0.00 | 1 | 48 | 11200 | 1.32 |
| | | 291000-10-1 | 210 | 180 MO | 24000 FH | 0.40 | 0.00 | 0.00 | 2 | 102.80 | 23986 | 2.4 |

**Table B.3:** Electrical System Maintenance Tasks from [59]

| Subsystems | Components | Task Number | Zone | Interval [mo] | Interval [FH] | Task MH | Access MH | Preparation MH | Required Men | First Interval to be reached [MONTHS] | First Interval to be reached [FH] | Required Maintenance Time [MH] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electrical System | IDG | 242000-21-1 | 438<br>448 | 6 MO | 800 FH | 0.40<br>0.40 | 0.04<br>0.04 | 0.00 | 1 | 3.40 | 793 | 2.64 |
| | | 242100-01-1 | 438<br>448 | 24 MO | 2400 FH | 0.30<br>0.30 | 0.04<br>0.04 | 0.00 | 1 | 10.20 | 2380 | 2.04 |
| | | 242100-02-1 | 438<br>448 | 2 MO | 300 FH | 0.02<br>0.02 | 0.04<br>0.04 | 0.00 | 1 | 1.20 | 280 | 0.36 |
| | | 242100-04-1 | 438<br>448 | Engine Ovh. | | 0.20<br>0.20 | 0.00 | 0.00 | 2 | Engine | Engine | 2.4 |
| | | 242100-05-1 | 438<br>448 | 252 MO | 36000 FH | 0.20<br>0.20 | 0.00 | 0.00 | 1 | 154.20 | 35980 | 1.2 |
| | AC Emerg. Generator | 242400-01-3 | 210 | 1 MO | 90 FH | 0.02 | 0.00 | 0.00 | 1 | 0.30 | 70 | 0.06 |
| | Static Inverter | 242800-01-3 | 210 | 1 MO | 90 FH | 0.10 | 0.00 | 0.00 | 1 | 0.30 | 70 | 0.3 |
| | Batteries | 243800-01-1 | 210 | 12 MO | 1000 FH | 0.10 | 0.00 | 0.00 | 1 | 4.20 | 980 | 0.3 |
| | | 243851-01-1 | 126 | 12 MO | | 0.15 | 0.02 | 0.00 | 1 | 12 | 2800 | 0.51 |
| | | | | | 1000 FH | 0.15 | 0.02 | 0.00 | 1 | 4.29 | 1000 | 0.51 |
| | | | | 6 MO | 2000 FH | 0.15 | 0.02 | 0.00 | 1 | 6.00 | 1400 | 0.51 |
| | | 243851-02-1 | 126 | 6 MO | 2000 FH | 0.15 | 0.02 | 0.00 | 1 | 6.00 | 1400 | 0.51 |
| | Other - Transfer Inhibition | 242200-01-1 | 210 | 108 MO | 12000 FH | 0.10 | 0.00 | 0.00 | 1 | 51.40 | 11993 | 0.3 |
| | Other -AC ESS Gen | 242500-01-1 | 210 | 72 MO | 7500 FH | 0.10 | 0.00 | 0.00 | 1 | 32.10 | 7490 | 0.3 |
| | Other - Bus Shedding | 242600-02-1 | 210 | 180 MO | 24000 FH | 0.10 | 0.00 | 0.00 | 1 | 102.80 | 23986 | 0.3 |
| | Other - DC Generation | 243200-01-1 | 210 | 72 MO | 7500 FH | 0.15 | 0.00 | 0.00 | 1 | 32.10 | 7490 | 0.45 |
| | | 243400-01-1 | 210 | 108 MO | 12000 FH | 0.15 | 0.00 | 0.00 | 1 | 51.40 | 11993 | 0.45 |
| | Other - AC/DC Distribution | 245100-01-1 | 210 | 180 MO | 24000 FH | 0.30 | 0.00 | 0.00 | 1 | 102.80 | 23986 | 0.9 |
| | | 245100-02-1 | 210 | 180 MO | 24000 FH | 0.10 | 0.00 | 0.00 | 1 | 102.80 | 23986 | 0.3 |

# Appendix C

# Aircraft Commerce Values

**Table C.1:** Routine Maintenance Values

| | **Pre-Flight** | **Transit** | **Daily** | **Weekly** | **Tot Routine Checks** |
|---|---|---|---|---|---|
| **Check per Year** | 355 | 1480 | 250 | 60 | |
| **MMH per Check** | 0.5 | 3 | 4.25 | 8 | |
| **MMH per year** | 180 | 4400 | 1250 | 660 | 6490 |
| **Labor Cost per year** | 15 700 $ | 310 750 $ | 101 700 $ | 52 000 $ | 480 150 $ |
| **Material Cost per year** | 1 600 $ | 13 200 $ | 158 200 $ | 53 200 $ | 226 200 $ |
| **Tot per year (LC+MC)** | 17 300 $ | 323 950 $ | 259 900 $ | 105 200 $ | 706 350 $ |

**Table C.2:** Line Maintenance Values

| | A1 | A2 | A3 | A4 | Tot A Check |
|---|---|---|---|---|---|
| **Intervals (FH)** | 750 | 1500 | 2250 | 3000 | |
| **MMH per single check** | 170 | 450 | 170 | 540 | 1600 |
| **Labor Cost per check** | 13 450 $ | 35 600 $ | 13 450 $ | 42 700 $ | 105 200 $ |
| **Material Cost per check** | 2 430 $ | 18 760 $ | 2 430 $ | 18 760 $ | 42 380 $ |
| **Tot per check (LC+MC)** | 15 880 $ | 54 360 $ | 15 880 $ | 61 460 $ | 147 580 $ |

**Table C.3:** Base Maintenance Values

| | Lighter C Check | | | C4 + S1 | Lighter C Check | | | C8 + S2 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **C1** | **C2** | **C3** | **C4** | **C5** | **C6** | **C7** | **C8** | **Tot 1st C-Check** | **Tot 2nd C-Check** |
| **Intervals (months)** | 20 | 40 | 60 | 72 | 100 | 120 | 140 | 144 | | |
| **MMH per Check** | 3500 | 3500 | 3500 | 13500 | 3500 | 3500 | 3500 | 22000 | 56500 | 73450 |
| **Labor Cost per Check** | 197.8k $ | 197.8k $ | 197.8k $ | 762.8k $ | 197.8k $ | 197.8k $ | 197.8k $ | 1.243M $ | 3.107M $ | 4.011M $ |
| **Material Cost per Check** | 43.5k $ | 43.5k $ | 43.5k $ | 180.8k $ | 43.5k $ | 43.5k $ | 43.5k $ | 237k $ | 1.412M $ | 1.751M $ |
| **Tot per Check (LC+MC)** | 241.3k $ | 241.3k $ | 241.3k $ | 943.5k $ | 241.3k $ | 241.3k $ | 241.3k $ | 1.480M $ | 4.52M $ | 5.424M $ |

# Appendix D

# Line and Base Maintenance Results

**Table D.1:** A-Check Cycles Maintenance Contributions

| A-Checks [MH] | A1 | A2 | A3 | A4 | A1 | A2 | A3 | A4 | Total MH | % Over the total MMH | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ailerons | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| Elevators | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| Rudder | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 2.4 | 0.075% | |
| Spoilers | 0 | 1.62 | 0 | 1.62 | 0 | 1.62 | 0 | 1.62 | 6.48 | 0.203% | |
| IDG | 8.94 | 8.94 | 10.98 | 8.94 | 8.94 | 10.98 | 8.94 | 8.94 | 75.6 | 2.363% | |
| Battery | 2.34 | 2.34 | 2.34 | 2.34 | 2.34 | 2.34 | 2.34 | 2.34 | 18.72 | 0.585% | |
| Other - Electr. | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 28.8 | 0.900% | |
| Hydr. Fluid | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| EDP | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 1.92 | 0.060% | |
| RAT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| PTU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| Reservoir | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 7.68 | 0.240% | |
| Accumulator | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 6.72 | 0.210% | |
| Filters | 0 | 0.48 | 0 | 0.48 | 0 | 0.48 | 0 | 0.48 | 1.92 | 0.060% | |
| Other | 0 | 1.02 | 0.36 | 1.02 | 0 | 1.38 | 0 | 1.02 | 4.8 | 0.150% | |
| | | | | | | | | | 155.04 | 4.845% | **Global** |
| | | | | | | | | | 1809.317 | 4.843% | **Over 24 years** |

**Table D.2:** First Base Cycle Maintenance Contributions

| 1st Base Cycle [MH] | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | Total MH | % Over the total MMH | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ailerons | 0.3 | 1.35 | 0.3 | 15.09 | 1.74 | 1.35 | 0 | 14.04 | 34.17 | 0.060% | |
| Elevators | 2.46 | 2.46 | 2.46 | 5.34 | 3.84 | 2.46 | 0.3 | 6.42 | 25.74 | 0.046% | |
| Rudder | 0.9 | 0.9 | 0.9 | 7.38 | 0.9 | 0.9 | 0 | 7.38 | 19.26 | 0.034% | |
| Spoilers | 0 | 0 | 0 | 17.04 | 0 | 0 | 0 | 17.04 | 34.08 | 0.060% | |
| IDG | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 1.2 | 0.002% | |
| Battery | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| Other - Electr. | 0.75 | 1.5 | 0 | 1.5 | 2.25 | 1.5 | 0 | 0.75 | 8.25 | 0.015% | |
| Hydr. Fluid | 7.32 | 7.32 | 7.32 | 7.32 | 7.32 | 7.32 | 0 | 7.32 | 51.24 | 0.091% | |
| EDP | 0 | 0.75 | 0 | 0.75 | 0.75 | 0 | 0.75 | 0 | 3 | 0.005% | |
| RAT | 0 | 0 | 0 | 0 | 9.24 | 0 | 0 | 0 | 9.24 | 0.016% | |
| PTU | 0 | 0.3 | 0 | 0.6 | 0.3 | 0 | 0.3 | 0.3 | 1.8 | 0.003% | |
| Reservoir | 0 | 0.3 | 0 | 0 | 0.3 | 0 | 0 | 1.38 | 1.98 | 0.004% | |
| Accumulator | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| Filters | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| Other | 0 | 3.84 | 0 | 1.32 | 4.92 | 1.32 | 0 | 4.32 | 15.72 | 0.028% | |
| | | | | | | | | | 205.68 | 0.364% | **Global** |

**Table D.3:** Second Base Cycle Maintenance Contributions

| 2nd Base Cycle [MH] | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | Total MH | % Over the total MMH | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ailerons** | 1.35 | 0.3 | 1.74 | 15.09 | 0.3 | 1.35 | 0 | 14.04 | 34.17 | 0.047% | |
| **Elevators** | 2.46 | 2.46 | 3.84 | 5.34 | 2.46 | 2.46 | 0.3 | 6.42 | 25.74 | 0.035% | |
| **Rudder** | 0.9 | 0.9 | 0.9 | 7.38 | 0.9 | 0.9 | 0 | 7.38 | 19.26 | 0.026% | |
| **Spoilers** | 0 | 0 | 0 | 17.04 | 0 | 0 | 0 | 17.04 | 34.08 | 0.046% | |
| **IDG** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.2 | 1.2 | 0.002% | |
| **Battery** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| **Other - Electr.** | 1.5 | 0.75 | 1.5 | 1.5 | 0.75 | 1.5 | 0 | 1.5 | 9 | 0.012% | |
| **Hydr. Fluid** | 7.32 | 7.32 | 7.32 | 7.32 | 7.32 | 7.32 | 0 | 7.32 | 51.24 | 0.070% | |
| **EDP** | 0.75 | 0 | 0.75 | 0 | 0.75 | 0 | 0.75 | 0 | 3 | 0.004% | |
| **RAT** | 0 | 0 | 2.4 | 0 | 0 | 0 | 0 | 0 | 2.4 | 0.003% | |
| **PTU** | 0.3 | 0 | 0.3 | 0.3 | 0.3 | 0 | 0.3 | 0.3 | 1.8 | 0.002% | |
| **Reservoir** | 0 | 0.3 | 0 | 0.3 | 0 | 0.3 | 0 | 1.08 | 1.98 | 0.003% | |
| **Accumulator** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| **Filters** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000% | |
| **Other** | 1.32 | 2.52 | 2.4 | 3.84 | 0 | 3.84 | 0 | 1.8 | 15.72 | 0.021% | |
| | | | | | | | | | 199.59 | 0.272% | **Global** |

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