POLITECNICO DI TORINO

Master's Degree in Aerospace Engineering

Master's Degree Thesis

Concept Development for Maintenance Cost Estimation for New Aircraft Systems

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Academic Year 2025–2026

Summary

Aviation industry, along with its greenhouse gas emissions, is expected to grow in the upcoming decades, requiring a substantial reduction in the environmental impact of air transport. Current research is investigating alternative energy carriers, such as hydrogen, together with increasing levels of electrification of both propulsive and secondary power systems.

The introduction of these innovative technologies is accompanied by economic uncertainties. Since operating costs constitute a major portion of the total Life Cycle Cost (LCC), and maintenance is one of the largest contributors to operating costs, the capability to estimate maintenance expenditures is essential. Cost assessments are especially important during the early design phases, where design flexibility is highest and multiple configurations can still be evaluated. While maintenance cost estimation methods are available for conventional aircraft, studies addressing hybrid-electric and hydrogen-powered concepts remain limited.

Thus, the aim of this thesis is to develop a maintenance cost estimation methodology sensitive to different novel aircraft propulsion technologies and suitable for application during the conceptual design phase, when only high-level aircraft information is available.

To achieve this, four short-to-medium-range concepts developed within Deutsches Zentrum für Luft- und Raumfahrt (DLR) are used as case studies. One of the aircraft serves as the reference configuration and employs conventional aircraft systems. The remaining three concepts incorporate novel technologies, including different degrees of hybridization, Liquid Hydrogen (LH_2) fuel systems, and Proton Exchange Membrane Fuel Cell Systems (PEMFCSs) replacing conventional Auxiliary Power Units (APUs).

The expected maintenance activity is obtained by developing a maintenance plan for each case study and simulating its implementation through a discrete-event simulation. Maintenance plans for the novel concepts are derived by identifying the expected differences relative to the reference aircraft. A Maintenance Planning Document (MPD) analysis is used to estimate the maintenance implications of changes in propulsion architecture. Maintenance activities associated with the novel technologies are derived from a Maintenance Steering Group-3 (MSG-3) analysis conducted by DLR, and complemented with information available in the literature.

The simulation results provide a maintenance cost database. The latter is subsequently analyzed to identify the principal maintenance cost drivers, maintaining a level of detail compatible with conceptual aircraft design. A regression analysis is then used to derive Cost Estimating Relationships (CERs) for the individual maintenance cost components. The combination of these CERs forms the proposed maintenance cost estimation method.

The developed methodology provides both a maintenance cost assessment for aircraft concepts incorporating hybrid-electric and hydrogen-based technologies, and a maintenance cost model suitable for early-stage aircraft design studies. The results demonstrate the influence of propulsion architecture, LH_2 systems, and battery replacement requirements on overall maintenance costs and establish a foundation for future maintenance cost assessments of advanced aircraft concepts.

Contents

Acronyms

AC Alternate Current

AD Airworthiness Directive

AEA All Electric Aircraft

AL Airworthiness Limitation

APU Auxiliary Power Unit

ATA Air Transport Association

BMS Battery Management System

CAIV Cost as an Independent Variable

CER Cost Estimating Relationship

CMR Certification Maintenance Requirement

DC Direct Current

DET Detailed Inspections

DIS Discard Tasks

DLR Deutsches Zentrum für Luft- und Raumfahrt

DMC Direct Maintenance Cost

DOC Direct Operating Cost

DOE Department of Energy

DY Days

EASA European Union Aviation Agency

EGT Exhaust Gas Temperature

EIS Entry-into-Service

EOL End-of-Life

ESV Engine Shop Visit

EXACT Exploration of Electric Aircraft Concepts and Technologies

FAA Federal Aviation Administration

FC Flight Cycle

FCS Fuel Cell System

FH Flight Hour

FNC Functional Checks

GDL Gas Diffusion Layer

GVI General Visual Inspections

HEA Hybrid-Electric Aircraft

HP High Pressure

IDG Integrated Drive Generator

IOC Indirect Operating Cost

ITT Inter-Turbine Temperature

LCC Life Cycle Cost

LH_2 Liquid Hydrogen

LIB Lithium-Ion Batteries

LLP Life Limited Part

LP Low Pressure

LRM Linear Regression Model

LSM Least Squared Method

LUB Lubrication

$LYFE^2$ Life Cycle Analysis Framework for Environment & $Economics^2$

MB Maintenance Burden

MEA More Electric Aircraft

MH Maintenance man-Hours

MO Months

MPD Maintenance Planning Document

MRBR Maintenance Review Board Report

MSG-3 Maintenance Steering Group-3

MTBF Mean Time Between Failures

MTBUR Mean Time Between Unscheduled Removal

NFF No Fault Found

OP Operational Checks

PCE Product Cost Estimation

PEMFCS Proton Exchange Membrane Fuel Cell System

PF Pre-Flight

PtL Power-to-Liquid

RCM Reliability Centered Maintenance

RST Restoration Tasks

SAF Sustainable Aviation Fuel

SB Service Bulletin

SDI Special Detailed Inspections

SOFC Solide Oxide Fuel Cell

SRV Servicing

SV Shop Visit

TMC Total Maintenance Cost

TR Transit

VC Visual Checks

WBS Work Break Down Structure

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Chapter 1

Introduction

The aviation industry is currently pushing the development of new technologies in order to adhere to the ambitious climate goal of achieving climate neutral air mobility [38]. Air transportation is a sector characterized by continuous traffic growth, despite the temporary decline experienced during the COVID-19 pandemic [82]. Conventional propulsion systems have already reached a high level of maturity in terms of efficiency, and radical innovations are required to achieve the targeted reductions in environmental impact [66]. Consequently, novel propulsion architectures and alternative energy sources are receiving increasing attention. For instance, hydrogen combustion engines represent an alternative to conventional kerosene-based propulsion systems. Hydrogen exhibits a gravimetric energy density approximately three times higher than kerosene and offers the possibility of eliminating in-flight CO_2 emissions [41, 9]. Furthermore, hydrogen can also be used to power Fuel Cell Systems (FCSs), which may replace conventional APUs [35]. Other concepts, such as Hybrid-Electric Aircraft (HEA), exploit battery-powered propulsion systems. These designs have the potential to reduce emissions, and noise, while also improving system reliability [15].

Beyond performance and environmental considerations, the economic implications of these technologies must also be addressed. In accordance with the Cost as an Independent Variable (CAIV) principle, operating costs should be considered during the early stages of aircraft design and requirements definition [47]. More accurate cost estimation methods can reduce the economic risks associated with the adoption of new technologies and enables trade-off analyses between competing configurations [55]. Among the various operating cost categories, maintenance represents one of the most significant contributors [81].

Several methods for estimating maintenance costs of conventional aircraft have been proposed in the literature, with some studies reaching subsystem-level resolution. However, only a limited number of publications address maintenance costs associated with novel aircraft propulsion technologies. Moreover, most of the studies are restricted to high-level economic assessments or focus exclusively on specific cost elements, such as labor or material costs.

The present work addresses this gap by developing a maintenance cost estimation methodology for aircraft employing hybrid-electric propulsion systems, LH_2 hydrogen fuel systems, and PEMFCSs. The objective is to provide a maintenance cost model suitable for application during the conceptual design phase, when only high-level design information is available and significant configuration changes remain possible. To achieve this objective, four short-to-medium-range aircraft concepts developed within DLR's Exploration of Electric Aircraft Concepts and Technologies (EXACT) project are analyzed. The aircraft are designed to satisfy top-level requirements derived from the A321neo, with the exception of a reduced design range. One of those aircraft is used as reference, as it employs conventional aircraft systems. The remaining three concepts incorporate different levels of hybridization, hydrogen-based energy systems, and PEMFCSs units replacing conventional APUs. In addition, two of the analyzed configurations employ turboprop propulsion systems, introducing further changes in the expected maintenance activities.

Maintenance plans are developed for each aircraft by identifying the expected differences relative to the reference configuration. Existing MPDs, namely the A320 family MPD [4] and ATR72 MPD [8], are used to estimate the maintenance implications associated with changes in system architecture. This Thesis also exploits a set of maintenance activities associated with the novel systems, derived from an MSG-3 analysis conducted internally at DLR. Maintenance efforts associated with the new tasks are based on the aforementioned MPDs, whenever tasks with comparable scope and expected effort could be identified. For activities for which no suitable analogy is identified, the required information is derived from the available literature. Maintenance plans are therefore associated with labor, material, and fixed cost. The latter is needed where a separate estimation of labor and material costs is not practical. The resulting cost assessment includes both scheduled and unscheduled maintenance activities.

Derived maintenance plans are subsequently implemented within the DLR's $LYFE^2$ discrete-event simulation framework to simulate the operational life of each aircraft and estimate the associated maintenance costs. Resulting outputs are then analyzed to identify the principal maintenance cost drivers and to derive CERs through regression analysis. The resulting model provides a means of estimating maintenance costs from a limited set of high-level design parameters, making it suitable for early-stage aircraft design studies involving advanced propulsion technologies.

The remainder of this thesis is organized as follows: Chapter 2 presents the theoretical background required for the study. Chapter 3 introduces the four aircraft configurations selected as case studies and summarizes their main characteristics. Chapter 4 describes the methodology used to generate the maintenance cost database employed for developing the model. Chapter 5 presents the development of the maintenance cost model, showcasing the regression technique applied. Finally, Chapter 6 summarizes the main findings of the study, discusses the achieved results, and outlines suggestions for future work.

Chapter 2

Fundamentals

This Chapter is dedicated to the fundamentals of the present thesis. An overview of aircraft maintenance is provided in Section 2.1. Then, conventional and novel propulsion systems are described in Section 2.2, highlighting the main expected changes in aircraft system architecture. Afterwards, Section 2.3 shows the main aircraft cost figures, and illustrates a classification of the available estimation techniques. Finally, Section 2.4 summarizes the state of research, highlighting the current gaps, and provides the goal of this thesis.

2.1 Aircraft Maintenance

The analysis of aircraft maintenance requires an understanding of the main maintenance strategies, the key documents used in maintenance program development and the principal maintenance tasks employed in aviation.

2.1.1 Maintenance Strategies

Maintenance can be defined as all those actions performed on an item to retain it in or to restore it to a specified state [16]. Aside from regulatory requirements, maintenance serves to keep the aircraft available, and to minimize value losses that are due to deterioration [53]. Maintenance activities can follow three main approaches: preventive, corrective, and predictive strategies [14]. Preventive maintenance is carried out at fixed intervals, before failure actually occurs, and it serves to retain the functionality of a system, or component, decreasing its failure probability [16]. Managing this strategy can be complex, and sometimes it shortens the useful lifetime of components, as it implies the removal of still functioning components [10]. Corrective maintenance refers to maintenance activity performed to restore functionality after a failure has occurred [16]. It requires minimal planning, and maximizes the use time of components [10]. However, it entails the capability to uncover and localize failures accurately [16], and it inherently accepts that failures will arise before maintenance actions are performed. Lastly, in contrast to preventive maintenance, the predictive approach does not follow predetermined maintenance intervals. The latter change depending on the actual condition of the item [14]. However, it requires the capability to detect the upcoming failure (diagnostic), and to estimate the remaining useful life (prognostic) through the use of pattern recognition or statistical analysis of physical parameters such as temperature or vibration [10][75]. Preventive maintenance includes all scheduled or routine maintenance actions [14], i.e., all measures that are carried out according to a defined calendar schedule or number of utilization units [83]. Typical examples are Flight Hours (FHs), and Flight Cycles (FCs). Corrective and predictive strategies include all unscheduled or non-routine activities [14], i.e., maintenance that is not carried out on a fixed schedule [83]. Unscheduled maintenance may result from scheduled maintenance tasks, pilot reports, or generic unforeseen events, such as failures [53][14]. The Figure 2.1 below provides a visual representation of the aforementioned strategies, and maintenance activity subdivision.

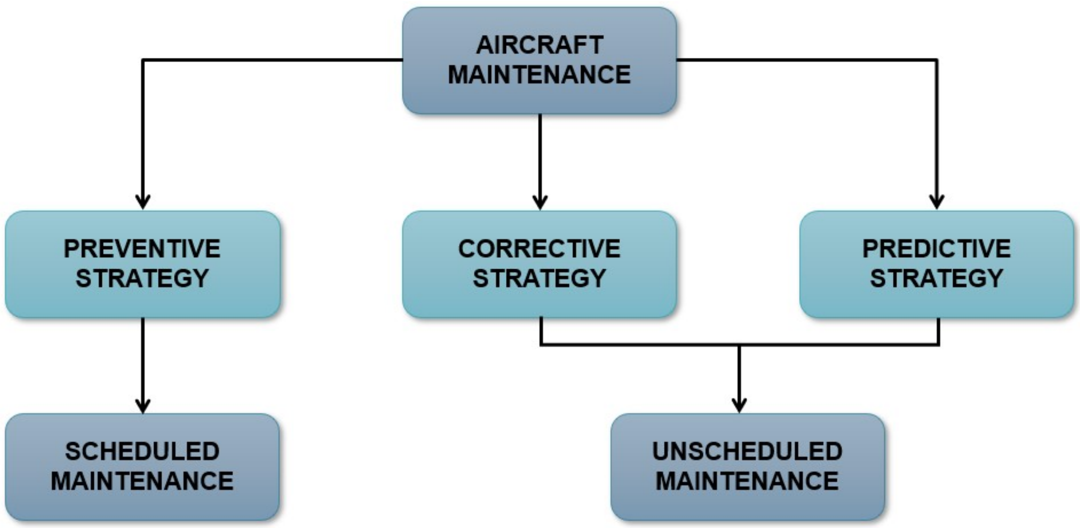


Figure 2.1: Overview of the main aircraft maintenance approaches and their classification

2.1.2 Maintenance Program Development

The maintenance and airworthiness of commercial aircraft are regulated by aviation authorities. In Europe, this responsibility is carried out by the European Union Aviation Agency (EASA), while in the United States it is performed by the Federal Aviation Administration (FAA) [36]. The resulting requirements are contained in multiple documents. A brief overview of these is provided below, following the descriptions reported by Ackert [53].

Among the documents forming the basis of a maintenance program, the Maintenance Review Board Report (MRBR) contains the minimum scheduled maintenance requirements proposed by the type certificate holder. Airworthiness Limitations (ALs) constitute part of the instructions for continued airworthiness and define mandatory maintenance requirements that must be complied with throughout the aircraft service life [53]. Certification Maintenance Requirements (CMRs) are established during the aircraft certification process, and they are incorporated into the type certificate as operating limitations. There are also additional requirements, some examples include Service Bulletins (SBs) and Airworthiness Directives (ADs).

Together, the CMRs, the ALs, and the MRBR constitute the aircraft MPD, as shown in Figure 2.2. Apart from mandatory tasks, each individual airline can decide what maintenance actions are executed, and when they are carried out. Therefore, operators use the MPD to ensure to fall within regulatory requirements, while building a customized maintenance program.

Figure 2.2: MPD documents composition from [53]

Also for unscheduled activities multiple documents are used as support. Some examples are included in Figure 2.3.

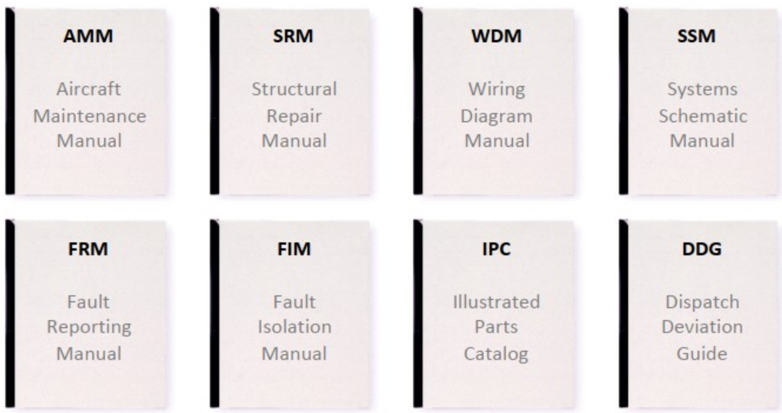


Figure 2.3: Non-routine support documentation from [53]

Maintenance Tasks Creation

Current scheduled tasks and intervals are developed through the MSG-3 process [32], which adopts the principles of Reliability Centered Maintenance (RCM) [70][53]. As RCM focuses on addressing system function failures, rather than system hardware [70], the resulting MSG-3 process differentiates between maintenance being done for safety reasons versus economic reasons, and it follows a top-down approach [53]. Thus, maintenance tasks are assessed at the system level. If the functional failure of a particular system has no effect on operational safety, or the economic repercussions is not significant, then there is no need to define a maintenance task associated to the system [53].

Task Codes

The resulting tasks are classified using standardized task codes according to the type of activity performed, as defined in [53]. Lubrication (LUB) and Servicing (SRV) tasks are intended to maintain the operational capability of aircraft systems and components. Operational Checks (OP) and Visual Checks (VC) are primarily aimed at detecting failures or abnormal conditions during operation or inspection. Functional Checks (FNC) are used to quantitatively verify the correct functioning of components and systems. Increasing levels of inspection intensity are represented by General Visual Inspectionss (GVIs), Detailed Inspections (DET), and Special Detailed Inspections (SDI), which provide progressively more in-depth assessments of component condition. Restoration Tasks (RST) include rework and overhaul activities, i.e. the item is reworked to restore it to its nearly new condition [50]. Finally, Discard Tasks (DIS) involve the replacement of components that have reached their defined End-of-Life (EOL).

2.1.3 Maintenance Activity Classification

Maintenance activities are commonly organized in checks [27]. These can be classified into different categories, depending on the frequency, the scope and the duration of the tasks performed during the check [14]. Specific intervals vary from one aircraft to another. As a large amount of information is available for the A320 aircraft family, its maintenance data is used as reference.

Maintenance Checks

Until January 2005 the A320's Family MPD tasks were grouped using letter checks with the same interval, i.e. A and C checks. This was changed in the 28th MPD revision, and now tasks are treated individually as they can have multiple interval criteria [27]. Therefore operators can create check packages more efficiently based on personal aircraft utilization parameters, and it is difficult to model an average A320 maintenance program. Nevertheless, many maintenance operators still use the letter check terminology, as the majority of MPD tasks can still be split into different interval categories [21]. Consequently, the same terminology is retained throughout this work.

The most frequent checks are Pre-Flight (PF), Transit (TR), daily, and weekly checks. These inspections include only a limited portion of scheduled maintenance activities, since the A320 MPD typically covers tasks with intervals down to approximately eight days [21]. Thus, the majority of the work performed during these checks is related to discrepancies identified during aircraft operation.

A-checks have a basic interval of 750 FHs, 750 FCs, or Months (MO); whichever is reached first [19]. They consist of general inspections of the interior and exterior of the airplane, such as GVIs. Selected areas may be opened when completing the checks [53]. Over time A-checks have incorporated what were previously defined as B-checks [56]. As a result, modern A-checks also include more extensive visual inspections. Checks ranging from PF to A-checks are classified as line maintenance activities [21]. Figure 2.4 shows the different maintenance activity classification.

C-checks are also performed on the basis of a calendar interval or utilization thresholds. The basic interval is 7,500 FH, 5,000 FCs, or 24 MO depending on the task [21][19]. They include more complex examinations at a system level, such as DETs. They also incorporate SBs requirements, and minor structural inspections [53].

D-checks, also referred to as structural inspections, are scheduled every 6 or 12 years [20]. They involve aircraft stripping, i.e. uncovering the airframe for a complete inspection, and cabin refurbishment [14]. C-checks and D-checks are classified as base maintenance [21] as shown in Figure 2.4. Some aircraft components, such as the APU and the engines have additional maintenance programs [21]. Their maintenance also involves aircraft removal, and subsequently Shop Visits (SVs), see Figure 2.4.

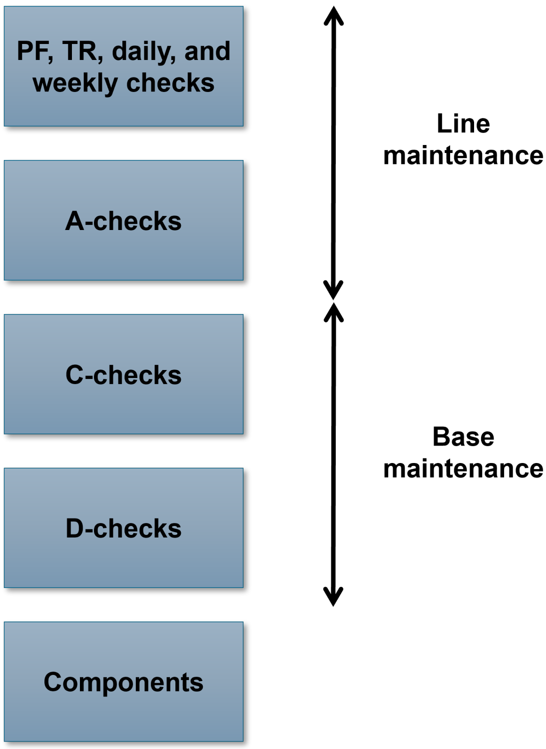


Figure 2.4: Maintenance activity classification

As engine overhaul activities account for more than 40% of total Direct Maintenance Cost (DMC), Engine Shop Visits (ESVs) play a central role in the economics of aircraft maintenance. The removal intervals are primarily driven by Exhaust Gas Temperature (EGT) margin deterioration and Life Limited Parts (LLPs) [25][52]. A comprehensive description of the engine architecture and the function of its main subsystems is presented in the following Section 2.2.

The EGT is the temperature of the exhaust gases leaving the nozzle. Excessive gas temperatures can cause severe thermal damage to turbine components, therefore EGT must be continuously monitored during engine operation [52]. The EGT margin is defined as the difference between the maximum allowable EGT and the actual EGT measured under specified operating conditions [52]. Initial EGT margins depend on the engine thrust rating. For example, the CFM56-5B4 and -5B7 variants, rated at 27,000 lb of thrust, have an initial margin of approximately 109°C, whereas the lower-rated CFM56-5B6, used on the A319 and rated at 23,500 lb, has an initial margin of about 145 °C [25]. The maximum EGT is typically reached near the end of the takeoff roll [52]. In turboprop engines, a similar parameter known as the Inter-Turbine Temperature (ITT) margin is monitored. The ITT is measured between the high-pressure and low-pressure turbine sections [24]. EGT margin deterioration is particularly significant for engines operating on short-haul routes due to the high frequency of FCs [25]. Regarding LLPs, these are components with a predefined service life established during certification [83]. These parts are subjected to mandatory replacement because their failure could amplify engine damage [10]. LLPs generally include disks, seals, spools, and shafts [52]. Their service life is typically expressed in FCs, due to the high mechanical and thermal stresses experienced during take-off [10]. Consequently, engine maintenance relies on a combination of predictive and preventive maintenance. In short-range operations, where aircraft have a high FC utilization, engine removals are often driven by LLP life consumption rather than by EGT margin deterioration [10]. Also APU SVs are driven by a combination of preventive and predictive maintenance criteria, including LLP life consumption and the monitoring of performance degradation [23].

2.2 Aircraft Systems

This section provides an overview of the aircraft systems currently employed. A legacy powerplant is presented, along with other systems that are affected by the introduction of novel concepts. An A320 propulsion system is used as a reference. The A320 is a subsonic, narrow-body, civil transport aircraft equipped with two high bypass turbofan engines. It represents an established medium-range aircraft, being the world's most adopted in 2019 [58]. Then, innovative propulsion concepts are presented, along with a brief summary of performance, and maintenance challenges associated with their adoption.

2.2.1 Conventional Propulsion Systems

In order to satisfy its mission and regulatory requirements an aircraft shall be able to perform a series of functions. These functions are carried out by a set of elements that are defined as aircraft systems, e.g., the avionics system is needed as the aircraft is required to communicate, and process data, among other purposes. Aircraft systems are not isolated components, their interconnections enable functions that would not be possible if each system were considered individually, e.g., engines and fuel distribution system. Other than a functional based approach, various methods can be used to classify aircraft systems. For instance, disciplinary, physical or perimeter-based strategies can also be used [49].

This thesis exploits the ATA 100 system methodology, which is a hierarchical classification developed by the Air Transport Association (ATA) in 1956, widely accepted by the main aircraft manufacturers [48]. It is based on a combination of the four aforementioned approaches [49], and it was created with the goal of obtaining a homogeneous and generic aircraft system taxonomy. It consists of a numbered chapters list that provides a description of all aircraft systems and components functions, as well as operating procedures, such as maintenance [76]. Table 2.1 provides a concise description of the chapters, and their content.

Table 2.1: Overview of ATA 100 main chapter partitioning [76]

Chapters	**Content Description**
00–18	Dimensions and zonal definition of major components; general maintenance practices and ground operations; vibration and noise analysis (for rotary-wing aircraft)
20–49	Airframe systems
51–57	Primary and secondary structural components
60–67	Propellers and rotor systems, including rotor transmission and flight control components
70–84	Powerplant systems, including engine, air intake, engine mounts, nacelle, cowling, air scoops, and cowl flaps

As already mentioned, aircraft systems are not isolated. This is particularly relevant when dealing with a key component such as the engine. Therefore, changes in the propulsion system entail modifications to various ATA chapters. It is safe to assume that the introduction of hydrogen, and electrified drive trains affects at least the aircraft power plant (ATA 70-84), the fuel storage and distribution system (ATA 28), and the auxiliary power system (ATA 49). Thus, a description of these groups is provided in the next paragraphs.

Powerplant

Information regarding the power plant is contained in ATA chapters 70-84 [76]. However, not all chapters are relevant to the aircraft category analyzed in this work. Table 2.2 contains the titles of the most pertinent chapters. For instance, chapter 84 is dedicated to propulsion augmentation, therefore it is not included.

Table 2.2: Powerplant related ATA chapters from [76]

Chapter	Content
71	General information about the overall power package
72	Engine components
73	Fuel and fuel control
74	Ignition system
75	Bleed air assembly
76	Engine control
77	Engine operating indicators
78	Exhaust components
79	Lubricating system
80	Starting system
82	Water injection system
83	Accessory gearboxes

Most A320 aircraft currently in operation are equipped with CFM International's CFM56-5A series engine [25]. It is a high-bypass turbofan engine with a single fan, four Low Pressure (LP) compressor stages, nine High Pressure (HP) compressor stages, a single HP turbine stage, and four LP turbine stages [3]. The HP drive shaft is connected to an engine mounted accessory gearbox, thus powering mounted accessories. Figure 2.5 provides a schematic of the engines main components.

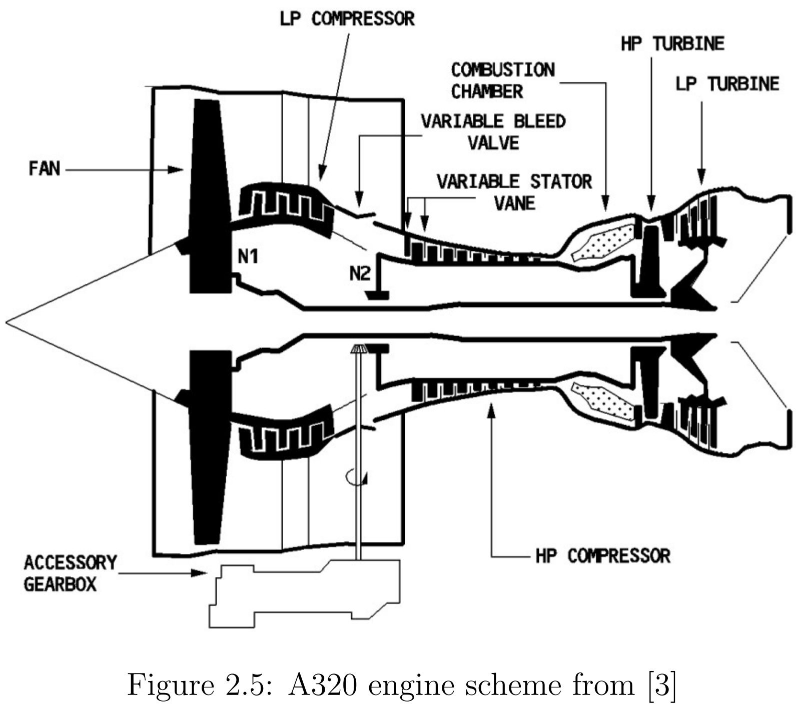


Figure 2.5: A320 engine scheme from [3]

Engines produce thrust, and also provide hydraulic power, pneumatic power and electrical power. Pneumatic energy is obtained by extracting bleed air at different compressor stages. The accessory gearbox is connected to an Integrated Drive Generator (IDG), which transforms mechanical power into electrical energy. Lastly, the engine provides hydraulic fluid pressurization through a dedicated pump.

Fuel System

Information regarding the fuel system is contained in ATA chapter 28. This system serves as fuel storage through the use of tanks, and it manages fuel flow during refueling. Fuel is supplied to the engines, the APU, and the IDG cooling system. It is also used to prevent flutter phenomena, by keeping the fuel in the outer tanks.

On an A320, fuel can be stored inside a center tank, two inner tanks, and two outer tanks [2]. A visual representation of the A320 fuel system is presented in Figure 2.6. Two additional vent tanks are available to address up to a 2% fuel expansion without spilling. In order to shift fuel between tanks, each wing possesses two transfer valves. The engines are supplied by a pump in the center tank, or via two pumps in the wing tanks, suction valves allows the engines to be fed by gravity in case of a pump failure. For further redundancy purposes, a total of six pumps are available trough a cross feed valve, and fuel flow can be stopped by a LP stop valve in case of an emergency, e.g., engine fire. As the APU is not equipped with a fuel tank, a connection to the main fuel tank is provided by a dedicated APU pump, also equipped with a LP stop valve.

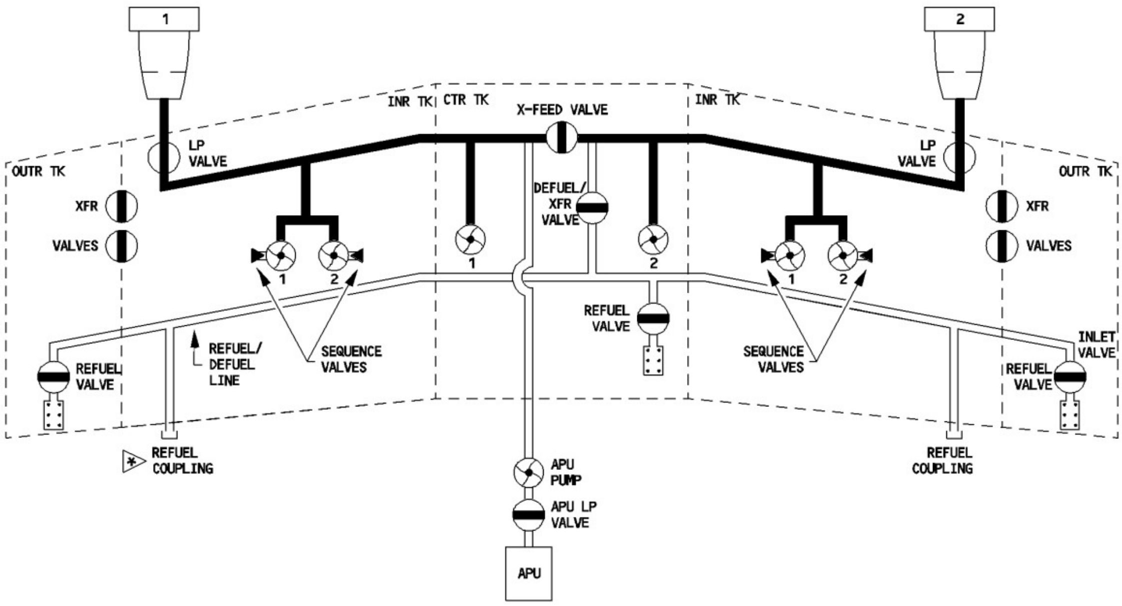


Figure 2.6: A320 fuel system scheme from [2]

Auxiliary Power Unit

The APU is a small, single-shaft, gas turbine engine that provides compressed air, electrical and hydraulic power [1]. Information regarding this system is available in ATA chapter 49. Figure 2.7 provides a representation of an A320 APU. This system is used as a main engine starter by supplying bleed air. In order to start the APU, either batteries or ground power units can be used. On the ground, it supplies electrical power to the electrical system (ATA 24), and bleed air for the air conditioning system (ATA 21) [59]. Thus, the aircraft is independent of external supplies. The APU also serves to enhance safety, as it backs up the electrical system, and can be used for engine restart. Also, it provides bleed air for the conditioning system during take-off. Thus, it eliminates thrust reduction caused by engine bleed air extraction during this flight phase [1]. APU's turbine delivers mechanical power to the accessory gear box, which is connected to the engine starter, the electric generator, and to the hydraulic pump. Lastly, compressed air is obtained through an APU bleed system [1].

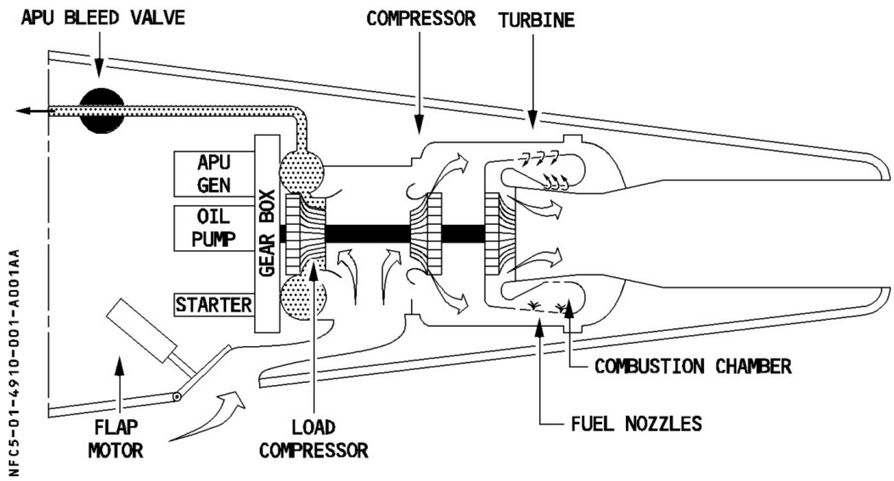


Figure 2.7: A320 APU scheme from [1]

2.2.2 Emerging Systems

This thesis focuses on kerosene fuel alternatives, and the electrification of propulsion systems. Figure 2.8 shows a visual representation of the novel concepts that are assessed in the present work. Sustainable Aviation Fuels (SAFs), such as Power-to-Liquid (PtL), are being investigated as fuel option, in order to reduce emissions, while limiting aircraft architecture modifications [69]. As SAF usage is only connected to minor changes in the aircraft concept, its maintenance activity assessment is not relevant for the scope of the present work.

Another promising fuel alternative lies in the form of hydrogen: its use has the potential to eliminate in-flight CO_2 emissions, although it requires massive infrastructure modification, and aircraft system changes [41][9][12][43]. Thus, hydrogen-fueled aircraft entails further cost assessment.

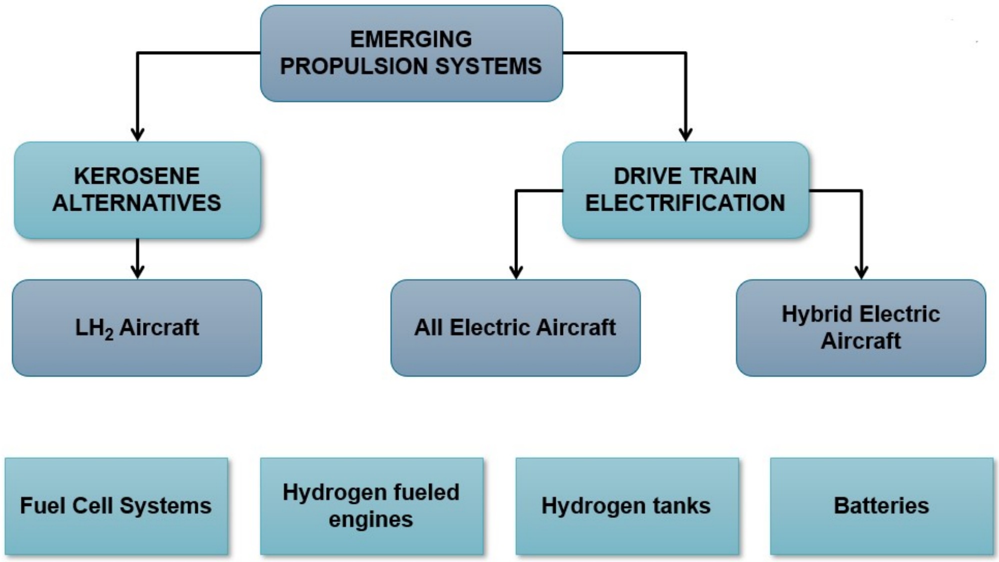


Figure 2.8: Overview of novel propulsion concepts and their main energy-provider subsystems

An alternative opportunity for emission reduction is represented by the electrification of the propulsion system [66] [17]. For the sake of completeness, it should be noted that electrification can affect either the propulsive power, thus implying changes in the aircraft drive train, or secondary power, that affects subsystems in various degree. Although aircraft drive train electrification is still at a conceptual stage, secondary power electrification is already implemented in existing aircraft. For instance, Airbus A350 and A380 flight controls electrification led to the elimination of one of the three hydraulic lines on board, and Boeing B787 eliminates the need for the bleed air system [58]. These aircraft are therefore defined as More Electric Aircraft (MEA) [58].

In regards to propulsive power electrification, aircraft can be categorized based on the degree of hybridization of their power and energy sources. Conventional aircraft use no electric power, nor electric energy storage for propulsion. HEA use a mix of fuel and electric energy storage, and power. The HEA need further classification, as two system architecture arrangements are possible: serial system architecture, and parallel system architecture [66][17]. In serial configurations, only the electric motors are connected to the propulsors, and combustion engines are used to drive an electrical generator that drives the electric motors,i.e., turboelectric aircraft, or charges the batteries [66][17]. In parallel configurations, propulsors can be powered either by electric motors, or by combustion engines. The most common parallel layout is the installation of an electric motor on the low-pressure shaft of a gas-turbine in order to support the operations of the gas-turbine or drive the propulsor device during segments of the mission, without combustion engine power [66]. Lastly, All Electric Aircraft (AEA) only use electric energy and power for its propulsion. In light of these considerations, the main systems associated with the aforementioned aircraft concepts are now presented.

Hydrogen Storage and Distribution

Hydrogen's gravimetric energy density is three times higher than conventional kerosene, and its combustion does not produce CO_2 [74]. However, hydrogen exhibits a lower volumetric energy density (10.1 MJ/l), and may cause increased NO_X release into the atmosphere [9]. In addition to that, its safe and efficient storage presents several challenges [9][12][51][28][7]. Within the context of aircraft application, hydrogen can currently be stored in two different ways: high pressure gaseous form (GH_2) or liquefied form (LH_2) [74] [9] [12] [28]. GH_2 is stored at ambient temperature using pressurized vessels (300-1000 bar) [9], that can be classified into five types [28] [9]. The taxonomy depends on the material composition and consequent gravimetric efficiency, as presented in Figure 2.9.

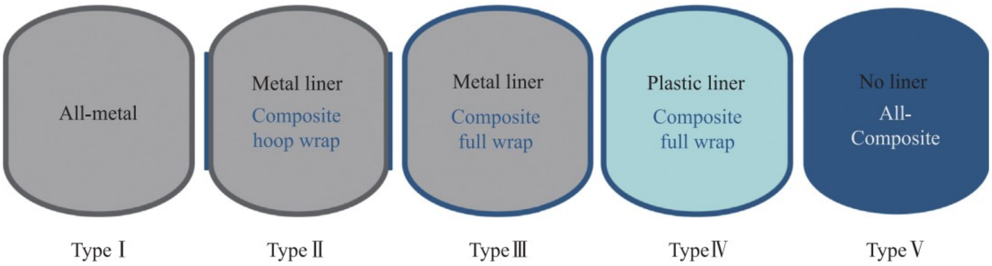


Figure 2.9: GH_2 vessels categories from [9]

Tank walls should be thick enough to sustain pressure and prevent tank failures, while minimizing the weight increase. Hydrogen embrittlement of steel, and aluminum tanks represents a major challenge [28] [51]. As shown in Figure 2.10, this mechanism consists in the accumulation of hydrogen atoms into micro cracks at high pressure, subsequent crack propagation, and fragile rupture can occur. While composite materials are more resistant and weigh less, they suffer from permeability, hence an additional polymer or metal liner is required to prevent hydrogen leaking [9].

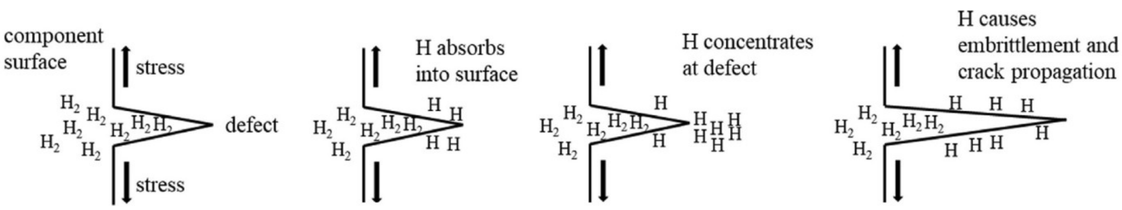


Figure 2.10: Hydrogen embrittlement mechanism from [28]

This thesis focus on storage of hydrogen in the form of LH_2, as it significantly enhances its energy per unit volume relative to gaseous hydrogen, reaching a volumetric density of 70 kg/m^3 [28]. However, temperatures as low as -253°C are needed to keep hydrogen in its liquid form [74]. Therefore, in addition to the still relevant hydrogen embrittlement, and permeation, thermal management issues need to be addressed for both the storage and the distribution subsystems [9]. Due to heat influx, LH_2 tends to boil, thus increasing the internal tank pressure, facing inherent safety risks if not expelled through a venting system [50]. This phenomena is known as hydrogen boil-off [51], and can result in consistent fuel losses if not addressed [9][54]. Notably, thermal insulation causes an increase in mass, thus a trade-off is needed.

Current literature recommends the use of a multi-layer insulation, that can be provided by thermal radiation shields perpendicular to the direction of the heat flow [9]. Added insulation can be achieved by exploiting a vacuum system, although this causes a mass increase [51]. For the the cryogenic hydrogen pipes, an ageing foam-based insulation can be exploited, although it requires periodic maintenance to account for its degradation [50].

Hydrogen Fueled Engines

From an architectural perspective, the overall engine layout remains unchanged. However, it is still unclear to what extent existing components can be directly transferred to hydrogen-fueled applications [41]. Propulsion systems will probably require an additional heat exchanger in order to reach combustion temperature [41][31][60].

The heat exchanger exploits the hydrogen high heat capacity as coolant liquid, and it can be placed at multiple engine locations by means of: precooling, intercooling, cooled turbine cooling air, and recuperation of exhaust gas heat [60][41]. Figure 2.11 depicts various heat exchange locations. While other heat transfer fluids can be exploited, e.g., nitrogen [31], using hydrogen as coolant has the potential to reduce specific fuel consumption up to 10%, as the temperature increase is paired with enthalpy rise [60].

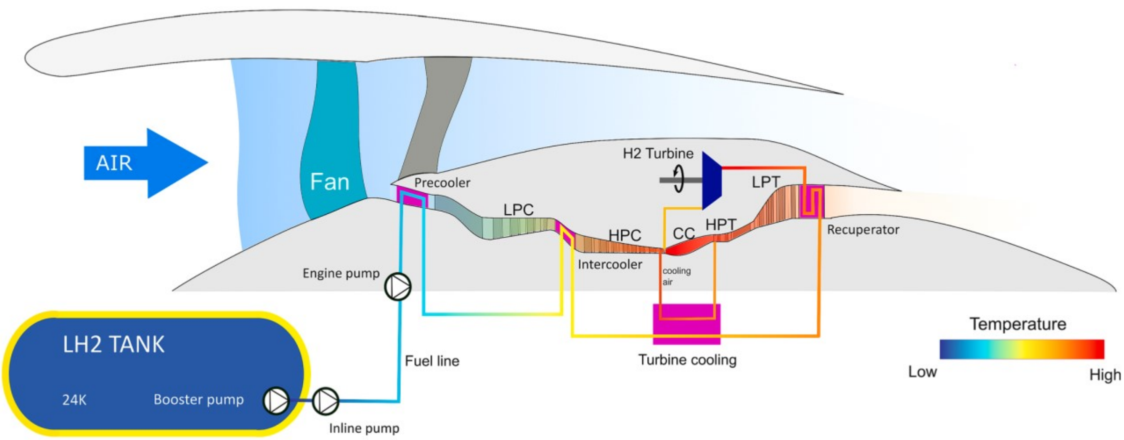


Figure 2.11: Conceptual hydrogen-fueled engine heat exchanger architecture, including precooling, intercooling, recuperation, and cooled turbine cooling air by [60]

However, there is still uncertainty regarding the overall maintenance cost implications of a fuel switch. Due to the different thermodynamic properties, the engine can operate at lower temperatures and more efficiently, with a higher engine core rotational speed [41]. Therefore, hydrogen-fueled engines could experience longer service lives than conventional kerosene-powered engines, due to the temperatures [29]. Nevertheless, other factors such as the higher rotational speed could also imply higher expenses. For instance, rotational speed is linked with the average ESV labor cost [46]. Thus, it is difficult to predict future maintenance implications without further analysis.

Batteries

Batteries can be used in order to store electric energy. Multiple battery chemistries are available, among those, Lithium-Ion Batteries (LIB) are currently the most efficient, and technology ready [83] [61]. A typical ion battery cell presents six components: two current collectors, two electrodes, i.e. the anode and the cathode, porous separator, an electrolyte. During charging process, the cathode is oxidized releasing positive ions that pass through the porous separator causing anode reduction, and electrons flow into the external circuit producing an electric current. During battery discharge, the opposite mechanism takes place [34]. Batteries gravimetric energy is still low when compared to conventional kerosene. State of the art LIB cells achieve a cell-level specific energy of only 250–300 Wh/kg, while kerosene stands at 12,000 Wh/kg [61]. Figure 2.12 provides the energy density of various carriers, including LIB.

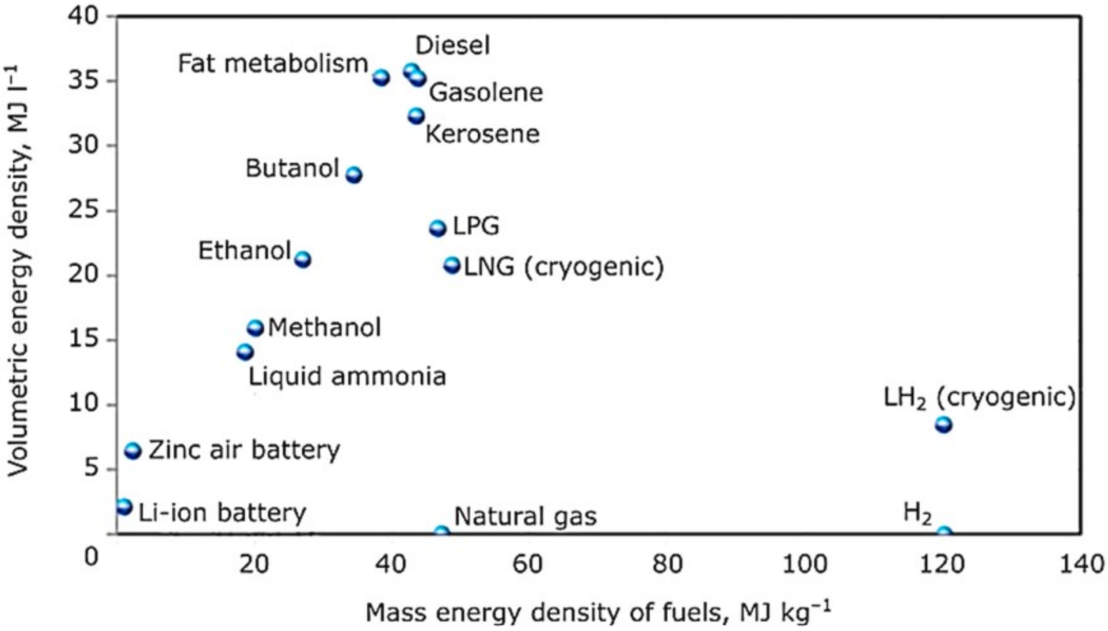


Figure 2.12: Energy densities of various carriers from [74]

Although batteries are not exempt from failure modes [42], e.g. thermal runaway, the implementation of advanced Battery Management System (BMS) helps to prevent those [61]. Nevertheless, a battery EOL is mainly limited by performance degradation [61][83][34]. A detailed analysis of LIB degradation is provided by Edge et al. [34]. However, such level of detail is out of scope of the present thesis, and the focus is placed only on the observable effects. Observable effects relate to the loss of capacity [34], i.e. the amount of electrical charge that the battery can store [83], and the peak power losses [34], i.e. the maximum amount of energy per time a battery can supply during operation [83]. The main drivers of battery degradation are high currents, fast charging, and low temperatures [61][83][34].

Fuel Cells

Among the various types of fuel cells devices, PEMFCS and Solide Oxide Fuel Cells (SOFCs) are the most promising in terms of aerospace applications [12]. This thesis focuses on PEMFCS, as SOFC operate at a higher temperature (600–1000 °C) compared to PEMFCS (10–100 °C), have a longer response time, and have a better mass-specific performance [74][12][10]. To provide electricity, different oxydo-reduction reactions occur within the cells, hence resulting in the overall reaction presented in Equation 2.1.

$$\begin{array}{rl} \text{Anode:} & 2H_2 \rightarrow 4H^+ + 4e^- \\ \text{Cathode:} & O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \\ \hline \text{Overall reaction:} & 2H_2 + O_2 \rightarrow 2H_2O + \text{electricity} + \text{heat} \end{array} \tag{2.1}$$

In order to reach the required power output, various cells are assembled together, thus creating the fuel cell stack. A fuel cell stack is composed of the following items: bipolar plates, Gas Diffusion Layers (GDLs), electrodes, membranes [45][11]. Figure 2.13 depicts the different components of a PEMFCS stack.

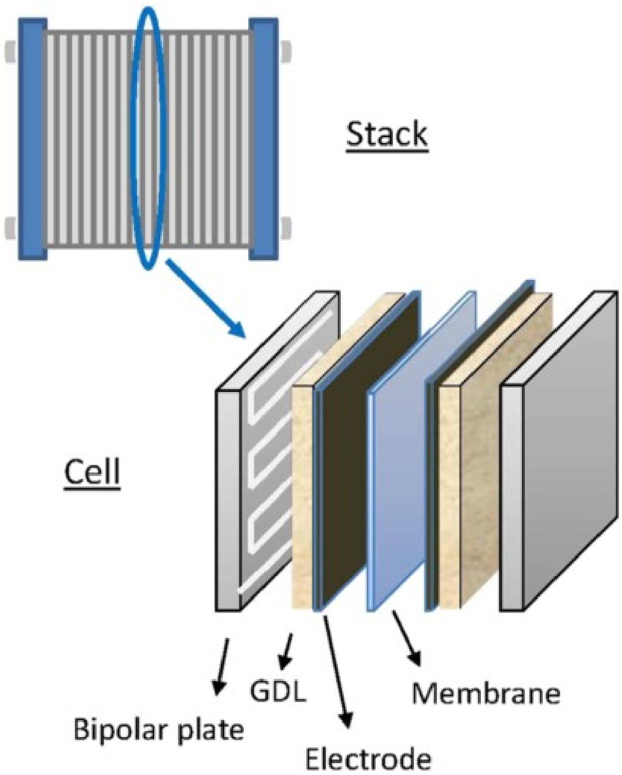


Figure 2.13: PEMFCS stack components from [45]

Bipolar plates mainly have structural functions, separating the cells inside the stacks, while providing current conduction. GDLs allow reactant diffusion and current conduction; electrodes provide catalyst support [11]. It is important to notice that every component must allow current conduction, and provide no issues in regard to water and thermal management, e.g. low thermal resistance [45].

The electrodes and the membrane are the most critical components of the stack in terms of degradation [45]. Similar to batteries, PEMFCS degradation is mainly driven by operating and environmental conditions, such as variable load demand, high temperature, and variable humidity [33] [45]. The observable effect consist in loss of voltage, and therefore power at a fixed current density [10].

Electric Motors and Power Conversion Components

Electric motors generate mechanical torque through the interaction between the magnetic fields of a stationary component, i.e. the stator, and a rotating component, i.e. the rotor [17]. Depending on the propulsion architecture, a gearbox may be used to couple the motor shaft to the propeller or fan system [83]. Power can be supplied through Alternate Current (AC) or Direct Current (DC) systems, and electric machines can be classified as synchronous or asynchronous according to the relative speed of the rotor and stator magnetic fields [17]. Among the available technologies, Permanent Magnet Synchronous Motors (PMSMs) are particularly attractive for aviation applications due to their high efficiency and power density [83].

Current aviation electric motors are limited to approximately half the power density of conventional turbofan engines [83]. Increasing current density can significantly improve the power-to-weight ratio of electric machines. For low levels of hybridization, the power density can increase from 4.54 kW/kg to 13.14 kW/kg, while for high hybridization levels it can increase from 6.01 kW/kg to 14.94 kW/kg [15]. Although electric motors may differ in terms of power, their design and degradation characteristics are generally similar [10]. Compared with turbofan engines, electric motors contain fewer moving parts and are thus less vulnerable to failure [83]. However, they may require more frequent replacement than conventional jet engines [10]. Their degradation behavior is influenced by mechanical, electrical, and thermal stresses, as well as environmental conditions [10].

Lightweight and efficient power conversion systems, including circuit breakers, converters, and inverters, remain an active area of research [17]. Current development efforts primarily focus on semiconductor materials, and cooling technologies for the thermal management of the system [17]. In addition to converting the DC supplied by the electrical distribution system into AC, required by the electric motor, the inverter functions as the motor control unit [83]. Advanced power electronic systems may achieve specific power ratings between 19 and 26 kW/kg while maintaining efficiencies above 99% [17].

2.3 Aircraft Cost Estimation

To assess aircraft maintenance cost, it is first necessary to understand how it fits within the broader LCC framework and how maintenance efforts are further categorized. Thus, this section presents the main cost elements contributing to aircraft LCC, with particular emphasis on the structure of maintenance costs. In addition, the principal cost estimation techniques commonly employed in the aerospace industry are introduced, providing the methodological basis for the analyses developed in the thesis.

2.3.1 Life Cycle Cost

Cost estimation plays an important role in the aeronautical sector, as it can help support decision-making among different design alternatives. This is especially relevant during the early phases of a project, as the large majority of the total avoidable cost is controllable at the design stage [30]. For instance, as shown in Figure 2.14, the majority of the total project cost is committed during the first project phases, while the design freedom is still high [18].

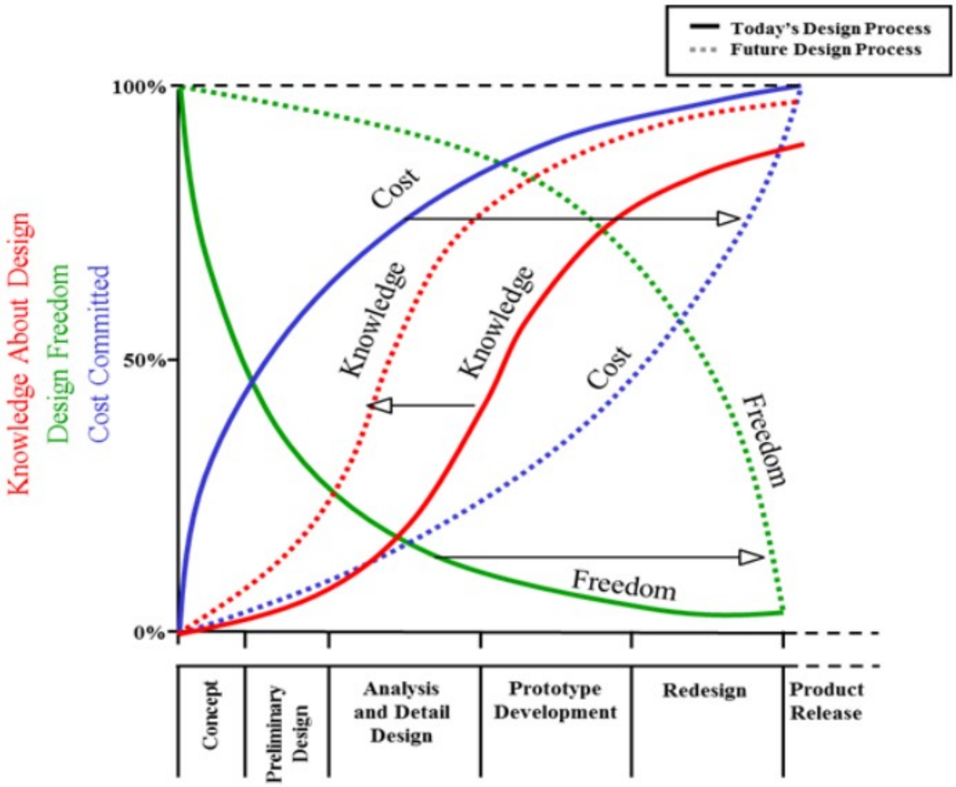


Figure 2.14: Design freedom and cost committment vs project progression from [18]

LCC is defined as the structured accounting of all labor, material and other efforts required during the aircraft entire life cycle [78]. The life cycle can be subdivided into four main parts [39]: design and development phase, production phase, operations phase, and recycling or disposal phase. The operations phase is, historically, the biggest in terms of costs for aircraft systems [78], with some estimates reaching 94% of total LCC [63]. Operating expenses can be subdivided into Direct Operating Costs (DOCs), and Indirect Operating Costs (IOCs). DOC is defined as the cost associated to all activities directly involved in flight operations, such as direct maintenance, fuel and oil consumption, insurance, depreciation and operating crew [62]. IOC include the rest of the expenses, such as ticketing and administration fees [39].

Maintenance Cost Breakdown

Among the various aircraft operating cost elements, maintenance costs are generally considered the most difficult to predict and quantify. While costs such as flight crew, fuel, insurance, depreciation, and spare holdings can be estimated from contractual agreements, performance specifications, market prices, or predefined financial assumptions, maintenance expenditures are subject to higher uncertainty [62].

DMC comprise the direct labor and material expenses associated with performing maintenance activities [37]. Labor costs are estimated by combining the maintenance workload, usually expressed in Maintenance man-Hours (MH), with an appropriate labor rate or hourly rate [50][39][69]. Maintenance costs include not only direct maintenance activities but also indirect costs, commonly referred to as Maintenance Burden (MB). MB comprises airline overhead, the cost of acquiring, maintaining equipment and tools, building facilities, and other indirect expenses [37]. Estimates from the 1960s suggest that maintenance accounts for between one-fifth and one-third of total DOCs [62]. More recent estimates bring this value between 10% and 20% [50][37]. Regarding MB, due to the heterogeneous nature of this cost element a quantification is accompanied by high uncertainty [37]. Estimates vary between 19% and 40% of Total Maintenance Cost (TMC) [37] [79].

2.3.2 Cost Estimation Techniques

A unique classification of cost estimation techniques is not viable, as different variables can be used to categorize the various methods, such as the format of data, the scope of application, and the resulting accuracy level. For the sake of completeness, it should be noted that highly detailed analysis of the various techniques are available in the literature. Some examples include the work of Niazi et al.[57], and Altavilla et al. [6] where comprehensive taxonomies are proposed. Nevertheless, such a thorough analysis exceeds the scope of the present work, and more compact reviews are preferred.

As stated in the NASA Cost Estimating Handbook [55], and the U.S. Government Accountability Office cost estimating and assessment guide [78], three main Product Cost Estimation (PCE) classes can be distinguished: analogy, parametric, and engineering build-up.

- Analogy approach uses the principle of similarity between an old product and a new one in order to estimate the cost of the latter.

- The parametric method relates cost to one or more technical parameters, also referred to as cost drivers, through a statistical relationship which is labeled as CER.

- The engineering method is a bottom-up approach, the overall cost are calculated as the sum of detailed estimates done at a lower Work Break Down Structure (WBS) level.

Other types of evaluations can be paired with the main method, thus they are referred to as support techniques [78]. An example includes the use of expert interview which can help evaluate data driven estimations. As may be observed in Figure 2.15, precision in performing the estimation progressively increases across the three PCE classes. Nevertheless, expected accuracy is not the only noteworthy evaluation parameter. Data availability and required effort need to be taken into consideration when choosing a method. As a result, each PCE class suits a different project phase [55]. An analysis of the currently available state-of-the-art methods is provided in the next section.

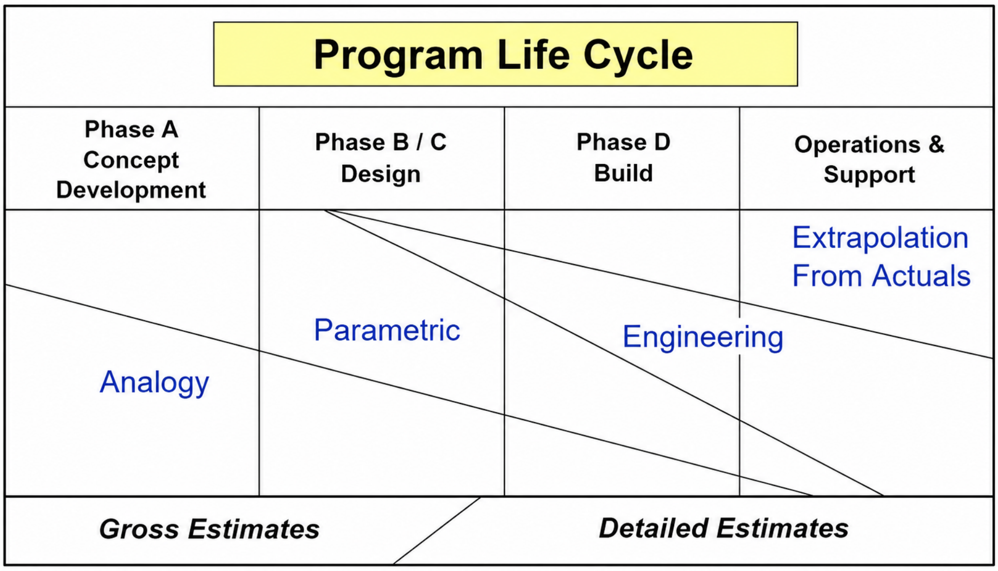


Figure 2.15: Use of cost estimating methodologies by program life cycle stages from [55]

2.4 State of Research

In order to understand the current state of research, a general overview of existing maintenance cost models, for both conventional and innovative aircraft technologies, is presented below. This section serves to highlight current research gaps, and to present the goal of this thesis.

2.4.1 Conventional Aircraft

A wide range of methods are available to assess maintenance costs of conventional aircraft, supported by the possibility of using real world operational data. Consequently, many of these methods rely on regression-based analysis, including several DOC estimations that incorporate maintenance expenses. A comprehensive overview of those is provided by Pohya et al. [64].

These methods break down maintenance expenses into engine costs and airframe costs, further differentiating between labor and material costs. Input demands vary among them, with some that might not be available during early design phases. For instance, the ATA model requires engine purchase price [64].

While DOCs estimations condense the overall on-board-systems effect under the airframe, other parametric studies reach a lower system architecture level [37] [13] [62]. In particular, Fioriti et al. [37] presents a model that provides total maintenance cost, and evaluates DMCs at a subsystem level, using CERs with input requirements similar to conventional DOCs methods.

Other studies permit more detailed estimations of propulsion systems maintenance costs [46][71], however, low level engine performance parameters are needed. For instance the model developed by Kang et al. [46] includes engine rotational speed, temperature, and pressure among the independent parameters.

Conventional regression-based methods cannot be applied if available data is inadequate, i.e. small sample with noise. Weng et al. [81] address this limitation by exploiting a fuzzy support vector machine, which uses reliability and maintainability parameters in order to estimate DMCs. While this method lowers database quality requirements, real operations data from similar aircraft is still needed.

2.4.2 Novel Concepts

When looking at maintenance cost estimations for novel propulsion systems, literature is scarce. A key limitations lies in the fact that many studies use conventional DOCs methods, and provide only qualitative estimations when addressing maintenance costs [40][44][43]. For instance, Goldberg et al. [40] foresee higher maintenance expenses when considering LH_2 powered aircraft, but no further assessment is made. Hoelzen et al. [44] do not expect relevant maintenance cost changes for HEA and AEA, as they expect a balancing between the added complexity of having two propulsion systems, and the lesser maintenance effort required by electric motors. A quantitative statement is only made for AEA, considering a fixed nine percent DMC reduction for the electric drive train. In another study, Hoelzen et al. [43] focus on LH_2 powered aircraft. While some hydrogen specific maintenance requirements are mentioned, LH_2 tank and fuel system are assessed with the same maintenance expenditures per mass as the rest of the airframe.

Further results regarding electrified aircraft are obtained by using a combination of analogous and parametric techniques [63][79]. In particular, Ploetner et al. [63] exploit on-shore wind turbine data to estimate electric drive maintenance cost. Vercella et al. [79] estimate the effect of MEA and AEA on maintenance cost by using an analogy with a study conducted by NASA and Lockheed [80], which showcases expected DMCs variations for various configurations characterized by advanced electronic/electric technologies. In [80], expected maintenance cost variations are expressed as percentage changes relative to a reference aircraft, namely the L-1011. Since the latter belongs to an older aircraft generation, the resulting estimates may not fully reflect the characteristics of modern technologies, although the study [80] incorporates the expected influence due to more advanced technologies installed on the reference aircraft.

Other approaches regarding maintenance implications for MEA and AEA are presented by Dell'Anna [73] and Ninotta [58], although their scope is limited to secondary power electrification. In particular Dell'Anna [73] exploits a document-based method that refers to the A320 MPD, in order to identify maintenance tasks, and thus MH that need to be eliminated in MEA and AEA architectures. Further results are obtained by Ninotta [58], by combining the MPD approach with an expert-based evaluation of maintenance tasks to be added.

While there are still uncertainties about the future regulation requirements, some maintenance activity assumptions are available in the literature. Barke et al. [10] estimate the impact of novel powertrain main components, i.e., batteries, fuel cells, and electric motors. Particular focus is placed on the estimation of replacement frequencies. Nevertheless, the degradation behaviour of the components is based on broad assumptions, without specific modelling, and does not consider further powertrain components.

A further analysis is conducted by Wolf et al. [83]. By defining a drive train for a hybrid electric, and all electric aircraft concepts powered by batteries, he estimates material cost for scheduled, and unscheduled maintenance activity. The influence of accessory subsystems and components is assessed, e.g., electric distribution system, gearbox, and propellers. Also, battery degradation behavior is evaluated by using a semi-empirical degradation model, which accounts for assumed operating conditions.

Meissner et al. [50] evaluate expected maintenance effort for a hydrogen powered fuel cell system that supplies auxiliary power. This is done by designing a LH_2 storage and distribution system with the electrical power demand of a conventional A320, and defining a preventive maintenance program. Maintenance intervals, and duration are estimated using existing standards and through a MPD analysis. Then, results are compared to A320 maintenance data. Depending on aircraft utilization rate, an increase in maintenance effort up to 30% is expected. However, while Meissner et al. [50] enable labor cost evaluation through MH estimate, further research is needed to address material cost, and unscheduled maintenance efforts.

A different approach is proposed by Ramm et al. [69]. By using a discrete event simulation model, they provide an aircraft life cycle analysis for three aircraft concepts: a baseline Jet-A1-powered aircraft, a conventional aircraft powered by

SAF, and a hybrid-electric hydrogen-powered aircraft concept. Although difference in engines between kerosene and LH_2 combustion is not taken into account, this paper provides a deep understanding of the economic implications of LH_2 tanks, and PEMFCS.

2.4.3 Science Gaps and Goal of the Thesis

In line with CAIV principle, novel propulsion technologies require tools to estimate operating costs since early design phases. Among operating costs, maintenance represents a major contributor. While conventional technologies already benefit from well-defined methodologies to perform maintenance cost analysis during the early design phase, when dealing with innovative concepts, researchers face multiple challenges. Although tech demonstrators have already flown, no consistent operational data is available yet. Hence, it is not possible to develop a regression method on an aircraft level. In addition to that, there is still uncertainty about maintenance requirement for the future technologies. A major limitation of the state of the art methods relies in the fact that maintenance cost is assessed on a high level, thus introducing inaccuracies, or is fragmented, and considers only specific aircraft subsystems or configurations, or is limited to the analysis of labor or material cost elements. Therefore, the goal of this thesis is to develop a maintenance cost estimation methodology suitable for the early design phases of aircraft incorporating hybrid-electric and hydrogen-based systems. The methodology aims to overcome the limitations of existing approaches by providing a comprehensive assessment of maintenance costs that accounts for the characteristics of novel aircraft subsystems without available operational data.

Chapter 3

Reference Aircraft Configurations

This Chapter introduces the four reference aircraft concepts that are used to generate the maintenance cost database. All four configurations are developed within the DLR EXACT internal project, which is briefly introduced in the first Section 3.1. The rest of the Chapter is subdivided into four sections, each of those is dedicated to one of the reference configurations.

3.1 EXACT Concepts Overview

The EXACT project is a study concerning sustainable aviation conducted by DLR. It explores the design of multiple aircraft configurations, and four of its short-to-medium range concepts are taken as reference in the present thesis. The designs are based on the A321neo, with the exception of a shorter range to grant a higher competitiveness. The top-elevel aircraft requirements of the A321neo are shown in the Table 3.1.

Table 3.1: A321neo top-level aircraft requirements

Parameter	**Unit**	**Value**
Range	km	4,630
Wing span	m	36
Passenger no.	–	236
Payload	kg	25,000
Cruise Mach no.	–	0.78
Approach speed	kt	136

As a comparison, the top-level EXACT aircraft characteristics are available in Table 3.2. All concepts are designed for an Entry-into-Service (EIS) in 2040, and an EOL in 2065.

Table 3.2: EXACT top-level aircraft characteristics

Parameter	Unit	D250-TF	TP-MHEP	TP-PHEP	TF-MHEP
Range	km	2,778	2,778	1,852	2,778
Wing Span	m	42	42	48	42
Passenger No.	–	250	250	250	250
Payload	kg	28,900	28,900	25,000	28,900
Cruise Mach No.	–	0.78	0.66	0.68	0.78
Approach Speed	kts	140	140	140	140

3.2 Reference Concept: D250-TF

The Design for a 250 passengers Turbofan (D250-TF) aircraft configuration can be powered with Jet-A1, or PtL. The fuel can be stored inside a center tank, two inner wing tanks and two outer wing tanks similarly to the A320 (Section 2.2). In the A321neo the wing tanks are not divided, and the fuel system features two bigger wing tanks [67].

This configuration serves as baseline for the maintenance analysis conducted in this thesis. While the system architecture has a different technology level, because of the 2040 EIS, the overall layout is assumed compatible with the A321neo. A description of the design process can be found in [69]. Figure 3.1 gives a visual representation of the D250-TF. Table 3.3 includes the main differences between the D250-TF and the A321neo, focusing on the fuel system, the auxiliary power system, and the engine. The data regarding the A321neo it is assumed that a LEAP-1A30 engine is installed, and that the aircraft is equipped with a APS 3200 APU [5][77]. The conventional fuel system, the APU, and the Powerplant characteristics are described in Section 2.2.

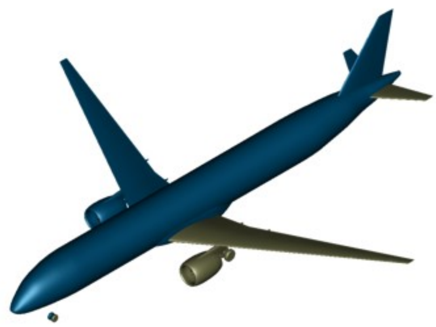


Figure 3.1: D250-TF aircraft configuration

Table 3.3: D250-TF aircraft characteristics confronted with the A321neo

Parameter	**Unit**	**D250-TF**	**A321neo**
Fuel type	–	A1 kerosene	A1 kerosene
Fuel storage	–	5 × tanks	3 × tanks
Total fuel mass	kg	17,480	18,440
Engine type	–	High Bypass Turbofan	High Bypass Turbofan
Engine thrust	kN	134.14	140.96
APU type	–	Conventional APU	Conventional APU
APU mass	kg	320	136

3.3 Novel Concepts

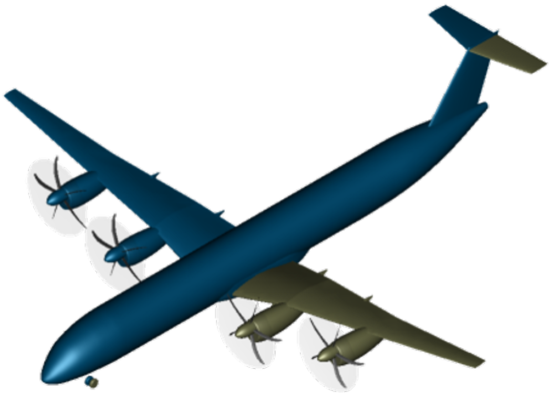
In addition to the reference conventional aircraft, the three alternative configurations analyzed in this study incorporate different levels of electrification and hydrogen-based propulsion technologies. It should be emphasized that the EXACT project is still at a conceptual stage, therefore the available data is limited to high level attributes such as total subsystems mass, and total power outputs. Therefore, some components are sized up using the assumptions presented in the Table 3.4. The data for the electric motors and the inverters is taken from [72], and it represents assumptions for a short-range hybrid aircraft, assuming a 2050 technology level. Batteries are sized up assuming a next generation technology energy density of 600 Wh/kg. A gearbox efficiency of 98% is assumed, while the PEMFCS stacks operate at an efficiency of 54%.

Table 3.4: Components performance assumptions

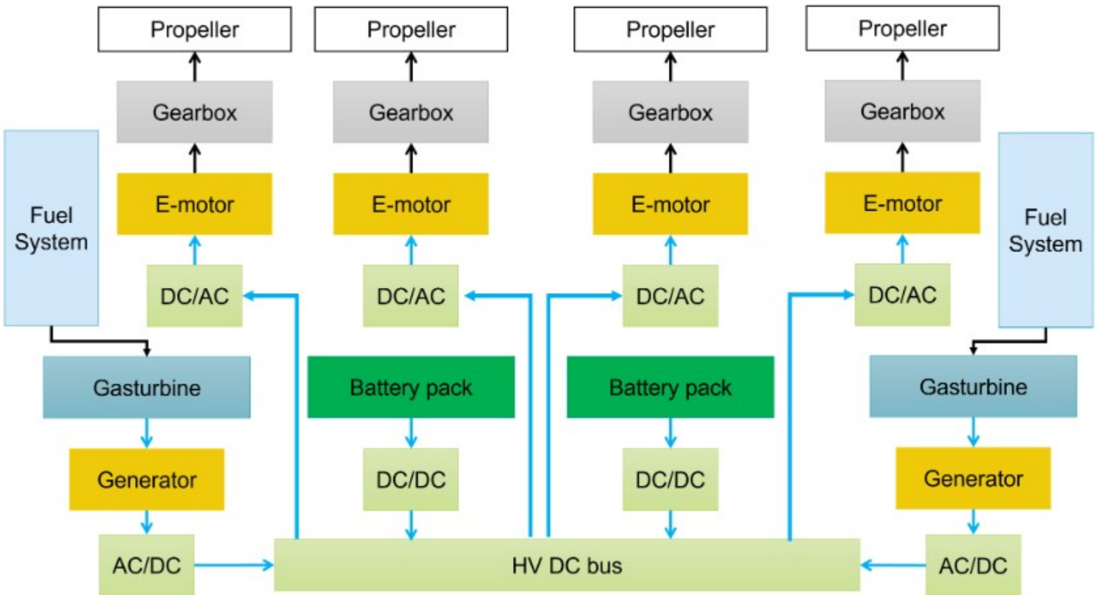
Component	**Parameter**	**Unit**	**Value**
E-motor	Sp. power	kW/kg	13
E-motor	Efficiency	–	98%
Inverter	Sp. power	kW/kg	19
Inverter	Efficiency	–	99%
Battery	Sp. energy	Wh/kg	600
Gearbox	Efficiency	–	98%
PEMFCS stack	Efficiency	–	54%

3.3.1 TP-PHEP

The Turboprop Plug-In Hybrid Electric Propulsion (TP-PHEP) aircraft design features four propellers powered by the same number of e-motors that permit a fully electric flight, using batteries as electric storage. The latter are placed in the two inner nacelles. Two kerosene-powered gas turbines are allocated in the outer nacelles, and they are used as range extender for missions exceeding 500 km, using a series hybrid architecture. The TP-PHEP fuel system is expected to be smaller, and simpler compared to the D250-TF, but a tank number is not yet available. There is still uncertainty regarding the presence of an APU system. This thesis assumes that this system is still needed. Figure 3.2 represents an overview of the aircraft configurations, and a simplified scheme depicting the relevant aircraft system. Table 3.6 helps to visualize the main differences between the TP-MHEP configuration and the D250-TF configuration.



(a) TP-PHEP aircraft representation



(b) TP-PHEP systems schematics. Black arrows depict mechanical connections, blue arrows depict electrical connections.

Figure 3.2: PHEP aircraft concept overview and relevant systems schematics

Table 3.5: TP-PHEP main systems information

System	Parameter	Unit	Value
E-motors	Max. power	kW	5,850
Battery system	Total capacity	kWh	14,000
Gas turbine	Mass	kg	1,935
Fuel system	Total fuel mass	kg	12,750

Table 3.6: TP-PHEP aircraft characteristics confronted with the D250-TF

Parameter	D250-TF	TP-PHEP
Fuel System	Conventional kerosene storage and distribution system	Reduced kerosene storage and distribution system
Auxiliary Power	Conventional APU	Conventional APU
Main Engine	2 × kerosene powered High Bypass Turbofan	4 × electric driven propellers in series with kerosene powered Gas turbine

3.3.2 TP-MHEP

The Turboprop Mild-Hybrid Electric Propulsion (TP-MHEP) aircraft design features two hydrogen powered turboprop engines as main power source. The hydrogen is stored inside two LH_2 tanks located between the pressure bulkhead and the vertical stabilizer trim mechanism, as shown in Figure 3.3.

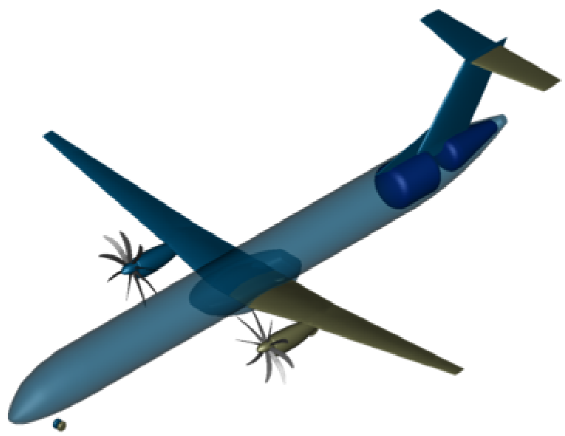


Figure 3.3: TP-MHEP aircraft representation

As explained in Section 2.2, LH_2 requires additional components to address its thermal characteristics. The tanks feature a double aluminum wall, with evacuated multilayer insulation as represented in Figure 3.4. This results in the installation of a pressurization system, a venting system, and a vacuum pumping system. There is still uncertainty regarding the insulation characteristics of the distribution system, i.e. closed-cell foam insulation, or vacuum insulation. An heat exchanger is then required to reach combustible temperature.

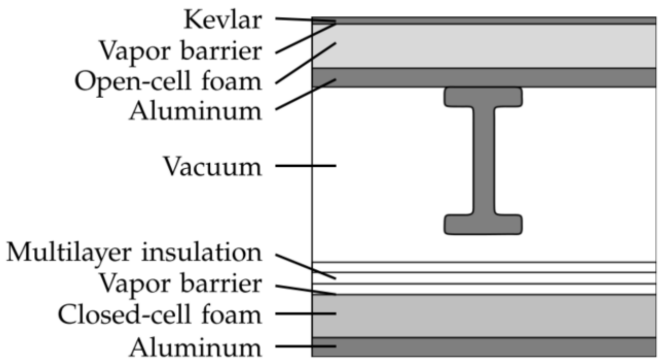


Figure 3.4: LH_2 tank insulation, from [69]

The conventional APU system is replaced by a low temperature PEMFCS that serves also as power source for an electrical taxi system integrated into the landing gear. It is also connected to the engines shafts via a parallel hybrid architecture. In particular, two electric motors provide power during descent to address the hydrogen combustion efficiency drop during off-design power request. A small battery system is also required to support PEMFC power response time. The relevant data about the aforementioned systems is available in the Table 3.7. Further information regarding the design assumptions can be found in [69]. Figure 3.5 gives a high level schematic representation of the relevant aircraft system architecture. Table 3.8 helps to visualize the main differences between the TP-MHEP configuration and the D250-TF configuration.

Table 3.7: TP-MHEP main systems information

System	**Parameter**	**Unit**	**Value**
PEMFCS	Max. total net power	kW	1,360
Battery system	Total capacity	kWh	60
LH_2 tanks incl. subsystems	Total mass	kg	3,500
Engine	Thrust	kN	119

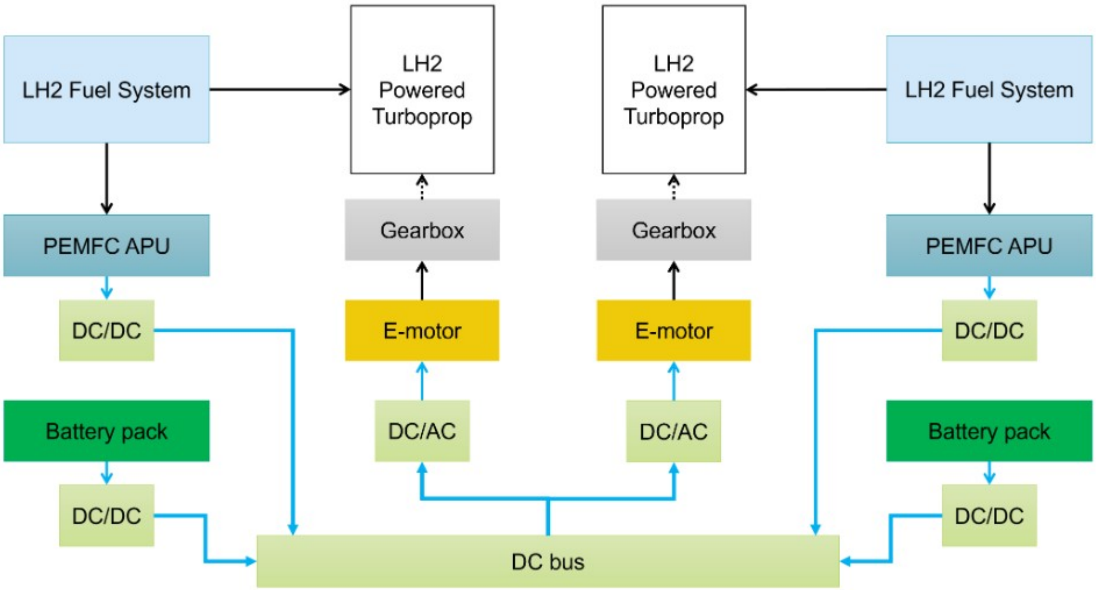


Figure 3.5: TP-MHEP systems schematics. Black arrows depict mechanical connections, blue arrows depict electrical connections

Table 3.8: TP-MHEP aircraft characteristics confronted with the D250-TF

Parameter	**D250-TF**	**TP-MHEP**
Fuel System	Conventional kerosene storage and distribution system	LH_2 storage and distribution system
Auxiliary Power	Conventional APU	PEMFCS APU
Main Engine	2 × kerosene powered High Bypass Turbofan	2 × LH_2 powered Turboprop paralleled with electric motors

3.3.3 TF-MHEP

The Turbofan Mild-Hybrid Electric Propulsion (TF-MHEP) is the last reference aircraft considered in this thesis. The design shares the same architecture characteristics as the TP-MHEP configuration, with the exception of featuring two hydrogen fueled high bypass turbofan engines. As shown in Figure 3.6 the LH_2 tank is positioned in the same location.

Figure 3.6: TF-MHEP aircraft representation

Figure 3.7 presents the drive train schematics together with a simplified representation of the relevant aircraft systems. The individual systems are not discussed in detail in this section, as the considerations previously presented for the TP-MHEP configuration remain applicable to the TF-MHEP aircraft. The main characteristics of the aircraft system can be found in Table 3.9.

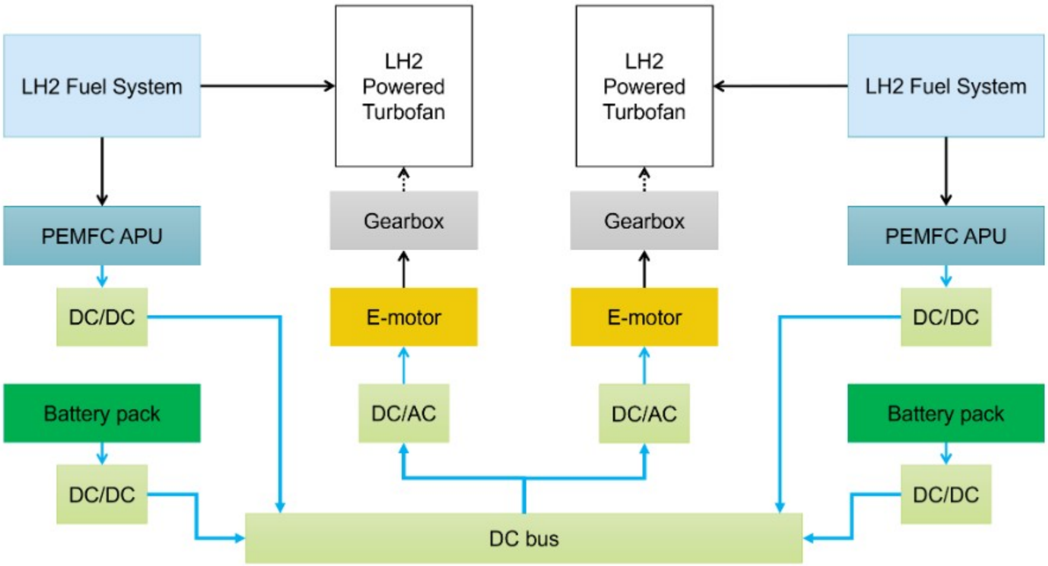


Figure 3.7: TF-MHEP systems schematics. Black arrows depict mechanical connections, blue arrows depict electrical connections

Table 3.9: TF-MHEP main systems information

System	**Parameter**	**Unit**	**Value**
PEMFCS	Max. total net power	kW	1,820
Battery system	Total capacity	kWh	60
LH_2 tanks incl. subsystems	Total mass	kg	4,165
Engine	Thrust	kN	125

Lastly, Table 3.10 helps to visualize the main differences between the TF-MHEP configuration and the D250-TF configuration. The conventional kerosene-based fuel system is replaced by an LH_2 storage and distribution architecture, while the conventional APU is substituted by a PEMFC APU. With regard to the hybrid propulsion architecture, similarly to the TP-MHEP configuration, hybridization is limited to off-design power requests, with the PEMFCS providing propulsive power during descent.

Table 3.10: TF-MHEP aircraft characteristics confronted with the D250-TF

Parameter	**D250-TF**	**TF-MHEP**
Fuel System	Conventional kerosene storage and distribution system	LH_2 storage and distribution system
Auxiliary Power	Conventional APU	PEMFC APU
Main Engine	2 × kerosene powered High Bypass Turbofan	2 × LH_2 powered Turbofan paralleled with electric motors

Chapter 4

Database Generation

This chapter presents the methodology used to estimate the maintenance inputs required over the operational life of the reference aircraft concepts that are introduced in Chapter 3. Section 4.1 outlines the methodology, along with a description of the discrete simulation tool used to model the maintenance activities. Section 4.2 outlines the approach used to define the baseline maintenance for the D250-TF aircraft. Then, Section 4.3 describes the methods used to model the maintenance inputs changes, compared to the reference aircraft. The remainder of the chapter shows the results of the maintenance cost analysis over the operational life for all aircraft configurations.

4.1 Methodology

For each reference aircraft, a dedicated maintenance plan is developed using data from Aircraft Commerce, a specialized industry magazine reporting empirical cost figures derived from interviews with maintenance experts. This source has been adopted in previous studies [50][83][58][69][73], supporting the reliability of the data used.

4.1.1 Maintenance Program Definition

The overall methodology follows the approach proposed by Ramm et al. [69]. First, the maintenance program for the D250-TF configuration is established. Then it is used as the baseline for estimating the maintenance cost figures for the rest of the concepts. Only the relevant technical differences are considered when assessing the required maintenance inputs of the latter.

To quantify these differences, the analysis begins by determining which of the maintenance activities required for the D250-TF are not applicable to the other concepts. This is carried out through a document-based review of the A320 MPD [4] to identify tasks that can be removed, as described in Section 4.3.1. Subsequently, additional maintenance tasks specific to the configurations are incorporated using the methodology outlined in Section 4.3.2. These tasks arise from an MSG-3 analysis conducted by DLR to assess the new powerplant components. The outcome is a separate maintenance plan for each reference aircraft, which is then used as input to a discrete-event simulation tool to estimate the maintenance costs over the aircrafts operational life. Figure 4.1 provides a visual overview of the workflow described above.

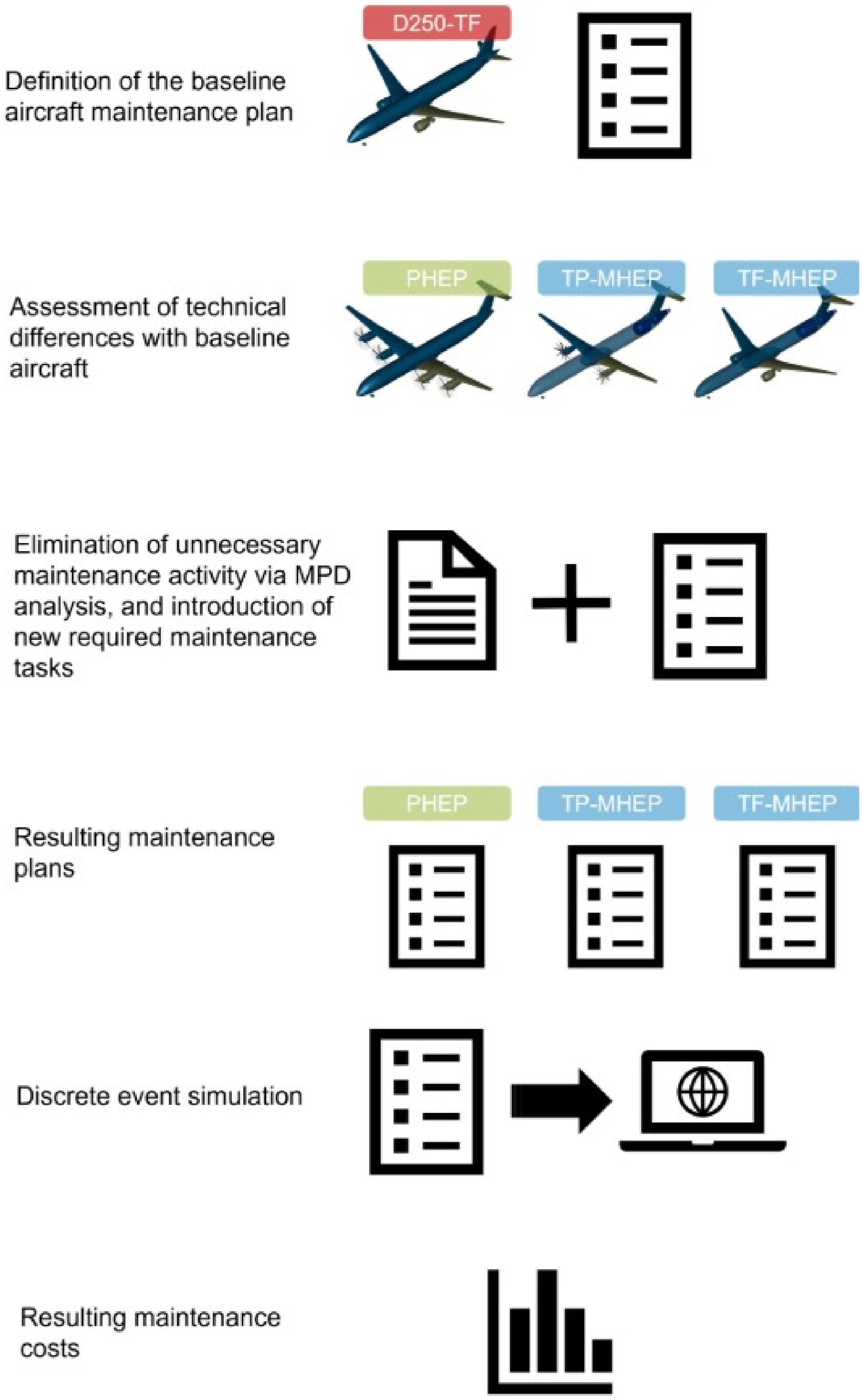


Figure 4.1: Database creation workflow

4.1.2 LYFE^2

LYFE^2 is a Python-based discrete-event simulation tool designed to model the life cycle of an aircraft, enabling economic and environmental analyses. For the purposes of this thesis, only the relevant features of the framework are presented. A more comprehensive description of the framework is provided by Pohya et al. [65]. Also, it should be noted that the framework remains under active development.

Operations

LYFE^2 generates flight events following a predefined flight plan based on an expected route network. For each flight, the plan contains information on the origin and destination airports, flight duration, taxi-in and taxi-out times, and turnaround times. Furthermore, it includes energy consumption parameters, such as fuel burn and, in the case of hybrid-electric aircraft, the fraction of shaft energy delivered by the battery system. Figure 4.2 represents an excerpt of the flight plan required by LYFE^2 as input.

The four aircraft configurations are evaluated using the same flight schedule. Apart from the differences in energy consumption, the only variation concerns the flight time. Thus, any differences in aircraft utilization are due only to the different average cruise speeds of the analyzed configurations. LYFE^2 combines aircraft operational data with airport capacity constraints to simulate the sequence of flights. All data required is obtained from DLR internal analyses. The result is a detailed flight history, including the associated energy consumption data.

Departure/Arrival Airport	Average Flight Distance (km)	Flight Time (hh:mm)	Kerosene Fuel Burn (kg)
VIE_DUB	1792.1	02:19	4806.021

Figure 4.2: Excerpt of flight plan data required as input by LYFE^2

Maintenance Activity

The maintenance events are generated following user-defined inputs. It is possible to specify maintenance activities cost, along with threshold intervals, expressed in FHs, FCs, or Days (DY). If multiple interval conditions are provided, the maintenance event is triggered by whichever threshold is reached first, based on the flight activity simulated by LYFE^2. Users can also determine whether an event occurs once or on a recurring basis.

For each maintenance event, the associated cost is determined either by assigning a fixed cost value or by defining the material and labor cost components. Labor costs are calculated based on the required MH and the associated labor rates. In addition to the maintenance intervals and required effort, it is necessary to define the downtime associated with each maintenance event. Furthermore, the fiscal year associated with the cost data must be specified. This allows LYFE^2 to account for inflation and adjust all cost figures to the year in which the maintenance check takes place. An excerpt of the relevant information contained within the maintenance plan is provided in Figure 4.3.

Check name	Downtime (FH)	Interval (FH)	Interval (FC)	Interval (DY)	Material cost	MH	Labor rate	Fixed cost	Fiscal Year
C1	116	6000	4500	540	$58.170	2908,5	$ 60	$ -	2011
C2	190	12000	9000	1080	$95.130	4756,5	$ 60	$ -	2011
C3	176	18000	13500	1620	$88.148	4407,3	$ 60	$ -	2011

Figure 4.3: Excerpt of maintenance plan

4.2 Reference Aircraft Maintenance Plan

As explained in Section 3.2, the D250-TF configuration is compatible with an A321neo. Therefore, it is assumed that the same maintenance inputs are needed. Since no specific maintenance data is available for the A321neo, the line maintenance costs, and the base maintenance cost inputs are estimated by applying a 5% increase relative to the corresponding values for the A320, in accordance with estimates provided by Aircraft Commerce [21]. To estimate maintenance downtime, the values proposed by Ramm et al. [69] are adopted. More specifically, the downtime associated with line and base maintenance activities is calculated as a function of the required maintenance workload, using the same downtime-to-MH ratio.

4.2.1 Line Maintenance

Line maintenance activities include TR checks, PF checks, daily checks, weekly checks, and A-checks. Table 4.1 contains the relevant line maintenance program information. The expenses include the non-routine activity, estimated using the average non-routine ratios. The A-checks data is sourced from [20], the non-routine ratios and the information related to the rest of the checks come from [21].

An A-check cycle is composed of four A-checks with intervals of 750 FH, 750 FC, or 4 MO. However most operators complete an A-check cycle every 2000 FH on average [20], therefore this thesis considers an interval of 500 FH, 750 FC, or 4 MO, whichever is reached first. The cost associated with each A-check is derived from the cost of an A-check cycle, and is assumed to be evenly distributed among the four individual checks. Labour cost is calculated using a labour rate of $ 70 per MH.

Table 4.1: D250-TF line maintenance program

Check	Interval	MH	Materials [$2006]	NR ratio
Transit	1 FC	3.2	7.35	–
Pre-flight	1 DY	0.5	7.35	–
Daily	36 h	4.5	525	–
Weekly	7 DY	11.5	735	0.5
A1	500 FH / 750 FC / 4 MO	420	9845	0.1
A2	1000 FH / 1500 FC / 8 MO	420	9845	0.1
A3	1500 FH / 2250 FC / 12 MO	420	9845	0.1
A4	2000 FH / 3000 FC / 16 MO	420	9845	0.1

4.2.2 Base Maintenance

Base maintenance activities comprise both C-checks and D-checks. A complete cycle is composed of eight C-checks with intervals of 6000 FH, 4500 FC, or 20 MO, while the structural checks have intervals of 72 MO, and 144 MO [20]. Considering the 20 MO C-check interval the first structural check would occur just 8 month before the C4 check (80 MO), as a consequence most airlines use a calendar interval of 18 MO to combine the C-checks and the structural checks [21][20].

It is important to note that the base maintenance checks contents heavily change during the aircraft life. This is due to MPD modifications, and non-routine activity increase. The A320 MPD is revised every six to eight months on average [27]: utilisation based intervals are usually escalated, and new tasks are added. Non-routine ratios increase due to aging, but they are also influenced by the check workscope [20]. Therefore, Aircraft Commerce [20] provides data that accounts for two subsequent base check cycles using two different MPD sources. As the thesis scope does not include modelling the MPD's evolution, the access MHs and routine tasks MHs are kept constant in both base check cycles, using the second base check data. The estimated non-routine ratios over the two cycles are still retained, as it is not possible to isolate the impact of aircraft age and check workscope on these ratios. The base maintenance information is summarized in the Table 4.2.

Table 4.2: D250-TF base maintenance program and non-routine ratios

Check	Interval	MH	Materials [$2011]	NR ratio
C1	6,000 FH / 4,500 FC / 18 MO	2,908	58,170	0.20
C2	12,000 FH / 9,000 FC / 36 MO	4,756	95,130	0.30
C3	18,000 FH / 13,500 FC / 54 MO	4,407	88,147	0.55
C4	24,000 FH / 18,000 FC / 72 MO	13,839	304,500	0.55
C5	30,000 FH / 22,500 FC / 90 MO	3,412	68,250	0.60
C6	36,000 FH / 27,000 FC / 108 MO	5,491	109,830	0.65
C7	42,000 FH / 31,500 FC / 126 MO	4,698	93,975	0.70
C8	48,000 FH / 36,000 FC / 144 MO	22,732	577,500	0.75
C9	54,000 FH / 40,500 FC / 162 MO	3,538	70,770	0.70
C10	60,000 FH / 45,000 FC / 180 MO	5,701	114,030	0.75
C11	66,000 FH / 49,500 FC / 198 MO	4,893	97,860	0.80
C12	72,000 FH / 54,000 FC / 216 MO	15,529	378,000	0.90
C13	78,000 FH / 58,500 FC / 234 MO	3,664	73,290	0.80
C14	84,000 FH / 63,000 FC / 252 MO	5,806	116,130	0.80
C15	90,000 FH / 67,500 FC / 270 MO	4,990	99,802	0.85
C16	96,000 FH / 72,000 FC / 288 MO	23,835	735,000	0.85

4.2.3 Heavy Components

The remaining D250-TF maintenance activities include landing gear maintenance, tyre maintenance, brake and thrust reverser maintenance, as well as APU SVs and ESVs. The maintenance information is presented in Table 4.3. For all maintenance activities except APU SVs and ESVs, the maintenance intervals and associated costs are derived from Aircraft Commerce [21]. Unlike line and base maintenance, no information is available regarding the scaling of these costs between the A320 and the A321. Therefore, the total maintenance cost values reported for the A320 are retained.

Regarding the APU, the shop visit (SV) cost is assumed to be representative of the APS3200, one of the APUs employed on the A321neo [5]. An average removal interval of 6000 APU operating hours (APUH) is adopted, with an APU SV cost of $350,000 [22]. To estimate APU utilization, a turnaround time of 45 minutes and a single-cycle APU event are assumed [59], i.e. the APU operates for 45 minutes during each FC. Thus, an average removal interval of 6000 APUH is equivalent to 8000 FC.

With regards to the engine, the A321neo can be equipped with the CFM LEAP-1A engine, or the PW 1100 G engine [5]. However, due to their relatively recent EIS these engines lack empirical Shop Visit Cost (SVC) data. Therefore the ESV costs are assessed considering the data from the CFM56-5B3, used by the A321ceo [5]. The ESV information is sourced from [26]. The average A321 CFM56-5B3 follows an ESV cycle composed of three SV. The corresponding intervals are 15,000 FC, 25,000 FC, and 35,000 FC, respectively. The first and third intervals are primarily driven by EGT margin deterioration, whereas the second interval is driven by LLPs. The average maintenance reserve, which also accounts for unscheduled removals, is around $200/FH. In order to obtain the FC reserve, an average 1.8 FH/FC ratio as reported by Aircraft Commerce [21] is applied.

Table 4.3: D250-TF heavy components maintenance program

Check group	Interval	Total cost	Fiscal info
Main Tyre Retread	300 FC	2,400	$ 2006
Main Tyre Replacement	1,500 FC	6,400	$ 2006
Nose Tyre Retread	200 FC	600	$ 2006
Nose Tyre Replacement	1,000 FC	800	$ 2006
Brakes	2100 FC	132,000	$ 2006
Landing Gear	28,000 FH/ 18,350 FC	340,000	$ 2006
Main Tyre Inspection	300 FC	1,800	$ 2006
Nose Tyre Inspection	1500 FC	500	$ 2006
Thrust reversers	12000 FC	340,000	$ 2006
APU SV	8000 FC	350,000	$ 2017
ESV 1	15,000 FC	10,800,000	$ 2014
ESV 2	25,000 FC	7,200,000	$ 2014
ESV 3	35,000 FC	7,200,000	$ 2014

4.3 Maintenance Differences Assessment

A two steps document based approach is used to estimate the differences in maintenance costs between the reference aircraft configuration, and the novel concepts. The first step relies on a an analysis of the A320 MPD [4], and the ATR72 MPD [8]. By examining the scheduled maintenance tasks it is possible to identify expected variations in maintenance efforts, and derive the associated costs. The second step involves the integration of new maintenance tasks that were internally developed by DLR via an MSG-3 analysis.

4.3.1 MPD Analysis

As described in section 2.1 the MPD represents the basis for building a maintenance program. In this analysis the A320 MPD [4], and the ATR72 MPD [8] are exploited to obtain information about maintenance tasks that are relevant for the baseline D250-TF aircraft, but are not required in the rest of the configurations. Specifically, the ATR72 MPD is used because two of the four analyzed configurations are based on turboprop propulsion systems rather than turbofan. Therefore some tasks from the A320 MPD are not eliminated but rather substituted with maintenance activity extracted from the ATR72 MPD.

A320 MPD

Each maintenance task contained in the A320 MPD is identified by a number. Figure 4.4 represents an excerpt of the A320 MPD, and is used as reference for the following explanation. The first two digits of the task number identify the ATA chapter associated with the component of which the task refer to, easying the task selection procedure. For instance, task no. 281100-01-02 introduced in the Figure 4.4 refers to the ATA Chapter 28 (fuel system). As introduced in Section 2.2, the analysis of the differences between the reference concept and the novel concepts focuses on the ATA chapters associated with the fuel system (ATA 28), the auxiliary power (ATA 49), and the powerplant system (ATA 70-79). The task code column contains the task category code, e.g. SVC. The 100% interval column states the maximum interval that can occur between each consecutive task execution, in this case the maximum interval is 10 DY. The applicability column states if the tasks is applicable to all A320 Family aircraft, or if there are some exceptions. Specifically, task no. 281100-01-02 is relevant for all A320 family aircraft. The rest of the columns give useful information about the labor efforts required for preparation, access, and task execution. For instance, the tasks total routine labor effort is obtained by multiplying the tasks MHs value with the number of men required.

TASK NUMBER	DESCRIPTION	TASK CODE	100% INTERVAL	MEN	TASKM.H.	ACCESSM.H.	PREP.M.H.	APPLICABILITY
281100-01-2	TANKS	SVC	10 DY	1	0.10	0.04		ALL
			NOTE	1	0.10			
	DRAIN WATER CONTENT			1	0.10			
	NOTE: INTERVAL: - DEPENDING ON OPERATING ENVIRONMENT AND OPERATORS EXPERIENCE, A LESS FREQUENT OR MORE FREQUENT INITIAL INTERVAL MAY BE USED.							

Figure 4.4: A320 MPD excerpt

ATR72 MPD

The information extracted by the ATR72 MPD is comparable with the content of the A320 MPD, as can be noticed in the Figure 4.5. For instance, the column identified as applicability in the A320 MPD is defined as effectivity in the ATR72 MPD. In the ATR72 MPD, the tasks associated ATA chapter cannot be identified by a task number. However, the MPD is organized in various sub-sections, and each of those is related to a different ATA chapter.

TASK REFERENCE (Source Document)	DESCRIPTION	THRESHOLD INTERVAL SAMPLE	M	M.H	EFFECTIVITY
122276-LUB-10000-1 (LUR : I=18MO) (MRBR : 760000-07)	ENGINE PUSH-PULL CABLES LUBRICATION OF CABLES, QUADRANTS, PULLEYS IN ENGINE COMPARTMENT (POWER AND CONDITION)	I: 4 A	1 a	0.20 0.54	ALL

Figure 4.5: ATR72 MPD excerpt

The main difference between the two MPDs concerns the definition of the tasks interval thresholds. In the A320 MPD these values are expressed through operational units, such as FH or FC, or through calendar units (DY, MO, YE). Conversely the ATR72 MPD frequently defines maintenance intervals through letter-coded checks, as shown is the Figure 4.5. Namely Line Checks, A-Checks, and C-Checks. However, the ATR72 MPD also provides the corresponding equivalence between the coded intervals. In particular the Line Checks are equivalent to 2 DY, A-checks correspond to 750 FH, and C-checks correspond to 8,000 FH. Therefore, the intervals defined in the A320 MPD and the ATR72 MPD can be consistently compared.

Task Allocation

When a maintenance task is considered unnecessary for one of the novel configurations, the associated maintenance cost is removed by allocating the task within the reference aircraft maintenance plan presented in Section 4.2. The allocation procedure is based on the maintenance intervals defined in the MPD.

In cases where a task is associated with multiple intervals, the allocation is based on the interval that is most likely to be reached first according to the aircraft utilization defined by Aircraft Commerce [21]. For instance, task no. 282100-01-1, *Operational check of wing tank pump pressure sense line check valves* presents two intervals: 252 MO or 36,000 FH. Based on the average aircraft utilization reported by Aircraft Commerce [21], i.e. 2,800 FH/YE and 1,850 FC/YE, the interval of 252 MO corresponds to approximately 58,000 FH. Therefore, the threshold most likely to be reached first is the 36,000 FH interval. This interval corresponds to the FH interval associated with the C6 check. Consequently, the task is allocated to the C6 and the C12 checks within the maintenance plan.

In general, the allocation is performed by associating the task with the maintenance check whose interval immediately precedes the tasks threshold. For instance task no. 491600-A1-1, *Detailed inspection of APU air intake diffuser elbow seals and felt metal* presents a 40 MO interval. Since the C3 check corresponds to a calendar interval of 54 MO, which exceeds the task's threshold, the task is instead allocated to the C2 check, characterized by a calendar interval of 36 MO. As a result, all the maintenance inputs associated with the task need to be deducted every two C-checks.

Task Input Estimation

The MPDs provide direct information regarding labor costs, since they include the MH associated with task preparation, access and execution. However, the aircraft concepts analyzed within this thesis are defined at a high level, and therefore using the same access estimates provided in the MPDs would be inaccurate. Furthermore, several tasks do not include information about preparation activity.

Therefore, only the actual task MH are considered in the estimation of the labor input associated with a task no longer included in the maintenance plans. It should be noted that the MHs values from the various MPDs are merely an indication of labor efforts, and they should always be multiplied by an appropriate factor that accounts for real maintenance operations, i.e. a labor efficiency coefficient [8]. Aircraft Commerce [27] estimates an average labor efficiency coefficient of 2.5 for the A320, but this value can reach 4.0. Therefore, this analysis applies a 3.0 coefficient. Also, it must be considered that the MH values reported in the MPDs represent only the routine maintenance input. Consequently, before subtracting the labor effort, the non-routine factors associated with the corresponding maintenance checks must also be taken into account.

The estimation of the material cost to be removed is performed by assuming the material cost to be proportional to the eliminated MH value. More precisely, the average material cost per MH of the maintenance checks in which the task is allocated is used. This assumption is consistent with the estimation methodology adopted by Aircraft Commerce [21][20], on which the reference aircraft maintenance plan is based. A visual representation of the methodology followed to allocate the tasks no longer necessary, and to estimate the associated maintenance inputs, as explained above, is available in the Figure 4.6.

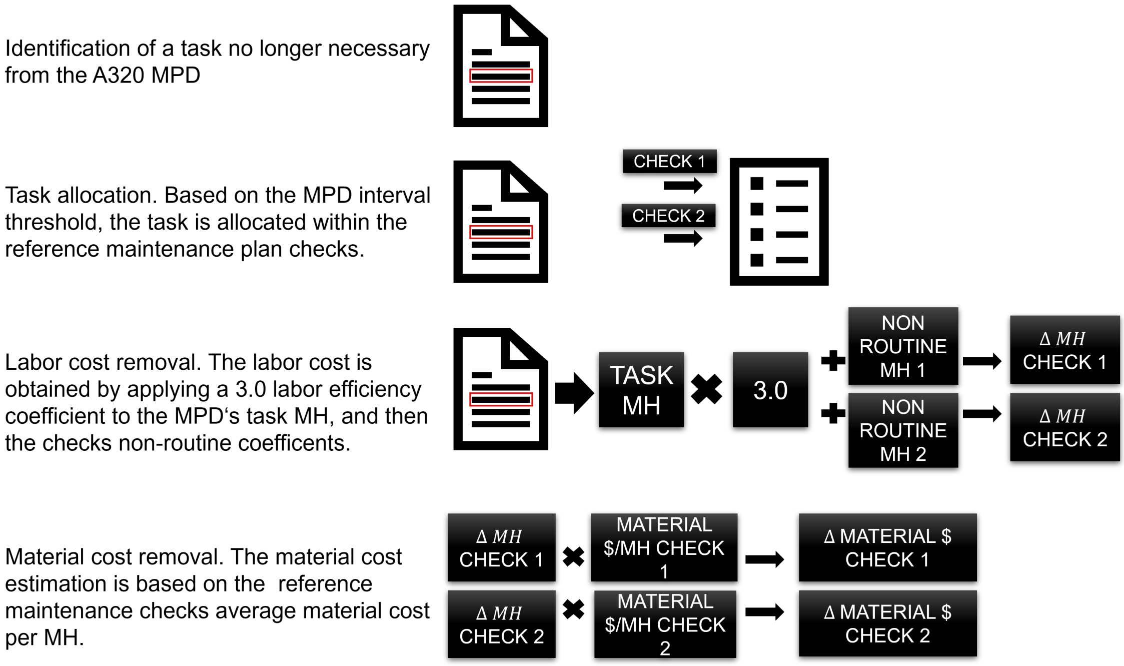


Figure 4.6: Workflow followed to deduct the maintenance cost of tasks no longer necessary

When a task needs to be replaced by a corresponding maintenance activity extracted from the ATR72 MPD, the estimation of the new maintenance input is performed following the same methodology described above. The only difference is that, unlike the removal of a maintenance task, the resulting variations in maintenance costs are positive.

4.3.2 New Components Tasks

The innovative aircraft concepts analyzed in this thesis include several subsystems that are not present in the reference aircraft configuration. These include electric drive trains, electric energy storage systems, hydrogen storage systems, and PEMFCS. Therefore, the additional maintenance activity associated with these new components must be considered in the maintenance cost estimation. To estimate the additional maintenance costs generated by the aforementioned subsystems, this thesis relies on an internally conducted MSG-3 analysis performed within DLR. The outcome of this analysis is a list of scheduled maintenance tasks associated with the newly introduced components. Table 4.4 represents an excerpt of the new scheduled tasks, the complete list is available in the Appendix.

Table 4.4: Excerpt of tasks required by the new configurations.

Component	**Task code**	**Task description**	**Applicability**
Gearbox	SRV	Checking oil level of gearbox	All
Gearbox	SDI	Special detailed inspection of gearbox (Endoscope)	All
Gearbox	SRV	Lubrication of gearbox	All
LH_2 tank	SDI	Special detailed inspection of the inner tank to detect damages	TP-MHEP, TF-MHEP
LH_2 tank	FNC	Functional check of the tank isolation	TP-MHEP, TF-MHEP
LH_2 tank	GVI	General visual inspection of the outer tank to detect damages and leakages	TP-MHEP, TF-MHEP

MH and Interval Definition

For each task, a threshold interval and an estimate of the required task MH are defined obtaining a structure similar to that adopted in the A320 MPD. The development of the intervals and MH database was started within DLR, while the completion and integration into the present maintenance cost assessment were carried out as part of this thesis work.

For the majority of the tasks, the information regarding the MH requirements and threshold intervals is derived from the A320 and ATR72 MPDs by considering maintenance tasks characterized by a comparable scope. For instance, the task *Checking oil level of gearbox* has a MH effort, and a repetition interval, based on the A320 MPD values of task no. 274451-02-1, *Check oil level of THS actuator gearbox*. For the tasks associated with the PEMFCS and the hydrogen storage and distribution system, the interval and MH information is obtained from Meissner et al. [50]. With regards to the battery system and the PEMFCS, two DIS-type tasks are defined. These tasks correspond to the replacement of the batteries and the PEMFCS stacks at the end of their operational life. The EOL condition of those components is due to the progressive degradation of their performance, which eventually prevents the aircraft from completing the mission. Therefore the maintenance interval adopted for these tasks is based on the EOL values defined during the design of the analysed configurations. For the PEMFCS stacks, the EOL is defined as 10,000 FH. For the battery cells, the EOL is equal to 3,000 battery cycles. Since the aircraft design assumes a final SOC of 20% at the end of the mission, a conservative assumption is adopted by considering 3,000 battery cycles equivalent to 3,000 FC. Lastly, for a limited number of tasks, no suitable references regarding the threshold interval could be identified. Consequently, these intervals are estimated exploiting a DLR internally developed methodology. Within these tasks the repetition interval is based on the probability of failure of the components, estimated through the average component's failure rate (λ) defined as the ratio between the FHs, and the number of failures of the component occurred during the latter interval [83] Equation 4.1:

$$\lambda = \frac{FH_t}{N_f} \tag{4.1}$$

where FH_t is the operative time expressed in FH, and N_f is the number of failures. If λ is assumed constant, the Mean Time Between Failures (MTBF) of the component can be calculated as Equation 4.2:

$$MTBF = \frac{1}{\lambda}, \quad \lambda(t) = const \tag{4.2}$$

and the probability of failure ($P_f(t)$) follows the exponential distribution Equation 4.3:

$$P_f(t) = 1 - e^{-\lambda t}, \quad t \geq 0 \tag{4.3}$$

therefore the probability of success (P_s), i.e. not having a failure can be expressed as in the Equation 4.4:

$$P_s(t) = 1 - P_f(t) = e^{-\lambda t}, \quad t \geq 0 \tag{4.4}$$

consequently it is possible to derive the time interval in which the component has a certain probability of success Equation 4.5:

$$t = -ln(P_s) \cdot MTBF \tag{4.5}$$

This value is chosen as task interval, considering different probability of success values depending on the task code, as showed in Table 4.5. The failure rate is calculated as the arithmetic mean of a failure rate collection. As some of the values are from Airbus World, and their value is confidential, the aforementioned collection is omitted, and only the resulting intervals are provided in the Appendix.

Table 4.5: Probabilities of success used to determine the tasks intervals

Task code	**Probability of success**
LUB	0.95
SRV	0.95
OPC	0.98
VCK	0.98
FNC	0.94
GVI	0.93
DET	0.94
SDI	0.93
RST	0.91
DIS	0.85

Labor Effort Estimation

Once the database containing the task MH and the maintenance intervals has been defined, the allocation of the corresponding labor effort within the reference maintenance plan becomes straightforward. The allocation procedure follows the same methodology described in Section 4.3.1, with the difference that the resulting MH variation is positive. Also in this case, a labor effort coefficient of 3.0 is applied when the MH information is derived from the A320 MPD, or the ATR72 MPD.

Material Cost Estimation

In the case of the new concept maintenance tasks, the estimation of the material maintenance cost is performed using two different approaches.

For the majority of the components, and their relative tasks, the material cost estimation is carried out following the methodology described in Section 4.3.1. Accordingly, the material cost is assumed to be proportional to the MH introduced, and it depends on the average material cost per MH associated with the maintenance checks in which the tasks are allocated. However, this approach may be inaccurate when evaluating the influence of newly introduced components characterized by particularly high replacement cost. For instance, LH_2 tanks do not require a significant MH effort, but the associated maintenance material cost is high if a tank replacement is required, as in the event of a failure. Therefore, the methodology described in Section 4.3.1 would likely underestimate the actual maintenance material cost associated with such components. Consequently, to provide a more accurate estimation of the material cost associated with the components presented in the Table 4.6, an additional assessment is performed.

Table 4.6: List of components for which the material maintenance cost estimation does not follow the proportional MH-based approach. The dashes indicate that a component is not present on board of the aircraft

Component	**TP-PHEP**	**TP-MHEP**	**TF-MHEP**
Propeller blades and hub	•	•	–
Drivetrain gearboxes	•	•	•
E-motors	•	•	•
Inverters	•	•	•
Batteries	•	•	•
LH_2 tanks	–	•	•
PEMFCS stacks	–	•	•

The following assessment of the material cost associated with these components is largely based on the methodology proposed by Wolf et al. [83]. As overhaul and restoration tasks are the main drivers of material cost in maintenance [83], the routine material maintenance cost is assumed to be driven by DIS and RST tasks. Not all components listed in Table 4.6 have scheduled discard, or restoration tasks. The list of the scheduled discards, and restorations is available in the Table 4.7.

Table 4.7: Scheduled RST and DIS tasks for the components shown in Table 4.6

Task	**Task code**	**Applicability**
Restoration/Overhaul of the propeller blades and hub	RST	PHEP, TF-MHEP
In-Shop restoration of motor unit and calibration of motor sensors	RST	all
Replacement of battery pack with new unit and calibration of sensors	DIS	all
Exchange of PEMFCS Stacks after EOL	DIS	TP-MHEP, TF-MHEP

A further distinction is made between DIS, and RST: if the task is a DIS it is assumed that the cost ($C_{\mathrm{r},DIS}$) is equal to the spare part cost of the component (C_{spare}) multiplied by the number of components installed (N_o) as shown in Equation 4.6. If a task is a RST ($C_{\mathrm{r},RST}$) the spare part cost is also multiplied by a 21.6% repair-replacement ratio ($SVCR$) that models the average material Shop Visit Cost (SVC) [83], as shown in Equation 4.7.

$$C_{\mathrm{r},DIS} = C_{\mathrm{spare}} \cdot N_o \tag{4.6}$$

$$C_{\mathrm{r},RST} = C_{\mathrm{spare}} \cdot N_o \cdot SVCR \tag{4.7}$$

The resulting costs are then allocated in the various checks based on the intervals, in the same way as the labor efforts. The majority of component spare part prices presented in Table 4.8 are obtained from Wolf et al. [83], as an optimistic cost forecast based on the automotive industry for the year 2050. For the LH_2 tank the price is from Silberhorn et al. [72], as assumed for the cryogenic tank design for an aircraft with a 2050 EIS. The PEMFCS stack cost is one of the Department of Energy (DOE) ultimate technical targets for fuel cell systems and stacks for transportation applications [32].

The RST task associated with the propeller blades and hub represents an exception, as its material maintenance cost is evaluated using the average repair and overhaul costs of the blades and hub from Aircraft Commerce [24]. The cost is then allocated into the maintenance plan using the average hub repair interval of 10,000 FH from Aircraft Commerce [24], which also account for non-routine overhauls.

Table 4.8: Spare parts prices

Component	**Unit**	**Spare part price**	**Fiscal year**
Drivetrain gearboxes	\$/kW	20.11	2023
E-motors	$\$/kW$	20.11	2023
Inverters	$\$/kW$	51.72	2023
Batteries	$\$/kWh$	64.18	2023
LH_2 tanks	Eur/kg	1,150	2019
PEMFCS stacks	$\$/kW_{net}$	15	2015

The non-routine expenses are assumed to be driven by failure related repair or replacement activity, accounting for failures due to physical degradation. These expenses are not allocated into the various baseline maintenance checks. Instead, an average material cost per FH is obtained. All non-routine expenses (C_{nr}) take into consideration the repair-replacement ratio as the RST tasks Equation 4.8. The only exception is represented by the battery, for which a replacement is assumed to always take place after a failure, Equation 4.9.

$$C_{\text{nr}} = \frac{C_{\text{spare}} \cdot N_o \cdot SVCR}{MTBUR} \tag{4.8}$$

$$C_{\text{nr,battery}} = \frac{C_{\text{spare}} \cdot N_o}{MTBUR} \tag{4.9}$$

Where $MTBUR$ is the Mean Time Between Unscheduled Removal (MTBUR). In Wolf et al. [83] the MTBUR values are estimated as a function of the MTBF through the No Fault Found (NFF) rate, according to Equation 4.10.

$$MTBUR = MTBF \cdot (1 - NFF) \; ; \; NFF = 0.15 \tag{4.10}$$

The NFF rate represents the percentage of component removals that occur even though no actual fault is present. Consistently with the assumptions adopted by [83], a constant NFF value of 15% is assumed for all the analysed components. The MTBF values used for the assessment are presented in the Table 4.9.

Table 4.9: MTBF values used for the non-routine material cost estimation

Component	**MTBF**
Drivetrain gearboxes	453,557
E-motors	89,300
Inverters	177,864
Batteries	153,051
LH_2 tanks	175,200
PEMFCS stacks	39,686

4.4 Novel Concepts Maintenance Plans

The previous Section 4.3 described the methodology adopted to estimate and integrate the maintenance differences between the reference aircraft and the analysed novel concepts. Growing from this premise, the present Section discusses the specific maintenance differences identified for each novel concept and the corresponding assumptions adopted in their assessment. Resulting maintenance plans provide the basis for the estimation of the maintenance costs associated with each concept.

4.4.1 TP-PHEP

For the different sections of the maintenance plan, the assumptions adopted for the TP-PHEP configuration relative to the reference D250-TF configuration are presented.

Line and Base Maintenance

For the TP-PHEP configuration, the maintenance tasks associated with the APU (ATA 49) remain necessary, as do the tasks related to the fuel system (ATA 28). However, since the TP-PHEP requires a lower kerosene quantity than the reference aircraft, its fuel system is expected to be characterized by a reduced size. Therefore, it is assumed that the labor effort associated with the fuel system remains the same, and no MH reduction is considered. This is considered true based on the fact that the overall system complexity and the maintenance activities required are comparable to those of the reference configuration. Conversely, a reduction in material costs proportional to the kerosene mass is assumed. The resulting material cost reduction is first estimated according to the methodology described in Section 4.3.1, and is then multiplied by the factor shown in Formula 4.11.

$$1 - \frac{m_{k,TP-PHEP}}{m_{k,A321neo}} \tag{4.11}$$

where $m_{k,TP-PHEP}$ is the maximum kerosene mass of the TP-PHEP configuration, and $m_{m_{k,A321neo}}$ is the maximum kerosene mass of the A321neo, obtained from [5]. The A321neo kerosene mass is selected because this aircraft served as the basis for defining the reference maintenance plan of the D250-TF reference aircraft. The resulting material cost difference for each maintenance check relative to the reference maintenance plan is reported in Table 4.10.

Table 4.10: TP-PHEP maintenance material cost differences due to the reduced fuel storage system with respect to the baseline maintenance plan

Check	**Δ Materials**	**Unit**
Transit	0	$ 2006
Pre flight	0	$ 2006
Daily	0	$ 2006
Weekly	26.5	$ 2006
A1	14.3	$ 2006
A2	20.3	$ 2006
A3	14.3	$ 2006
A4	20.3	$ 2006
C1	4.4	$ 2011
C2	22.6	$ 2011
C3	5.7	$ 2011
C4	124	$ 2011
C5	8.9	$ 2011
C6	43.9	$ 2011
C7	6.3	$ 2011
C8	2,858	$ 2011
C9	6.3	$ 2011
C10	33.7	$ 2011
C11	6.7	$ 2011
C12	189	$ 2011
C13	6.7	$ 2011
C14	31.3	$ 2011
C15	10.3	$ 2011
C16	3,667	$ 2011

Subsequently, the maintenance plan differences due to the powerplant system differences are considered. Since the TP-PHEP configuration does not employ turbofan engines, but instead incorporates two gas turbines and four propellers, it is assumed that the powerplant maintenance tasks extracted from the A320 MPD are no longer applicable. Therefore, these tasks are removed and replaced by the powerplant-related tasks extracted from the ATR72 MPD. The resulting variation in maintenance cost is reported in Table 4.11.

Table 4.11: TP-PHEP maintenance cost differences due to the different powerplant system with respect to the baseline maintenance plan

Check	Δ MHs	Δ Material cost	Unit
Transit	0	0	$ 2006
Pre flight	0	0	$ 2006
Daily	0	0	$ 2006
Weekly	-2.5	-160.4	$ 2006
A1	1.3	30.9	$ 2006
A2	5.9	139.2	$ 2006
A3	1.3	30.9	$ 2006
A4	-33.9	-793.5	$ 2006
C1	-9.7	-192.96	$ 2011
C2	2.7	53.04	$ 2011
C3	11.1	223.2	$ 2011
C4	4.6	100.3	$ 2011
C5	-13.7	-266.9	$ 2011
C6	28.5	570.2	$ 2011
C7	-13.7	-273.36	$ 2011
C8	56.3	1,429.7	$ 2011
C9	12.2	244.8	$ 2011
C10	3.0	60.9	$ 2011
C11	-14.5	-289.44	$ 2011
C12	34.6	840.8	$ 2011
C13	-14.5	-289.4	$ 2011
C14	31.1	622.1	$ 2011
C15	12.8	255.3	$ 2011
C16	59.5	1,834.7	$ 2011

The maintenance costs associated with the new maintenance tasks required by the novel systems are considered, following the methodology described in Section 4.3.1. The cost differences are reported in Table 4.12. These expenses do not include the material costs derived from the components for which the material cost is not assumed to be proportional to the introduced MH.

Table 4.12: TP-PHEP maintenance cost differences due to the new components

Check	Δ MHs	Δ Material cost	Unit
Transit	0	0	$ 2006
Pre flight	0	0	$ 2006
Daily	0	0	$ 2006
Weekly	0	0	$ 2006
A1	20.8	69.6	$ 2006
A2	23.4	100.5	$ 2006
A3	20.8	69.6	$ 2006
A4	39.1	262.9	$ 2006
C1	190.8	1,138.3	$ 2011
C2	240.4	1,906.3	$ 2011
C3	265.1	1,656.3	$ 2011
C4	286.6	2,521	$ 2011
C5	254.4	1,537	$ 2011
C6	328.1	2,701	$ 2011
C7	271.4	1,653.4	$ 2011
C8	323.6	3,286.3	$ 2011
C9	290.8	1,837	$ 2011
C10	323.6	2,587	$ 2011
C11	286.3	1,729	$ 2011
C12	377.9	3,786.3	$ 2011
C13	286.3	1,729.1	$ 2011
C14	333.9	2,682.7	$ 2011
C15	316.4	1,999	$ 2011
C16	342.1	4,217	$ 2011

Lastly, the routine material cost of the aforementioned components is also included in the maintenance plan. The material costs associated with the restoration/overhaul of the propeller blades and hub, as well as the in-shop restoration of the motor unit, are allocated into the C-checks, totaling $358,616. The costs related to battery pack replacement and sensor calibration are assigned to the A4 checks, on the basis of the FC battery limit, adding $666,149 in this check.

Heavy Components

No differences are considered for the maintenance activities associated with the landing gear and tyres, as the variations are assumed to be negligible with respect to the reference configuration. Likewise, the APU SVs remain necessary for the TP-PHEP configuration, and it is retained without modification relative to the D250-TF aircraft. Conversely, the ESV costs and the thrust reversers maintenance costs associated with the reference turbofan engines are removed and replaced by new ESV costs, corresponding to the PW 127 E/F turboprop engines, which are installed on the ATR72. The average ESV interval, which include non-routine visits is 5,000 FC [24], with an average cost reserve equal to 80 $/FH, excluding the propeller overhaul costs which is already accounted for as it is one of the new tasks derived from the MSG-3 analysis. Based on the FH/FC ratio adopted for the definition of the reference baseline maintenance costs [21], the resulting average fixed cost of each ESV is approximately $ 600,000 per engine. Since the TP-PHEP configuration employs two gas turbines, the total ESV cost is estimated as $ 1,200,000.

Resulting Maintenance Plan

Once the differences with respect to the reference maintenance plan have been adopted, the resulting TP-PHEP maintenance plan is reported in Figure 4.7. This maintenance plan is then used as an input to the LYFE^2 simulation tool, as described in Section 4.1.2. The costs reported are comprehensive of all maintenance costs, and they incorporate both routine and non-routine maintenance activities. The only costs not included are those discussed in the following subsection, as they are assessed separately after the LYFE^2 simulation.

Check	Downtime	Interval (FH)	Interval (FC)	Interval (DY)	Material cost	MH	Labor Rate	Fixed cost	Fiscal Year
Transit	0,55	0	1	0	$ 7	3,2	$ 70	$ -	2006
Pre Flight	1	0	0	1	$ 7	0,5	$ 70	$ -	2006
Daily	1	0	0	1,5	$ 525	4,4	$ 70	$ -	2006
Weekly	2	0	0	7	$ 869	14,1	$ 70	$ -	2006
A1	49,9	500	750	120	$ 9.868	439,5	$ 70	$ -	2011
A2	49,7	1000	1500	240	$ 9.785	437,5	$ 70	$ -	2011
A3	49,9	1500	2250	360	$ 9.868	439,5	$ 70	$ -	2011
A4	56,0	2000	3000	480	$ 677.029	492,9	$ 70	$ -	2011
C1	124,4	6000	4500	540	$ 418.113	3109,0	$ 60	$ -	2011
C2	199,8	12000	9000	1080	$ 455.577	4994,2	$ 60	$ -	2011
C3	186,5	18000	13500	1620	$ 448.191	4661,3	$ 60	$ -	2011
C4	564,8	24000	18000	2160	$ 665.413	14121,1	$ 60	$ -	2011
C5	147,2	30000	22500	2700	$ 428.662	3680,3	$ 60	$ -	2011
C6	231,6	36000	27000	3240	$ 470.534	5791,1	$ 60	$ -	2011
C7	199,4	42000	31500	3780	$ 454.512	4983,8	$ 60	$ -	2011
C8	920,0	48000	36000	4320	$ 935.115	22999,8	$ 60	$ -	2011
C9	152,7	54000	40500	4860	$ 430.972	3817,0	$ 60	$ -	2011
C10	240,9	60000	45000	5400	$ 475.139	6022,1	$ 60	$ -	2011
C11	207,7	66000	49500	5940	$ 458.488	5193,7	$ 60	$ -	2011
C12	634,9	72000	54000	6480	$ 739.372	15872,8	$ 60	$ -	2011
C13	158,6	78000	58500	7020	$ 433.918	3965,2	$ 60	$ -	2011
C14	244,4	84000	63000	7560	$ 476.776	6109,3	$ 60	$ -	2011
C15	211,8	90000	67500	8100	$ 460.153	5293,8	$ 60	$ -	2011
C16	964,7	96000	72000	8640	$ 1.092.331	24117,6	$ 60	$ -	2011
Main tyre retread	1	0	300	0	$ -	0	$ 50	$ 2.400	2006
Main tyre replacement	1	0	1500	0	$ -	0	$ 50	$ 6.400	2006
Nose tyre retread	1	0	200	0	$ -	0	$ 50	$ 600	2006
Nose tyre replacement	1	0	1000	0	$ -	0	$ 50	$ 800	2006
Brakes inspection	1	0	2100	0	$ -	0	$ 50	$ 132.000	2006
Landing gear	1	28000	18350	0	$ -	0	$ 50	$ 340.000	2006
Main tyre inspection	1	0	300	0	$ -	0	$ 50	$ 1.800	2006
Nose tyre inspection	1	0	1500	0	$ -	0	$ 50	$ 500	2006
APU SV	1	0	8000	0	$ -	0	$ 50	$ 350.000	2017
ESV	1	0	5000	0	$ -	0	$ 70	$1.200.000	2007

Figure 4.7: TP-PHEP resulting maintenance plan used as input into LYFE^2

Other Costs

Lastly, the non-routine material costs associated with the components for which the material cost is not assumed to be proportional to the maintenance MH must also be considered. As explained before, these costs are not directly included within the maintenance plan. Instead, they are accounted separately after the $LYFE^2$ simulations. This approach is adopted due to the difficulty of integrating these costs directly into the maintenance program used as input to $LYFE^2$. Since the methodology described in Section 4.3.2 provides the resulting costs in term of average $/FH, the contribution can be incorporated easily into the final maintenance cost assessment. It is assumed that the downtime associated with the repair or replacement activities for these components is small compared with the overall maintenance downtime. Therefore, the impact that these activities would have on aircraft utilization can be neglected. The resulting costs are reported in the Table 4.13.

Table 4.13: TP-PHEP non-routine material expenses due to components failure

Component	Material cost	Unit
Drivetrain gearboxes	0.49	$/FH 2011
E-motors	0.99	$/FH 2011
Inverters	1.28	$/FH 2011
Batteries	5.12	$/FH 2011

4.4.2 TP-MHEP

Consistently with the procedure described for the TP-PHEP configuration, the assumptions adopted for the TP-MHEP configuration are outlined.

Line and Base Maintenance

For the TP-MHEP configuration, the introduction of an innovative LH_2 fuel system, and a PEMFCS performing the functions of the APU allows the maintenance tasks extracted from the A320 MPD associated with ATA 28, and ATA 49 to be removed, together with their corresponding labor and material costs. The resulting expense reduction is presented in the Table 4.14 below.

Table 4.14: TP-MHEP maintenance cost differences due to the elimination of tasks related to the conventional APU and kerosene fuel system

Check	**Δ MHs**	**Δ Material cost**	**Unit**
Transit	0	0	\$ 2006
Pre flight	0	0	\$ 2006
Daily	0	0	\$ 2006
Weekly	-1.4	-85.9	\$ 2006
A1	-2	-46.4	\$ 2006
A2	-2.8	-65.7	\$ 2006
A3	-2	-46.4	\$ 2006
A4	-3	-69.6	\$ 2006
C1	-4.7	-93.6	\$ 2011
C2	-16.2	-324.5	\$ 2011
C3	-6.05	-120.9	\$ 2011
C4	-33.3	-732.6	\$ 2011
C5	-6.7	-134.4	\$ 2011
C6	-23.1	-461.3	\$ 2011
C7	-6.6	-132.6	\$ 2011
C8	-382	-9,704	\$ 2011
C9	-6.6	-132.6	\$ 2011
C10	-22.4	-447.3	\$ 2011
C11	-7	-140.4	\$ 2011
C12	-43.7	-1,062	\$ 2011
C13	-7	-140.4	\$ 2011
C14	-22.5	-449.3	\$ 2011
C15	-7.8	-155.4	\$ 2011
C16	-403.8	-12,453	\$ 2011

Furthermore, the powerplant-related maintenance tasks extracted from the A320 MPD are replaced by the corresponding tasks extracted from the ATR72 MPD. The resulting maintenance effort variation due to the powerplant is assumed to be identical to that adopted for the TP-PHEP configuration (Table 4.11). The maintenance tasks derived from the MSG-3 analysis of the new components must also be introduced. In Table 4.15 the labor and material cost changes, compared to the reference aircraft, due to these tasks are presented. The expenses exclude the material cost of those components whose material cost is assumed not proportional to the MH effort.

Table 4.15: TP-MHEP maintenance cost differences due to the introduction of the new tasks

Check	Δ MHs	Δ Material cost	Unit
Transit	0	0	$ 2006
Pre flight	0	0	$ 2006
Daily	0	0	$ 2006
Weekly	0	0	$ 2006
A1	10.9	38.7	$ 2006
A2	13.9	92.8	$ 2006
A3	10.9	38.7	$ 2006
A4	31	314.8	$ 2006
C1	238.6	1,747	$ 2011
C2	328	2,881	$ 2011
C3	323	2,461	$ 2011
C4	408.4	4,161	$ 2011
C5	319.1	2,349	$ 2011
C6	437.8	3,988	$ 2011
C7	339.0	2,495	$ 2011
C8	465.3	5,530	$ 2011
C9	354.3	2,699	$ 2011
C10	450.4	4,056	$ 2011
C11	357.9	2,621	$ 2011
C12	525.4	6,107	$ 2011
C13	357.9	2,621	$ 2011
C14	454.1	3,989	$ 2011
C15	387.8	2,982	$ 2011
C16	491.9	7,097	$ 2011

To account for the remaining routine material costs, a battery replacement task with an associated cost of $2,849 is included in every A4 check as explained in Section 4.3.2. Furthermore, each C-check includes the material costs associated with the restoration/overhaul of the propeller blades and hub and the in-shop restoration of the motor unit, as in the TP-PHEP configuration. In addition, the replacement of the PEM fuel cell stacks at the end of their service life is considered, resulting in a total material cost of $168,860 allocated to every C-check.

Heavy Components

With regard to heavy component maintenance, the assumptions concerning the differences relative to the reference maintenance plan remain largely the same as those adopted for the TP-PHEP configuration. Therefore, the maintenance costs associated with the thrust reversers and the ESVs are removed. According to the data reported by Aircraft Commerce [24], once the costs associated with propeller blade and hub maintenance are excluded, the total engine maintenance reserve remains approximately constant at $80/FH for different engine variants employed on the

ATR 42 and ATR 72, including the PW120, PW121, PW124B, and PW127E/F. This is observed despite the differences in engine shaft power ratings.

Also, to account for non-routine maintenance costs, Aircraft Commerce [24] adopts an average engine removal interval of 5,000 FC, which includes removals driven both by turbine temperature limitations and by hot section deterioration effects. Aircraft Commerce [24] data do not allow the individual contributions of these factors to be isolated. Therefore, the difference in engine rating and hybridation between the TP-MHEP and TP-PHEP configurations is considered negligible, in accordance with the level of detail supported by the available source data. Furthermore, as discussed in Section 2.2, the maintenance costs of hydrogen-fueled gas turbine engines may be comparable to those of conventional kerosene-fueled engines. Thus, the same ESV cost figures used for the TP-PHEP configuration are retained. The APU SV is no longer required, since the APU functions are performed by the PEMFCS. Consequently, the APU SV cost is eliminated from the TP-MHEP maintenance plan.

Resulting Maintenance Plan

The resulting maintenance plan is presented in the Appendix. After the simulations, as for the TP-PHEP aircraft, the non-routine expenses due to the components shown in Table4.6 must also be included. The average $/FH is presented in the Table4.16 below

Table 4.16: TP-MHEP non-routine material expenses due to components failure

Component	Material cost	Unit
Drivetrain gearboxes	0.05	$/FH 2011
E-motors	0.10	$/FH 2011
Inverters	0.14	$/FH 2011
Batteries	0.02	$/FH 2011
Fuel cell stacks	0.12	$/FH 2011
Hydrogen tanks	5.91	$/FH 2011

4.4.3 TF-MHEP

Line and Base Maintenance

As for the TP-MHEP architecture, the maintenance activities extracted from the A320 MPD associated with the fuel system and the APU are no longer required, and removed from the maintenance plan. In contrast, no variations with respect to the reference configuration are assumed for the powerplant maintenance tasks. The maintenance tasks associated with the new components are then introduced. Table 4.17 contains the labor cost, and the material cost except that of those components whose material cost is assessed independently.

Table 4.17: TF-MHEP maintenance cost differences due to the introduction of the new tasks

Check	Δ MHs	Δ Material cost	Unit
Transit	0	0	$ 2006
Pre flight	0	0	$ 2006
Daily	0	0	$ 2006
Weekly	0	0	$ 2006
A1	0	0	$ 2006
A2	0	0	$ 2006
A3	0	0	$ 2006
A4	6.5	152	$ 2006
C1	86.7	1,733	$ 2011
C2	143.3	2,866	$ 2011
C3	115.4	2,308	$ 2011
C4	188.2	4,141	$ 2011
C5	115.5	2,311	$ 2011
C6	188.8	3,766	$ 2011
C7	122.8	2,455	$ 2011
C8	216.7	5,504	$ 2011
C9	126.6	2,532	$ 2011
C10	192.9	3,858	$ 2011
C11	130	2,600	$ 2011
C12	238.7	5,809	$ 2011
C13	130	2,600	$ 2011
C14	198.4	3,968	$ 2011
C15	137.8	2,755	$ 2011
C16	229	7,063	$ 2011

Regarding the rest of the material cost, the difference between the TF-MHEP and the TP-MHEP is that no restoration/overhaul of propellers is needed, and the input required for the exchange of the fuel cells stacks is increased. The input required for the battery exchange is kept equal, as the battery mass is the same. Thus, these tasks require an additional cost of $ 2,849 every A4 check, and $ 36,224 every C-check.

Heavy Components

With regard to heavy components maintenance, no differences relative to the reference configuration are assumed. The ESV of the kerosene and LH_2 powered engines is assumed as equal (Section2.2). The only exception is the elimination of the conventional APU SV, which is no longer required.

Resulting Maintenance Plan

The resulting maintenance plan used as input for LYFE^2 is available in the Appendix. As for the other novel concepts, the cost included in Table 4.18 are added after the simulation.

Table 4.18: TF-MHEP non-routine material expenses due to components failure

Component	**Material cost**	**Unit**
Drivetrain gearboxes	0.07	$/FH 2011
E-motors	0.14	$/FH 2011
Inverters	0.18	$/FH 2011
Batteries	0.02	$/FH 2011
Fuel cell stacks	0.16	$/FH 2011
Hydrogen tanks	5.68	$/FH 2011

4.5 Results

After defining the maintenance activities for each configuration, this section presents the results obtained from the LYFE^2 simulations. The reported maintenance costs already incorporate the additional cost contribution that are estimated outside the LYFE^2 framework, and subsequently integrated into the final results, as described in Section 4.3.2.

4.5.1 Utilization

Aircraft operations simulated for all configurations are based on the same flight schedule. Therefore, the differences in aircraft utilization are exclusively due to the different cruise speeds of the analyzed configurations.

Figure 4.8 presents the average FH/YE and FC/YE obtained for each configuration.

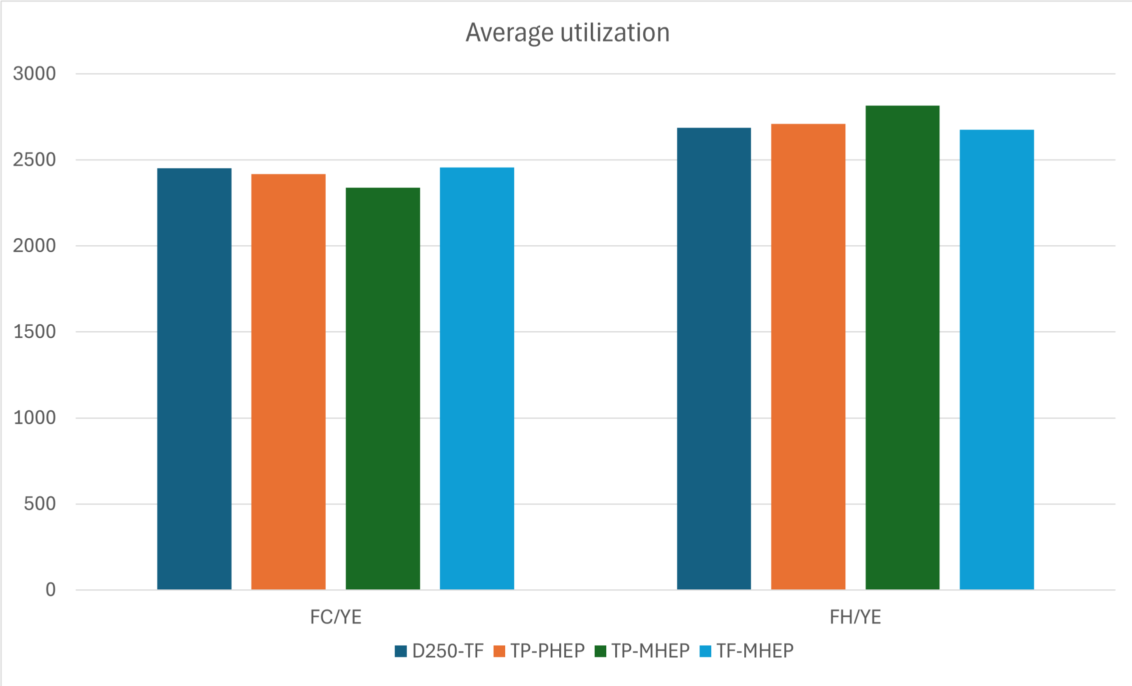


Figure 4.8: Average utilization (FH/YE, and FC/YE) obtained for each configuration

All configurations exhibit similar utilization levels in terms of both FH and FC. Therefore, the comparison of the resulting maintenance costs among the different architectures can be considered meaningful, since the differences are not driven by significantly different utilization patterns. The largest deviation with respect to the reference configuration is observed for the TP-MHEP configuration, which exhibits approximately 4.6% fewer FC/YE, and 4.8% more FH/YE. The other two configurations show absolute differences below 1.5% for both utilization parameters. These percentages are visually represented in Figure 4.9. Also, none of the configurations operates outside the utilization limits prescribed by the A320 MPD. According to Aircraft Commerce [27], the utilization range for the A320 family is between 1,800 and 4,400 FH/YE, and between 1,000 and 2,500 FC/YE. Operators exceeding these limits are required to consult the aviation authority in order to define a customized maintenance program for their fleet. This result provides additional confidence in the A320 MPD task analysis.

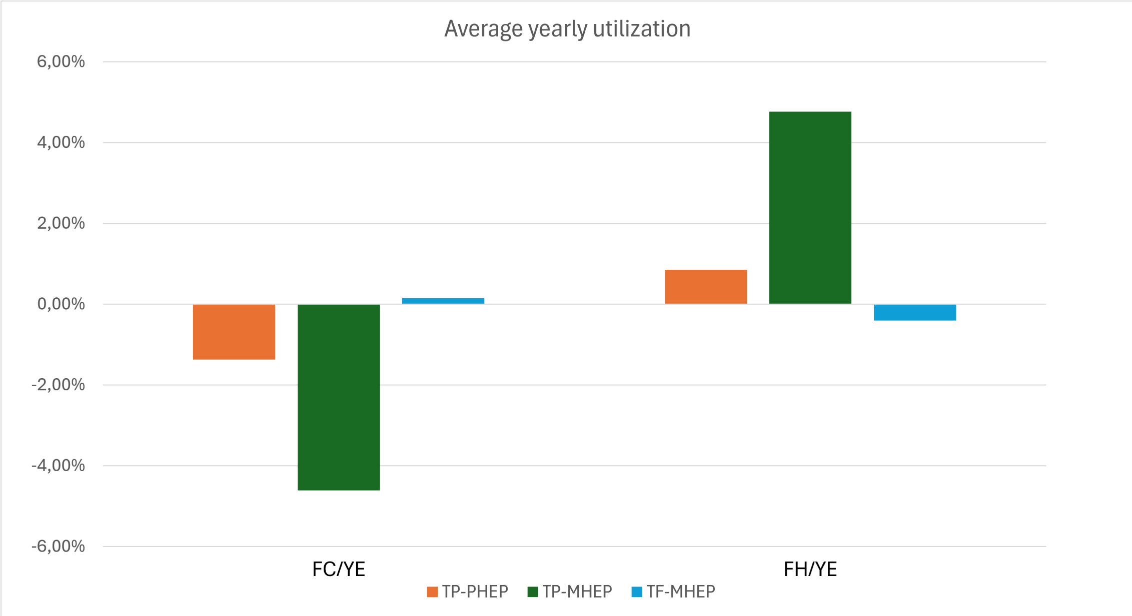


Figure 4.9: Average utilization (FH/YE, and FC/YE) deviation, expressed through percentage, with respect to the reference D250-TF configuration

4.5.2 Maintenance Costs

The resulting maintenance costs are discussed in terms of labor cost, material cost, fixed cost, and total DMC. The labor and material cost contributions originate from the line and base maintenance activities included in the maintenance plans. The fixed cost is associated with the remaining maintenance activities related to heavy components, such as ESVs and other major overhaul events.

It is important to note that this cost breakdown does not correspond to the maintenance cost classifications commonly adopted in the literature or by aircraft operators. Instead, it is solely a consequence of the methodology used to implement maintenance costs within the LYFE² framework. Therefore, the distinction bewteen labor, material and fixed costs should be interpreted as a modeling convention adopted for the present analysis rather than as a standard maintenance cost categorization. This limitation only affects the interpretation of the individual cost breakdown. The labor and the material cost results can still be meaningfully compared across the analyzed configurations, since they are derived using a consistent methodology. However, these categories do not encompass all cost items that would tipically be classified as labor or material costs in aircraft maintenance cost accounting.

Fixed Cost

Figure 4.10 shows the average annual fixed maintenance cost for the analyzed configurations. The reference configuration exhibits the highest fixed maintenance cost, amounting to aproximately $ 4.88 million per year. It is followed by the TP-MHEP comfiguration, with an annual fixed cost of $ 4.66 million. Significantly lower values are obtained for the TP based configurations, with approximately \$ 2.83 million per year for the TP-PHEP and \$ 2.59 million per year for the TP-MHEP.

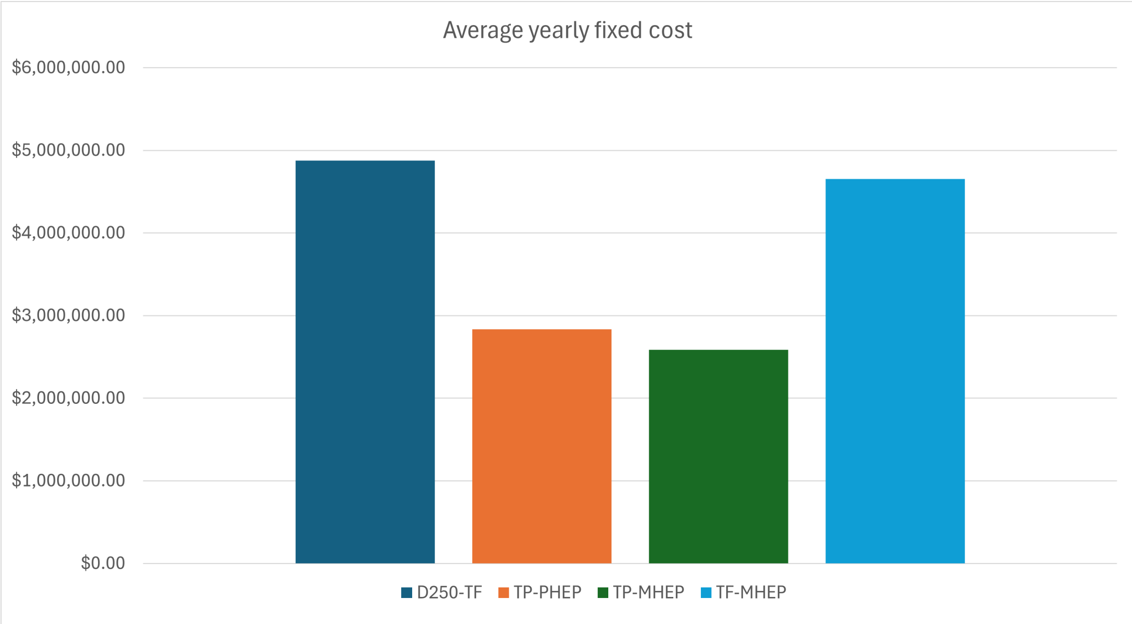


Figure 4.10: average annual fixed maintenance cost

This ranking is consistently observed across the different fixed-cost metrics considered in this study. Figure 4.11 presents the fixed cost normalized by FH, FC, and flown distance, expressed through percentage difference relative to the reference configuration. In all cases the same trend can be observed: TP-MHEP is the least expensive configuration, followed closely by the TP-PHEP, while the TF-MHEP presents a fixed cost value only slightly lower to the reference aircraft.

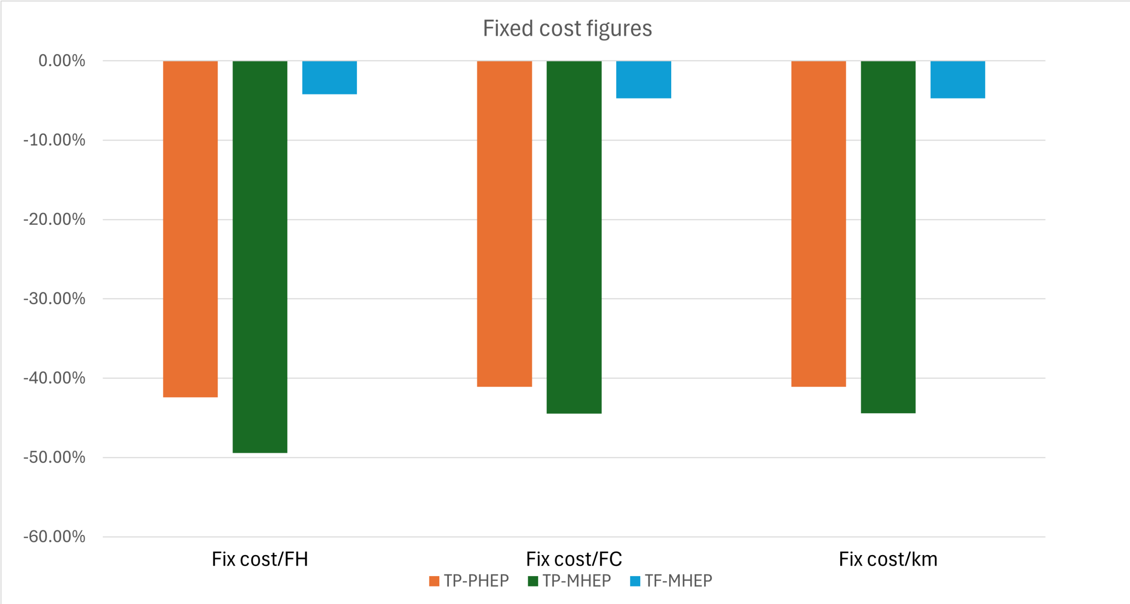


Figure 4.11: Fixed cost figures expressed through percentage difference relative to the reference configuration

This result is not unexpected, since for all novel configurations a reduction of maintenance activities that contribute to the fixed maintenance cost was involved. The most evident contributor is the propulsion system architecture, as the turbofan engines have a higher ESV cost. Also, the hydrogen-powered architectures benefit from additional fixed cost reductions due to the elimination of APU SV.

Material Cost

The average annual material maintenance cost is presented in Figure 4.12. The TP-PHEP configuration exhibits the highest cost, exceeding \$ 4.14 million dollar per year. Its is followed by the TP-MHEP configuration, with an average annual cost sliglty below \$ 1.4 million. The reference configuration, and the TF-MHEP aircraft present the lowest material cost, amounting to approximately \$ 1.0 million and \$ 1.1 million per year, respectively. Figure 4.13 shows the material cost normalized by FH, FC and flight km. The data is expressed as percetnage difference relative to the D250-TF. The same trend can be observed across all metrics.

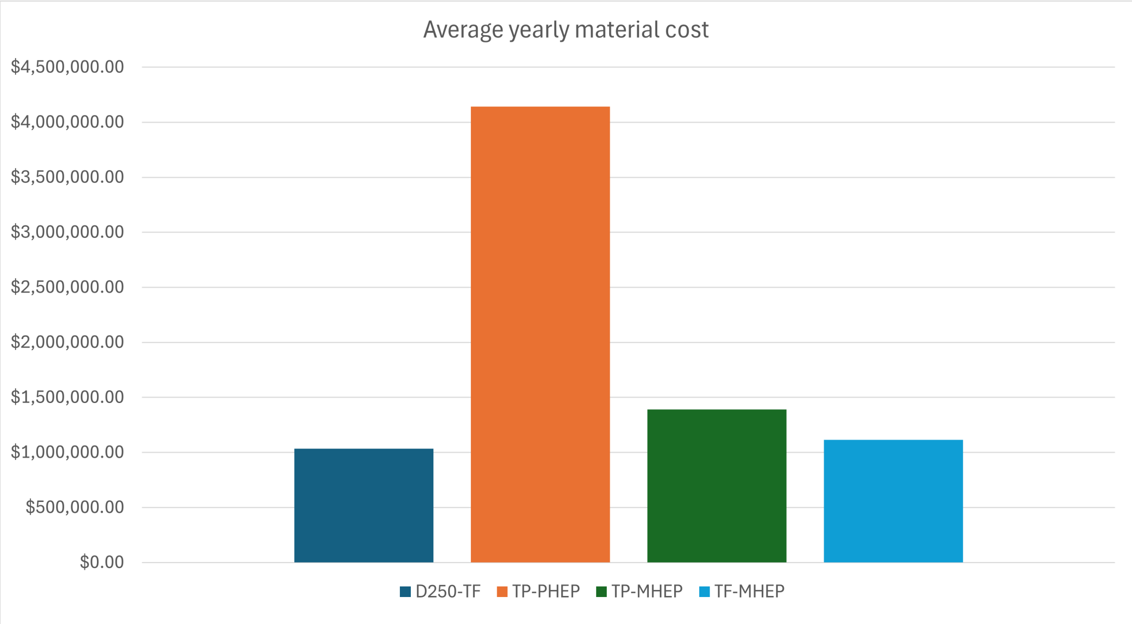


Figure 4.12: average annual material maintenance cost

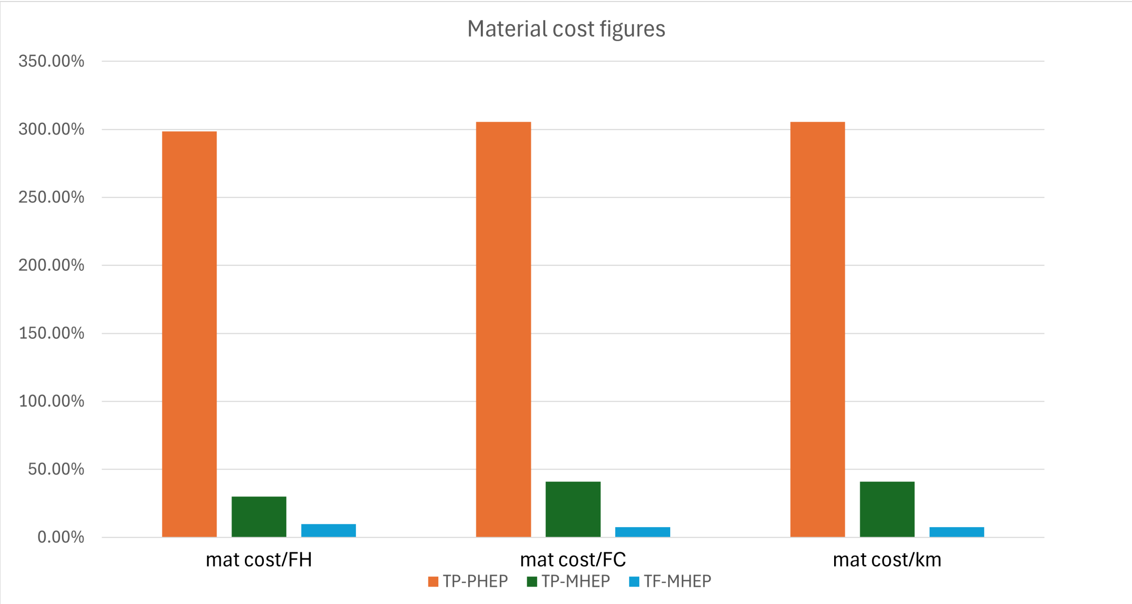


Figure 4.13: Material cost figures expressed through percentage difference relative to the reference configuration

The most evident result is the high material maintenance cost of the TP-PHEP aircraft, which is approximately three times higher than that of the reference aircraft. This increase is due to the battery replacement task which has a material cost of approximately $ 666,000. Also the TP-MHEP configuration has a much higher material cost when compared to the reference aircraft, around 30% more when normalizing for the FH, and 40% more when considering the FC and flight distance.

A notable result is obtained for the TF-MHEP. The material cost increase with respect to the reference configuration is roughly 1%. To understand why this result is obtained, Table 4.19 and Figure 4.14 can be used as reference for the following explanation. Table 4.19 contains the relative difference between the reference configuration and the TF-MHEP in terms of material cost for each line and base check. It can be observed that, for base maintenance, the material cost increase relative to the reference configuration exceeds 34% for most checks. In contrast, for line maintenance, a cost increase is observed only for the A4 check, for which material cost increases by 29%. The remaining line maintenance checks either exhibit no variation or a reduction in material costs, with the the weekly check experiencing the largest decrease. For instance the weekly check material cost is approximately 11% lower than that of the reference configuration.

Furthermore, each of the 16 base maintenance checks is performed only once during the simulated aircraft life. Conversely, line maintenance activities are more frequent. In addition to the maintenance costs figures, $LYFE^2$ provides the number of occurrences of each maintenance check over the simulation. By multiplying the occurrence count and the material cost associated with a given check, it is possible to determine its cumulative contribution over the aircraft lifetime. Figure 4.14 shows the contribution of the weekly checks, total line maintenance, and total base maintenance to the overall material costs of the TF-MHEP configuration. It can be seen that line maintenance accounts for approximately 58% of the total material expenditure, while base maintenance represents the remaining 42%. Also, the weekly checks alone contribute about 9% of the total material maintenance cost. Thus, despite the significant increase observed for individual base maintenance checks, the overall material maintenance cost of the TF-MHEP configuration remains very close to that of the reference aircraft, with a total increase of less than 1%.

Table 4.19: TF-MHEP material maintenance cost differences compared with the reference configuration. Reported percentages represent the relative change with respect to the corresponding cost of the reference configuration.

Check	**Δ Material cost (%)**
Transit	0
Pre flight	0
Daily	0
Weekly	-11.7
A1	-0.5
A2	-0.7
A3	-0.5
A4	29.8
C1	65.1
C2	40.7
C3	43.6
C4	13.0
C5	56.3
C6	36.0
C7	41
C8	5.5
C9	54.6
C10	34.8
C11	39.5
C12	10.8
C13	52.8
C14	34.2
C15	38.9
C16	4.2

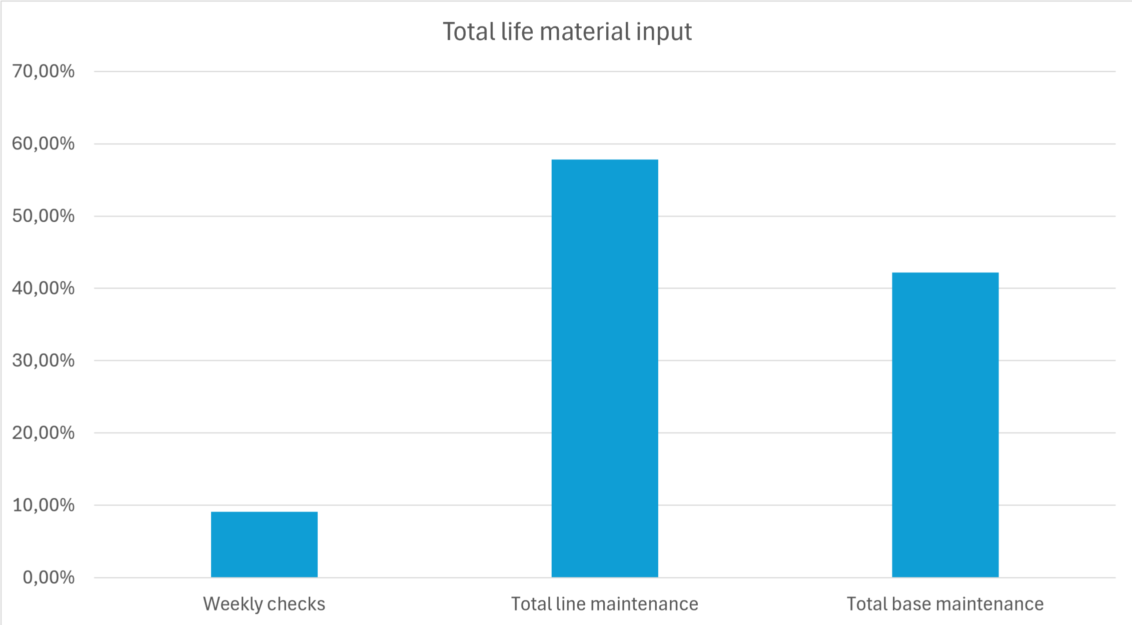


Figure 4.14: Total life material input relative percentages

Labor Cost

Lastly, the maintenance labor cost results are assessed. The total values present only limited differences among the configurations. As shown in Figure 4.15, the average annual labor cost is approximately $ 3.2 million for all configurations. The least expensive configuration is the D250-TF, with an annual labor cost of approximately $3.14 million, while the most expensive is TP-PHEP, with an annual labor cost of roughly $3.24 million.

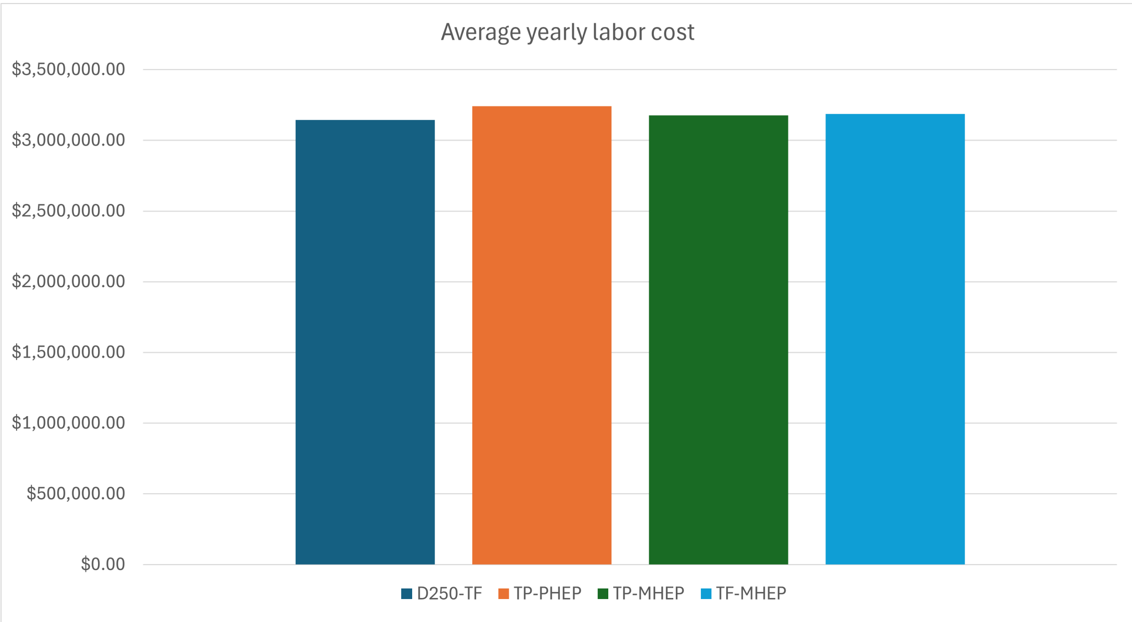


Figure 4.15: Average annual labor maintenance cost

A more detailed comparison can be obtained from the normalized cost metrics presented in Figure 4.16, where the labor cost is expressed per FH, FC and flown distance as a percentage difference relative to the D250-TF.

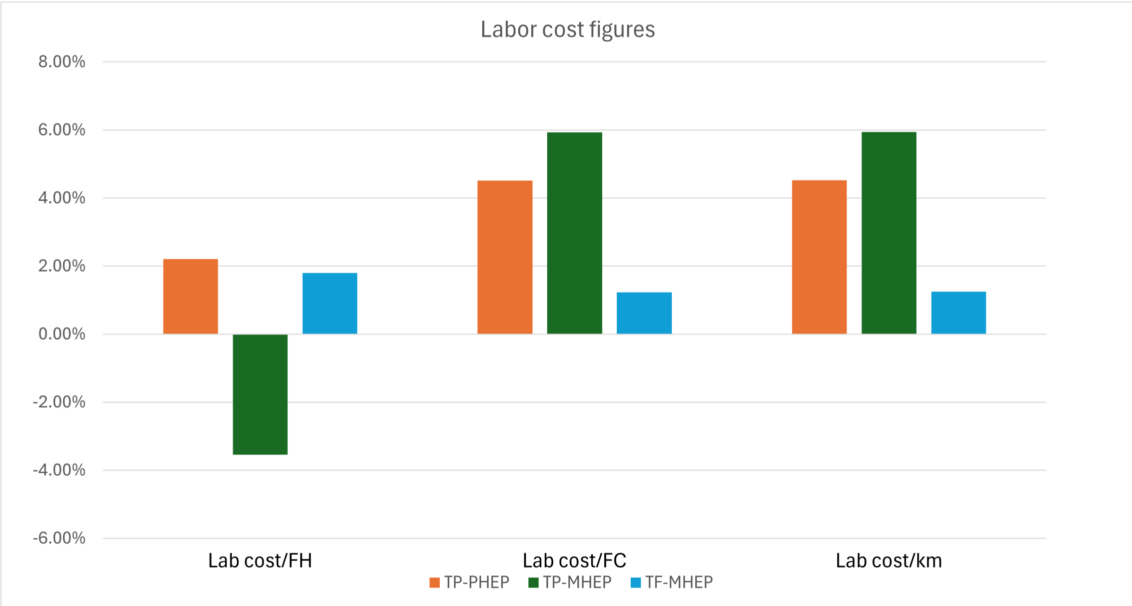


Figure 4.16: Labor cost figures expressed through percentage difference relative to the reference configuration

The results indicate that all novel architectures are generally characterized by a higher labor cost than the reference aircraft. This is not unexpected, since the MH associated with each maintenance check are consistently higher for the novel configurations than for the reference aircraft, as shown in Table 4.20.

Table 4.20: Relative MH differences with respect to the reference configuration

Check	**TP-PHEP** **Δ MH (%)**	**TP-MHEP** **Δ MH (%)**	**TF-MHEP** **Δ MH (%)**
TR	0.0	0.0	0.0
PF	0.0	0.0	0.0
Daily	0.0	0.0	0.0
Weekly	21.8	10.1	-11.7
A1	4.6	1.8	0.1
A2	4.2	1.2	0.6
A3	4.6	1.8	0.1
A4	17.4	14.7	3.7
C1	6.9	8.4	6.4
C2	5.0	6.5	5.5
C3	5.8	6.9	5.8
C4	2.0	2.7	2.3
C5	7.8	9.5	7.3
C6	5.5	7.0	6.4
C7	6.1	7.4	5.6
C8	1.2	0.1	0.1
C9	7.9	9.5	7.9
C10	5.6	7.5	6.3
C11	6.1	7.5	5.7
C12	2.2	2.9	2.6
C13	8.2	10.0	7.6
C14	5.2	6.9	6.2
C15	6.1	7.4	6.1
C16	1.2	0.1	0.1

A particularly interesting result is observed when the cost is normalized by FH. In this case, the TP-MHEP configuration exhibits a labor cost lower than the reference aircraft, although the difference is less than 4%. This observation provides a useful insight into the scope of the present methodology. The maintenance labor cost assessment is based on a document based analysis of the A320 and ATR72 MPDs. Both sources focus on maintenance tasks with intervals ranging from weekly inspections to 12 years. As a consequence, no differences are assumed for maintenance activities that have a higher frequency, such as transit, pre-flight, and daily checks. The effort associated with those activities remain identical across all configurations and therefore their contribution to labor cost variation is driven by the slight differences in aircraft utilization. As a result, utilization effects can offset the increase in scheduled maintenance effort introduced by the novel configurations. However, this phenomenon is observed only when the labor cost is normalized by the FH. The results expressed per FC and per flown distance remain consistent with the expected trend, with all novel configurations showing higher costs than the D250-TF.

Total Maintenance Cost

By combining the fixed, material and labor cost contribution the TMC is obtained. The average annual TMC for the four configurations is presented in Figure 4.17, where the individual contributions of the three cost categories are also highlighted. As for the various cost categories, Figure 4.18 reports the percentage difference of the novel configurations relative to the reference aircraft, expressed for the three utilization parameters previously adopted.

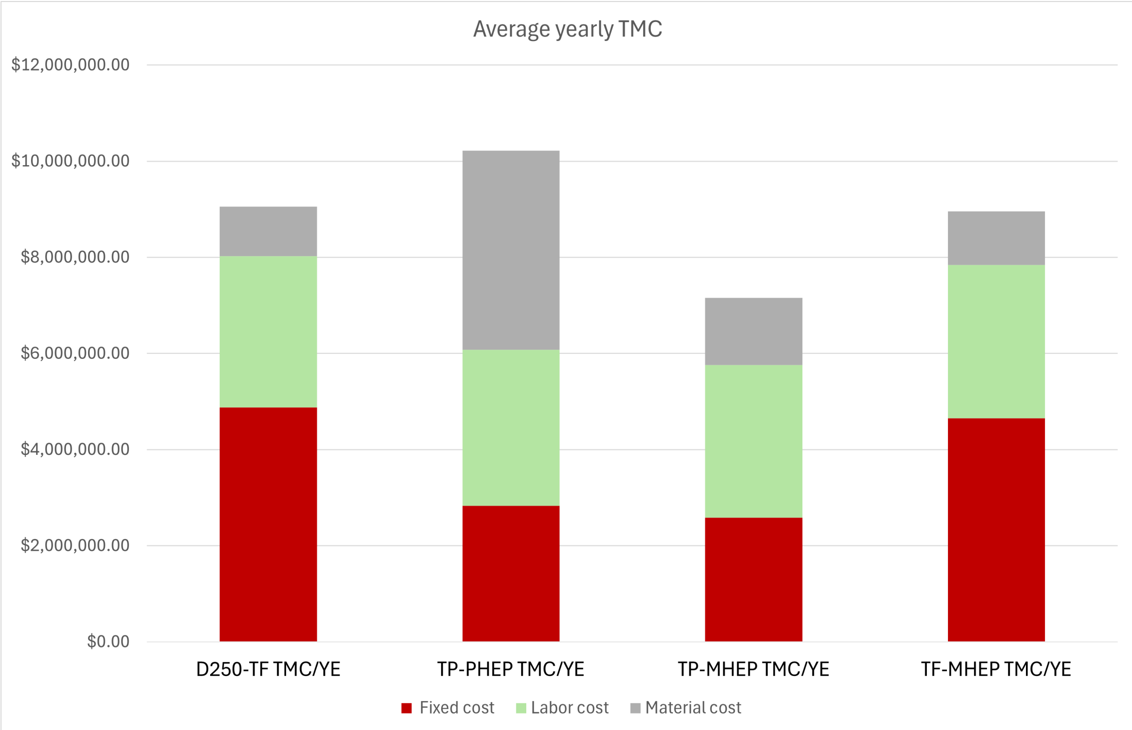


Figure 4.17: Average annual TMC

The highest TMC is obtained for the TP-PHEP aircraft, with an average yearly TMC of $ 10 million. The reference D250-TF configuration, and the TF-MHEP configuration both exhibit a yearly TMC close to $ 9 million, with the TF-MHEP being slightly less expensive. The lowest TMC is obtained for the TP-PHEP configuration, which presents an average annual TMC sliglty above $ 7 million.

Several important observations can be drawn from these results. First, the overall trends are consistent across all utilization metrics, as can be noticed from Figure 4.18. This confirms that the differences in utilization do not significantly influence the comparison. In particular, the results expressed per FC and per distance are very similar, reflecting the trend already observed for the individual cost contributions.

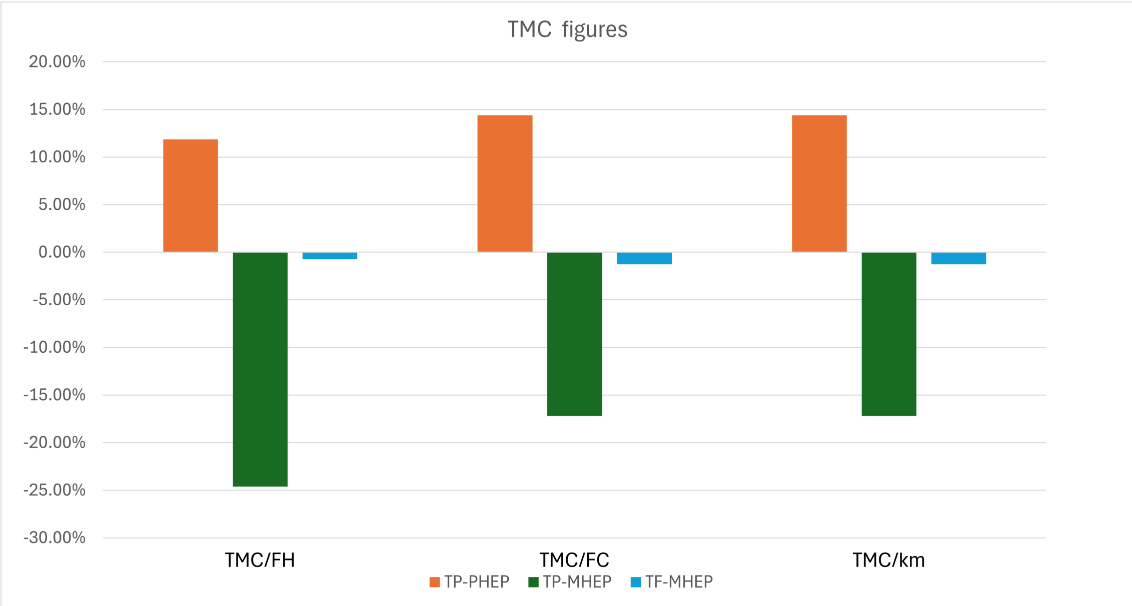


Figure 4.18: TMC figures expressed through percentage difference relative to the reference configuration

For the turbofan-powered configurations, the fixed cost contribution represents a major share of the TMC, accounting for more than 50%. This highlights the importance of the ESV cost in determining the overall maintenance effort also for the novel configurations. The labor cost contribution remains relatively stable across the configurations, accounting for approximately 30% of the TMC. The only exception is the TP-MHEP configuration for which the labor cost represents around 40% of the total expediture. Regarding material costs, the turbofan-powered configuration show a lower relative contribution, with material costs accounting for approximately 10% of the TMC. The most notable result is observed for the TP-PHEP configuration, where material cost exceeds 40% of the TMC. This finding showcases the influence of batteries on the overall maintenance effort of hybrid aircraft.

Chapter 5

Maintenance Cost Modelling

The previous Chapter presented the maintenance cost assessment results obtained for the reference aircraft, and the analysed novel propulsion concepts. The results obtained constitute the basis for the maintenance cost model developed in this chapter. In the first Section 5.1 identifies the elements that have the greatest influence on the fixed, the material, and the labor maintenance costs. These variables are the cost drivers in the equations governing the maintenance cost model. In the previous Chapter where fixed, labor, and material cost results were presented, the main cost drivers influencing each cost category were already introduced. In the present section, these cost drivers are further selected and formally defined, taking into account both the characteristics of the cost database and the assumptions adopted in its construction. Then, the maintenance cost model itself is presented, introducing the selected equation forms and the regression methodology adopted to derive the model parameters. Lastly, in Section 5.2 the resulting cost obtained using the model are compared with the maintenance expenses obtained via $LYFE^2$.

5.1 CERs Definition

Before defining the cost drivers, it is necessary to specify the CERs that constitute the maintenance cost model. The proposed approach estimates the total DMC as the sum of three independent CERs, corresponding to the fixed, material, and labor cost components. Each CER is based on a Linear Regression Model (LRM) [55]. Thus, each cost component is estimated as

$$\hat{y} = \hat{\beta}_0 + \sum_{i=1}^{n} \hat{\beta}_i \cdot x_i \tag{5.1}$$

where $(\hat{y})$ is the predicted cost element, $(\hat{\beta}_0)$ is the intercept term, $(\hat{\beta}_i)$ are the estimated regression coefficients, and (x_i) are the independent variables, i.e., the selected cost drivers. The hat notation is used to indicate that these quantities are estimates obtained through regression. The model development process consists of two steps. First, the cost drivers are identified and defined. Subsequently, the regression coefficients are estimated using the Least Squared Method (LSM) [68]. An important consideration in the model formulation is the limited size of the available dataset, which consists of four aircraft configurations and therefore four independent cost observations. To obtain a meaningful regression result, the system must remain overdetermined, meaning that the number of available observations must exceed the number of unknown regression parameters. Consequently, the number of independent variables that can be included in each CER is restricted to a maximum of two, as a fixed intercept term is present. At the same time, the scope of the model is to capture the maintenance cost variations associated with aircraft characterized by different propulsion technologies. The analyzed configurations include both turbofan and turboprop propulsion systems, different levels of hybridization, and different energy carriers, namely kerosene and hydrogen. Therefore, ensuring that the selected cost drivers adequately represent these technological differences imposes additional constraints on the model formulation. This consideration is found to be relevant for the fixed CER, and the material CER. In these two cases, a formulation without an intercept term is adopted, allowing the inclusion of up to three cost drivers. The two CERs, therefore, take the form

$$\hat{y} = \sum_{i=1}^{n} \hat{\beta}_i \cdot x_i \tag{5.2}$$

where the estimated material cost is expressed exclusively as a linear combination of the selected cost drivers.

5.1.1 Cost Drivers

Fixed Cost Drivers

For the fixed cost component, the results presented the previous Chapter show that the maintenance cost is primarily driven by the engine type, affecting the ESV cost, and the APU SVs. In the maintenance plan definition, the ESV cost is not directly related to engine thrust, but rather to the propulsion technology employed, as well as to the number of installed engines. Consequently, two cost drivers that account for the engine type are introduced: **TF**, and **TP**. The former is defined as the no. of turbofan engines installed on the aircraft, the letter is the no. of turboprop engines. No differences are assumed in the APU SV cost between the two configurations equipped with a conventional APU, namely the reference aircraft and the TP-PHEP. Thus, a binary cost driver is defined: **APU**. This driver can assume a value of 1 when a conventional APU is installed on board, and a value of 0 otherwise. The values of these cost drivers for the analysed aircraft configurations are reported in Table 5.1.

Table 5.1: Fixed cost drivers values for the case study configurations

Configuration	TF	TP	APU
D250-TF	2	0	1
TP-PHEP	0	2	1
TP-MHEP	0	2	0
TF-MHEP	2	0	0

Material Cost Drivers

The material cost drivers are associated with the presence of battery systems and the fuel type employed by the aircraft. Drive-train battery replacement cost represents a significant contribution to the material maintenance cost of hybrid configurations, while the hydrogen-powered aircraft exhibit additional material costs associated with the LH_2 storage system, and PEMFCS. Using only cost drivers associated with batteries and hydrogen would not adequately represent the reference configuration. Therefore, another cost driver associated with kerosene-fueled aircraft is introduced. The following material cost drivers are defined: **BAT**, **KER**, and **HYDRO**

The **BAT** cost driver is defined as the total drive-train battery mass on board (kg), and it is chosen because the same battery energy density and replacement interval are assumed for all battery-equipped configurations. Consequently, the material cost associated with battery replacement is directly related to the installed battery mass. The maximum kerosene fuel mass (kg) defines the **KER**. This parameter is selected because the maximum kerosene mass stored within the fuel system is directly linked to the reduction in material maintenance cost associated with the smaller fuel system of the TP-PHEP. The **HYDRO** cost driver value is equal to the LH_2 fuel system mass (kg). The latter is chosen as it is used to estimate the non-routine replacement cost associated with the LH_2 tanks. The values of the material cost drivers for the analyzed configurations are reported in Table 5.2.

Table 5.2: Material cost drivers values for the case study configurations

Configuration	BAT	KER	HYDRO
D250-TF	0	18,439	0
TP-PHEP	23,377	12,757	0
TP-MHEP	100	0	3,501
TF-MHEP	100	0	3,365

Labor Cost Drivers

For the labor cost figure, the main cost drivers are identified as the engine type and the fuel type. The influence of the engine type originates from the replacement of the powerplant maintenance tasks extracted from the A320 MPD with the corresponding tasks extracted from the ATR72 MPD. As discussed in the previous Chapter, this substitution results in an increase in the MH associated with the A-checks, which significantly affects the overall labor cost due to their high frequency. The fuel type influences the labor cost through the maintenance activities associated with the systems introduced in the LH_2-powered configurations.

As for the fixed cost component, binary cost driver variables are considered more appropriate in this case, since the aforementioned influences are primarily related to the presence of the specific technologies. Consequently, the following cost drivers are defined: **ENG**, and **FUEL**. The former is related to the propulsion technology, it is equal to 0 for turbofan-powered aircraft, and 1 for turboprop-powered aircraft. The latter addresses the fuel type, it is equal to 0 for kerosene-fueled aircraft and 1 for LH_2-powered aircraft. The values of these cost drivers for the analyzed configurations are reported in Table 5.3.

Table 5.3: Labor cost drivers values for the case study configurations

Configuration	**ENG**	**FUEL**
D250-TF	0	0
TP-PHEP	1	0
TP-MHEP	1	1
TF-MHEP	0	1

5.1.2 Regression Coefficients

After defining the cost drivers, the next step is to estimate the regression coefficients used in the CERs. The regression problem can be expressed in matrix form. The formulation presented below refers to the fixed cost CER, although the same procedure is also applied to the material and labor cost estimations. The vector containing the fixed maintenance costs of the four analyzed configurations is defined as expressed in the Equation 5.3 below.

$$\mathbf{Y}_{\text{Fixedcost}} = \begin{bmatrix} Y_{\text{D250-TF}} \\ Y_{\text{TP-PHEP}} \\ Y_{\text{TP-MHEP}} \\ Y_{\text{TF-MHEP}} \end{bmatrix} \tag{5.3}$$

where each element corresponds to the fixed maintenance cost obtained from the simulations. The order of the configurations follows the convention adopted throughout the thesis. The matrix containing the fixed cost driver values is defined as

$$\mathbf{X}_{\text{Fixedcost}} = \begin{bmatrix} APU_{\text{D250-TF}} & TF_{\text{D250-TF}} & TP_{\text{D250-TF}} \\ APU_{\text{TP-PHEP}} & TF_{\text{TP-PHEP}} & TP_{\text{TP-PHEP}} \\ APU_{\text{TP-MHEP}} & TF_{\text{TP-MHEP}} & TP_{\text{TP-MHEP}} \\ APU_{\text{TF-MHEP}} & TF_{\text{TF-MHEP}} & TP_{\text{TF-MHEP}} \end{bmatrix} \tag{5.4}$$

where each column contains the values of one cost driver, and each row refers to a different aircraft. The vector of regression coefficients is defined as

$$\hat{\boldsymbol{\beta}}_{\text{FixedCost}} = \begin{bmatrix} \hat{\beta}_{\text{APU}} \\ \hat{\beta}_{\text{TF}} \\ \hat{\beta}_{\text{TP}} \end{bmatrix} \tag{5.5}$$

where each element represents the contribution of the corresponding cost driver to the fixed maintenance cost. Using the LSM, the regression coefficients can be estimated as

$$\hat{\boldsymbol{\beta}}_{\text{FixedCost}} = \left(\mathbf{X}^T_{\text{FixedCost}}\mathbf{X}_{\text{FixedCost}}\right)^{-1}\mathbf{X}^T_{\text{FixedCost}}\mathbf{Y}_{\text{FixedCost}} \tag{5.6}$$

The resulting coefficient vector is subsequently used to define the fixed cost CER. The same methodology is applied to the labor and material cost components, using the corresponding cost vectors and cost driver matrices. For the labor cost CER, the formulation differs slightly because only two cost drivers are employed. Thus, the first column of ($\mathbf{X}_{LaborCost}$) is composed of ones, representing the intercept term ($\hat{\beta}_0$). The resulting regression coefficients for the fixed, material, and labor cost CERs are reported in Equations 5.7, 5.8, and 5.9, respectively.

$$\hat{\boldsymbol{\beta}}_{\text{FixedCost}} = \begin{bmatrix} 0.103 \\ 1.225 \\ 0.708 \end{bmatrix} \tag{5.7}$$

$$\hat{\boldsymbol{\beta}}_{\text{MaterialCost}} = \begin{bmatrix} 7.83 \times 10^{-5}{}_{\text{BAT}} \\ 2.95 \times 10^{-5}{}_{\text{KER}} \\ 1.95 \times 10^{-4}{}_{\text{HYDRO}} \end{bmatrix} \tag{5.8}$$

$$\hat{\boldsymbol{\beta}}_{\text{LaborCost}} = \begin{bmatrix} 1.652_{\hat{\beta}_0} \\ 0.076_{\text{ENG}} \\ 0.022_{\text{FUEL}} \end{bmatrix} \tag{5.9}$$

These coefficients are subsequently used in Equation 5.10 to estimate the three maintenance cost components according to the proposed model.

$$\hat{Y} = \mathbf{X}\hat{\boldsymbol{\beta}} \tag{5.10}$$

5.2 Results

A comparison between the maintenance cost components obtained from the LYFE^2 simulations and the corresponding values predicted by the regression model is presented in Figures 5.1, 5.3, and 5.2. The relative errors associated with each configuration are reported in Table 5.4. Resulting errors are very small for all the three cost categories. However, this result should be interpreted with caution and should not necessarily be regarded as a strong validation of the model. Due to the limited number of available observations, the regression problem is marginally overdetermined. Therefore, a close agreement between the model predictions and the original dataset is expected and does not, by itself, guarantee that the model will retain the same level of accuracy when applied to configurations outside the database.

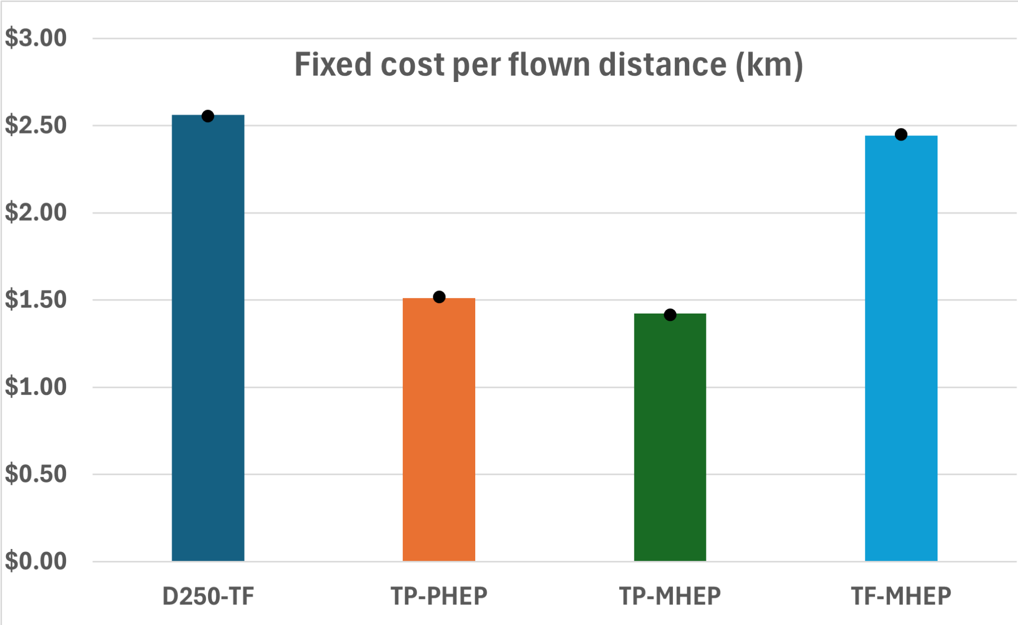


Figure 5.1: Fixed cost per flown distance

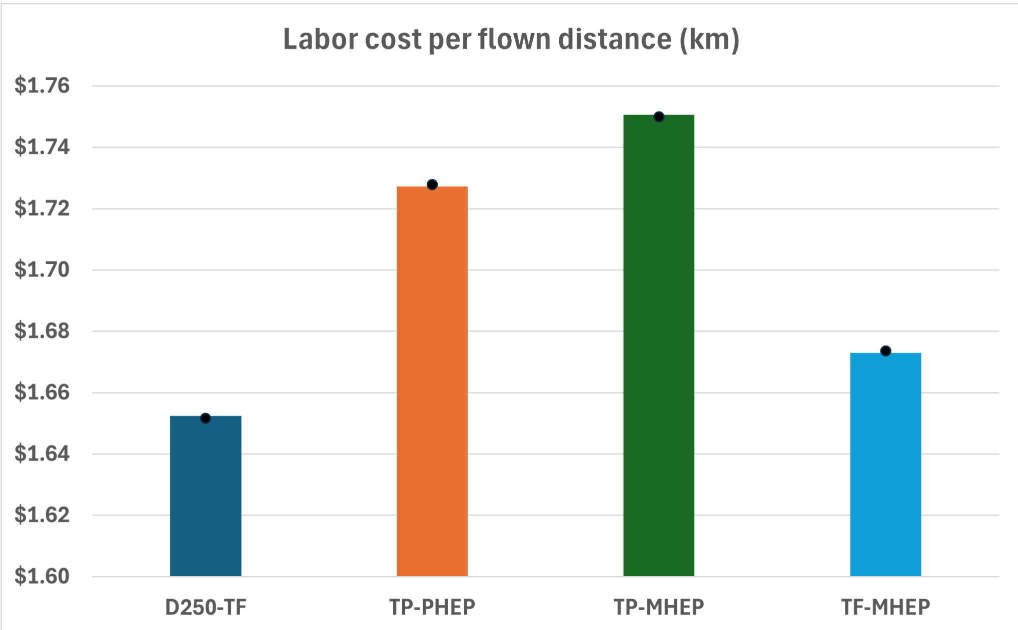


Figure 5.2: Labor cost per flown distance

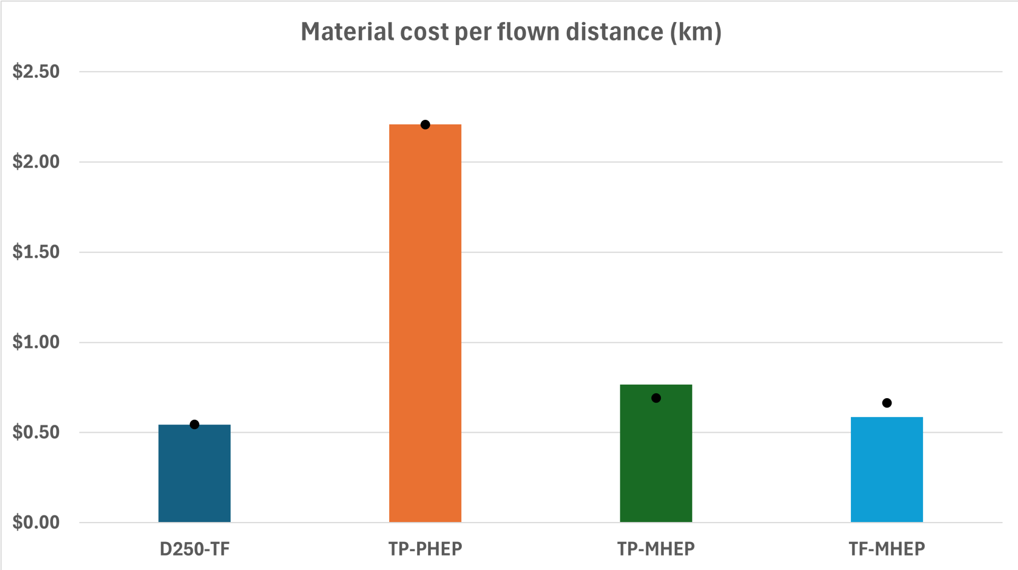


Figure 5.3: Material cost per flown distance

The DMC is obtained by summing the fixed, labor, and material cost contributions predicted by the corresponding CERs. According to Fioriti et al. [37], the DMC represents approximately 60% of the TMC. Consequently, the TMC can be estimated as

$$TMC = \frac{DMC}{0.6} \tag{5.11}$$

The resulting TMC values, expressed per kilometer flown, are presented in Figure 5.4. The predicted total maintenance reserve varies from a maximum of \$5.45/km for the TP-PHEP configuration to a minimum of \$3.86/km for the TP-MHEP configuration. The D250-TF and TF-MHEP configurations exhibit very similar values, equal to \$4.75/km and \$4.78/km, respectively.

Table 5.4: DMC model relative errors

Configuration	**Fixed cost**	**Material cost**	**Labor cost**	**Unit**
D250-TF	3.00×10^{-3}	-1.75×10^{-5}	4.32×10^{-4}	%
TP-PHEP	-6.00×10^{-3}	5.95×10^{-6}	-4.32×10^{-4}	%
TP-MHEP	6.00×10^{-3}	9.90×10^{-2}	4.32×10^{-4}	%
TF-MHEP	-4.00×10^{-3}	-1.35×10^{-1}	-4.32×10^{-4}	%

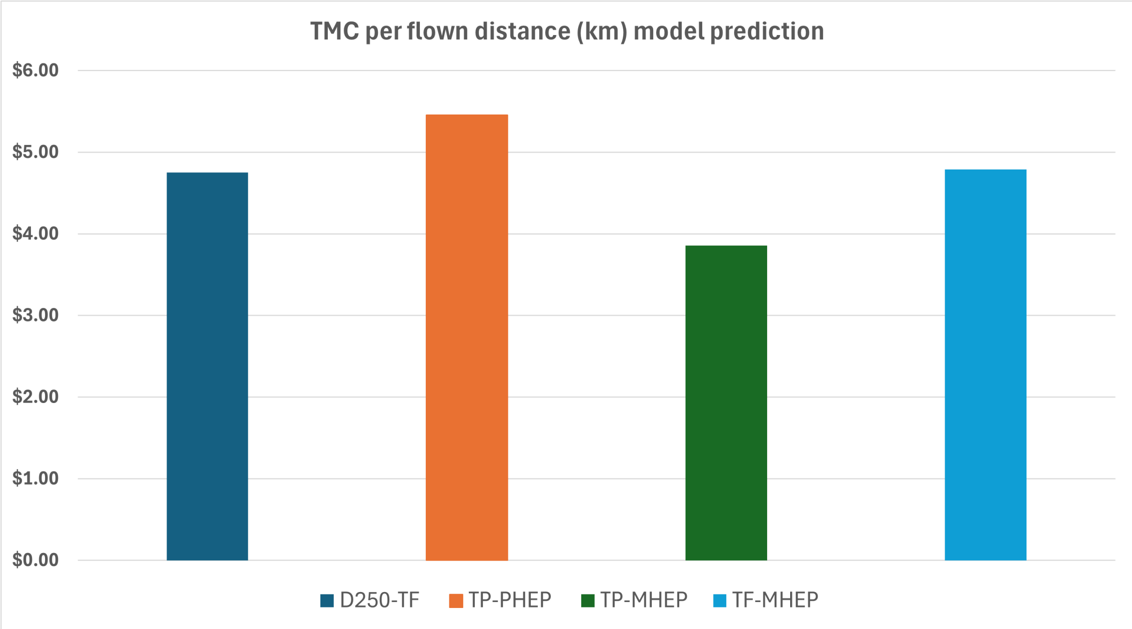


Figure 5.4: Resulting TMC per flown distance for the various configurations

Chapter 6

Conclusion

The aviation industry is currently investigating a wide range of novel aircraft concepts aimed at reducing environmental impact through the adoption of hybrid-electric propulsion architectures, hydrogen-based energy systems, and new onboard technologies such as PEMFCs. While these technologies are receiving increasing attention, maintenance cost models capable of assessing their overall maintenance expenses are currently limited. This represents an important gap, as maintenance costs constitute a significant portion of DOC. Furthermore, according to the CAIV principle, operating cost estimations should be incorporated as requirements into the early design process. Therefore, the scope of this thesis was to develop a maintenance cost model capable of estimating the maintenance costs associated with aircraft employing these emerging propulsion technologies. To achieve this objective, four short-to-medium-range aircraft concepts developed within the DLR's EXACT project were analyzed. These aircraft are designed to satisfy requirements derived from the A321neo, with the exception of a reduced design range. One of the aircraft, the D250-TF, was selected as the reference configuration as it employs conventional system technologies, differing from current aircraft only in their technology level. The remaining three configurations incorporated novel technologies, including different degrees of hybridization, LH_2 fuel systems, and PEMFCSs that replaced conventional APUs.

A maintenance plan was developed for each configuration. For the novel concepts, the maintenance plans were defined by identifying the expected differences relative to the reference aircraft. The A320 family MPD was used to identify maintenance activities that would no longer be required and to estimate the associated maintenance cost reductions. In addition, because two of the analyzed aircraft employed propellers instead of turbofan engines, the ATR72 MPD was used to replace the relevant powerplant-related maintenance activities extracted from the A320 MPD. The maintenance requirements associated with the novel technologies were derived from an MSG-3 analysis conducted internally at DLR. This analysis provided a set of scheduled maintenance tasks for the new systems. Whenever comparable maintenance activities were available in the A320 and ATR72 MPDs, the corresponding maintenance effort estimates were used as references. For technologies for which no suitable maintenance analogies could be identified, the required information was obtained from the available literature.

Derived maintenance plans were subsequently implemented within the LYFE^2 discrete-event simulation framework in order to simulate the operational life of each aircraft. This process produced a maintenance cost database for the four configurations, including labor, material, and fixed maintenance cost contributions. Fixed costs were introduced whenever it was not practical to separately define labor and material expenditures for specific maintenance activities.

The estimated maintenance costs were analyzed separately for the three cost categories. Based on this analysis, the principal maintenance cost drivers were identified while maintaining a level of detail compatible with conceptual aircraft design. The selected drivers included the number and type of installed engines, the maximum fuel mass, the battery mass associated with electric propulsion systems, and the mass of the hydrogen fuel storage system. A regression analysis was then applied to derive three CERs, corresponding to the fixed, labor, and material maintenance costs. The combination of these CERs allowed the estimation of the overall DMC.

Results presented in this thesis provide two main contributions. First, they deliver a maintenance cost assessment for three aircraft concepts employing technologies that are not yet widely represented in the existing maintenance cost literature. Second, they provide a maintenance cost model suitable for application during the early design phases, since the selected cost drivers are based on high-level design parameters. As a result, the proposed methodology can serve as a basis for estimating the maintenance costs of future hybrid-electric and hydrogen-powered aircraft equipped with PEMFCS replacing conventional APUs.

Several opportunities exist for future work. The methodology could be extended by considering a larger and more diverse set of aircraft configurations covering different aircraft classes and sizes. This would allow the influence of aircraft scale on maintenance effort to be explicitly captured while simultaneously increasing the amount of data available for regression, thus improving the robustness and predictive capability of the CERs. In addition, the current model could be complemented by a probabilistic analysis. Many of the maintenance cost estimates used in this work rely on high level assumptions and average correction factors, particularly those related to the majority of non-routine maintenance and the labor effort derived from the MPDs analysis. Introducing uncertainty distributions for these parameters would enable the development of a probabilistic maintenance cost model capable of quantifying confidence intervals and risk levels associated with the predictions. This extension would provide a more comprehensive tool for evaluating maintenance costs during the aircraft design process, and it would enhance the applicability of the proposed methodology to future aircraft concepts.

Appendix A

MPD task selection

A.1 A320 MPD fuel system tasks

SECTION	TASK NUMBER	DESCRIPTION	100% INTERVAL	MEN	TASK M.H.	TASK ALLOCATION
2-28	281100-01-2	TANKS DRAIN WATER CONTENT NOTE: INTERVAL: - DEPENDING ON OPERATING ENVIRONMENT AND OPERATORS EXPERIENCE, A LESS FREQUENT OR MORE FREQUENT INITIAL INTERVAL MAY BE USED.	10 DY NOTE	1 1 1	0.10 0.10 0.10	weekly
2-28	281100-02-1	TANKS OPERATIONAL CHECK OF LEAK MONITOR FOR EVIDENCE OF FUEL LEAKAGE AND CORRECT CLOSURE OF THE VALVE	12 MO OR 1000 FH	1	0.05	a2, a4
2-28	281100-05-1	TANKS GENERAL VISUAL INSPECTION OF FUEL TANKS FOR MINOR EXTERNAL LEAKS	6 MO	1 1 1	0.10 0.10 0.10	a1, a2, a3, a4
2-28	281100-06-1	TANKS OPERATIONAL CHECK OF WATER DRAIN VALVES NOTE: PLANNING: - CREDIT CAN BE TAKEN FROM THE ACCOMPLISHMENT OF MPD TASK 281100-01-2 PROVIDING THE INTERVAL IS NOT EXCEEDED.	6 MO	1 1 1	0.10 0.10 0.10	a1, a2, a3, a4
2-28	281200-01-1	TANK VENTING SYSTEM VISUAL CHECK OF VENT SURGE TANK BURST DISC (EXTERNAL)	24 MO OR 2000 FH	1 1	0.10 0.10	a4
2-28	281247-01-1	NACA VENT INTAKE VISUAL CHECK OF NACA INTAKE FOR SIGNS OF BLOCKAGE	36 MO	1 1	0.02 0.02	c2, c4, c6, c8, c10, c12, c14, c16

Figure A.1: ATA 28 MPD tasks selected, page 1

2-28	281600-01-1	FUEL RECIRCULATION COOLING OPERATIONAL CHECK OF PYLON CHECK VALVE TO ENSURE VALVE NOT FAILED OPEN	108 MO OR 12000 FH	1 1	0.10 0.10	c2, c4, c6, c8, c10, c12, c14, c16
2-28	281800-01-1	IGNITION PREVENTION FUNCTIONAL CHECK OF TANK VAPOUR SEAL AND VENT DRAIN SYSTEM (SFAR88)	72 MO OR 36000 FH	1 1	1.00 1.00	c4, c8, c12, c16
2-28	281800-02-1	IGNITION PREVENTION DETAILED INSPECTION OF VAPOUR SEAL (SFAR88)	72 MO	1 1	0.40 0.40	c4, c8, c12, c16
2-28	281800-03-1	IGNITION PREVENTION DETAILED INSPECTION OF TANK BONDING LEADS (SFAR88)	144 MO	1 1 1 1 1	10.00 10.00 10.00 10.00 10.00	c8, c16
2-28	281800-04-1	IGNITION PREVENTION GENERAL VISUAL INSPECTION OF INTERNAL TANK WIRING AND PROBE ATTACHMENTS (SFAR88)	144 MO	1 1 1 1 1	1.60 1.60 1.60 1.60 1.60	c8, c16
2-28	281800-05-1	IGNITION PREVENTION GENERAL VISUAL INSPECTION OF CENTER TANK FWD CARGO BAY INSULATION BLANKETS (SFAR88).	72 MO	1 1	0.05 0.05	c4, c8, c12, c16
2-28	281800-06-1	IGNITION PREVENTION GENERAL VISUAL INSPECTION OF WIRING HARNESSES ABOVE CENTER TANK (SFAR88)	144 MO	1 1	0.05 0.05	c8, c16
2-28	281800-07-1	IGNITION PREVENTION GENERAL VISUAL INSPECTION OF WING LEADING EDGE AND TRAILING EDGE ELECTRICAL WIRING AND CONNECTIONS (SFAR88)	144 MO	1 1 1 1	0.50 0.50 0.50 0.50	c8, c16
2-28	281800-08-1	IGNITION PREVENTION GENERAL VISUAL INSPECTION OF WING FUEL PUMP ELECTRICAL CONNECTIONS AND UNDERWING ELECTRICAL SUPPLY CABLE (SFAR88)	144 MO	1 1	0.10 0.10	c8, c16

Figure A.2: ATA 28 MPD tasks selected page 2

2-28	281800-09-1	IGNITION PREVENTION GENERAL VISUAL INSPECTION OF FUEL PUMP CANISTERS (SFAR88)	144 MO	1 1 1	1.50 1.50 1.50	c8, c16
2-28	282100-01-1	MAIN FUEL PUMP SYSTEM OPERATIONAL CHECK OF WING TANK PUMP PRESSURE SENSE LINE CHECK VALVES	252 MO OR 36000 FH	1	0.1	c6, c12
2-28	282100-03-1	MAIN FUEL PUMP SYSTEM OPERATIONAL CHECK OF AIR RELEASE VALVES TO ENSURE ADEQUATE FUEL FLOW UNDER SUCTION FEED CONDITIONS NOTE: FOR ETOPS A/C ONLY: THRESHOLD: - AT A MAINTENANCE OPPORTUNITY BETWEEN 750 FH AND 1000 FH AFTER AIRCRAFT DELIVERY AND AFTER ANY TANK REPAIR (TANK ENTRY WHERE SIGNIFICANT DEBRIS MAY BE GENERATED). - PRIOR TO ETOPS OPERATIONS IF MORE THAN 1000 FH SINCE AIRCRAFT DELIVERY OR TANK REPAIR AND TASK WAS NOT ACCOMPLISHED.	216 MO OR 30000 FH	1	0.1	c5, c10, c15
2-28	282100-05-1	FUEL PUMP SYSTEM VISUAL CHECK OF PIPES, COUPLINGS AND LP VALVE EXTERNAL TO TANK FROM FRONT SPAR TO DISCONNECT PANEL FOR LEAKS WITH BOOSTER PUMP ON AND LP VALVE OPEN	108 MO OR 12000 FH	1 1 1 1	0.05 0.05 0.05 0.05	c2, c4, c6, c8, c10, c12, c14, c16
2-28	282100-10-1	MAIN FUEL PUMP SYSTEM REMOVE AIR RELEASE VALVE FOR FUNCTIONAL CHECK OF FLOAT	144 MO	1 1	0.40 0.40	c8, c16

Figure A.3: ATA 28 MPD tasks selected page 3

2-28	282400-01-1	ENGINE LOW PRESSURE SHUT OFF OPERATIONAL CHECK OF LP SHUT OFF VALVES AND THEIR CONTROLS TO ENSURE NO FLOW WHEN SELECTED CLOSED WITH BOOSTER PUMP ON NOTE: INTERVAL: - TASK MAY BE PERFORMED AT OPPORTUNITY OF ENGINE REMOVAL PROVIDED INTERVAL NOT EXCEEDED	108 MO OR 15000 FH NOTE	1 1 1	0.10 0.10 0.10	c2, c4, c6, c8, c10, c12, c14, c16
2-28	282400-02-1	ENGINE LOW PRESSURE SHUT OFF OPERATIONAL CHECK OF LP SHUT OFF VALVES INCLUDING OPERATION BY INDIVIDUAL MOTORS	180 MO OR 24000 FH	1	0.1	c4, c8, c12, c16
2-28	282541-01-1	COUPLING REFUEL/DEFUEL DETAILED INSPECTION OF COUPLING REFUEL/DEFUEL.	72 MO OR 5000 FC	1 1	0.10 0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
2-28	282900-02-1	APU LOW PRESSURE FUEL SHUT OFF OPERATIONAL CHECK OF APU LP FUEL VALVE FOR EVIDENCE OF INTERNAL LEAKAGE WITH LEFT WING TANK PUMP ON	252 MO OR 36000 FH	1 1	0.20 0.20	c6, c12

Figure A.4: ATA 28 MPD tasks selected page 4

A.2 A320 MPD auxiliary power tasks

SECTION	TASK NUMBER	DESCRIPTION	100% INTERVAL	MEN	TASK M.H.	TASK ALLOCATION
2-49	491200-A2-1	APU MOUNTS GENERAL VISUAL INSPECTION OF APU SUSPENSION SYSTEM FOR CONDITION AND SECURITY. NOTE: INTERVAL: - TASK MAY BE ACCOMPLISHED AT OPPORTUNITY OF APU CHANGE.	36 MO OR 5200 FC NOTE	1 1	0.55 0.55	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
2-49	491300-A1-1	FIRE SEALS GENERAL VISUAL INSPECTION OF ALL APU COMPARTMENT FIRE WALLS AND SEALS: - COMPARTMENT DOORS - FWD AND AFT FIRE WALLS - SIDE FIRE WALLS - UPPER FIRE WALL	36 MO	1	1.42	c2, c4, c6, c8, c10, c12, c14, c16
2-49	491600-A1-1	AIR INTAKE SYSTEM DETAILED INSPECTION OF APU AIR INTAKE, DIFFUSER ELBOW, SEALS AND FELT METAL	40 MO	1	0.3	c2, c4, c6, c8, c10, c12, c14, c16
2-49	491600-A2-1	AIR INTAKE SYSTEM OPERATIONAL CHECK OF AIR INTAKE FLAP AND DIVERTER	48 MO	1	0.3	c2, c4, c6, c8, c10, c12, c14, c16
2-49	494000-A1-1	IGNITION AND STARTING REMOVE AND DISCARD IGNITER PLUGS	24 MO OR 2250 FH	1	0.05	a4
2-49	498000-A4-1	EXHAUST GENERAL VISUAL INSPECTION OF APU COMPARTMENT EXHAUST MUFFLER INSULATION COVERS AND BELLOWS	36 MO	1	0.1	c2, c4, c6, c8, c10, c12, c14, c16

Figure A.5: ATA 49 MPD tasks selected

A.3 A320 MPD powerplant tasks

SECTION	TASK NUMBER	DESCRIPTION	100% INTERVAL	MEN	TASK M.H.	TASK ALLOCATION
2-71	711000-C1-1	COWLINGS GENERAL VISUAL INSPECTION OF AIR INTAKE COWL AFT BULKHEAD	108 MO OR 12000 FH	1 1	0.05 0.05	c2, c4, c6, c8, c10, c12, c14, c16
2-71	711000-C4-2	COWLINGS GENERAL VISUAL INSPECTION OF FAN COWL DOORS	24 MO	1 1	0.45 0.45	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
2-71	711000-C5-1	COWLINGS FUNCTIONAL CHECK OF PRESSURE RELIEF DOOR LATCH TENSION.	36 MO	1 1	0.25 0.25	c2, c4, c6, c8, c10, c12, c14, c16
2-71	711000-C6-1	COWLINGS GENERAL VISUAL INSPECTION OF FAN COWL LATCHES AND ADJACENT STRUCTURE	24 MO OR 7500 FH	1 1	0.40 0.40	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
2-71	711000-C7-1	COWLINGS GENERAL VISUAL INSPECTION OF FAN COWL DOOR FIRE SEALS	36 MO OR 12000 FH	1 1	0.42 0.42	c2, c4, c6, c8, c10, c12, c14, c16
2-71	711300-C1-1	FAN COWLINGS FUNCTIONAL CHECK OF FAN COWL LATCH TENSION	20 MO	1 1	0.27 0.27	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure A.6: Powerplant MPD tasks selected page 1

2-71	711300-C2-1	FAN COWLINGS DETAILED INSPECTION OF THE KEEPER ASSY FAN COWL LOCKING DEVICE	24 MO OR 2000 FC	1 1	0.15 0.15	a2, a4
2-72	722000-C1-1	FAN SECTION DETAILED INSPECTION OF SPINNER, ENGINE INLET, FAN BLADES, FAN OUTLET AND ABRADABLE MATERIAL. NOTE: INTERVAL: - DEPENDING ON OPERATING ENVIRONMENT AND OPERATORS EXPERIENCE, A LESS FREQUENT OR MORE FREQUENT INITIAL INTERVAL MAY BE USED.	24 MO OR 2000 FC NOTE	1 1	0.30 0.30	a2, a4
2-72	722000-C3-1	FAN SECTION DETAILED INSPECTION AND RELUBRICATION OF FAN BLADE DOVETAILS, MIDSPAN SHROUDS, SPACERS, PLATFORMS AND FAN DISK DOVETAIL SLOTS.	3000 FC	1 1	1.20 1.20	a4
2-72	724000-C1-1	COMBUSTION SECTION BORESCOPE INSPECTION OF COMBUSTION CHAMBER LINERS, DOME AREAS, HPT NOZZLE VANES AND SHROUDS (AS FAR AS VISIBLE THROUGH TWO OPPOSITE PORTS)	36 MO OR 1600 FC	1 1	0.60 0.60	a2, a4
2-72	725000-C1-3	TURBINE SECTION BORESCOPE INSPECTION OF HPT BLADES (FROM THE FRONT AND THE REAR)	24 MO OR 1600 FC	1 1	0.60 0.60	a2, a4
2-73	730000-C3-1	ENGINE FUEL & CONTROL-GENERAL READ ENGINE SCHEDULED MAINTENANCE REPORT (SMR) FOR UNLIMITED (ASTERISKED) FAULTS.	1200 FH	1	0.1	a2, a4

Figure A.7: Powerplant MPD tasks selected page 2

2-73	730000-C4-1	ENGINE FUEL AND CONTROL REMOVE, INSPECT AND REPLACE FUEL FILTER ELEMENT	36 MO OR 4000 FH	1 1	0.40 0.40	a4
2-78	781100-C2-1	HOT EXHAUST GENERAL VISUAL INSPECTION OF INNER AND OUTER SEALS	72 MO OR 6000 FH	1 1	0.10 0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
2-78	781112-C1-1	CENTERBODY DETAILED INSPECTION OF THE EXHAUST CENTERBODY NOTE: PLANNING: - CENTERBODY WITH P/N 238-0451-511, 238-0451-513 AND 238-0451-523 DO NOT REQUIRE INSPECTION.	3000 FH	1 1	0.42 0.42	a4
2-78	781112-C1-2	CENTERBODY DETAILED INSPECTION OF THE EXHAUST CENTERBODY NOTE: INTERVAL: - CENTERBODY WITH P/N 238-0451-505, 238-0451-515, 238-0451-519 AND 238-0451-521 CAN BE INSPECTED EVERY 3000 FH IF A REINFORCEMENT DOUBLER HAS BEEN INSTALLED (POST VSB RA32078-65).	400 FH NOTE	1 1	0.42 0.42	weekly
2-78	783000-C2-1	THRUST REVERSER GENERAL VISUAL INSPECTION OF BLOCKER DOOR SEALS (BLOCKER DOORS DEPLOYED)	108 MO OR 12000 FH	1 1	0.20 0.20	c2, c4, c6, c8, c10, c12, c14, c16

Figure A.8: Powerplant MPD tasks selected page 3

2-78	783000-C4-1	THRUST REVERSER GENERAL VISUAL INSPECTION OF THRUST REVERSER HALF TENSION HOOK LATCH AND ADJACENT STRUCTURE (C DUCTS OPEN)	36 MO	1 1	0.20 0.20	c2, c4, c6, c8, c10, c12, c14, c16
2-78	783000-C8-1	THRUST REVERSER GENERAL VISUAL INSPECTION OF INNER BARREL HEATSHIELD, FIRE PROTECTIVE COATING AND FIRE SEALS (C DUCTS OPEN)	72 MO OR 7500 FH	1 1	0.20 0.20	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
2-78	783000-C9-1	THRUST REVERSER DETAILED INSPECTION OF TRU STRUTS.	108 MO OR 12000 FH	1	2	c2, c4, c6, c8, c10, c12, c14, c16
2-78	783100-C1-1	THRUST REVERSER CONTROL AND INDICATING CHECK HYDRAULIC CONTROL UNIT FILTER POP-OUT INDICATOR POSITION	12 MO OR 1500 FH	1 1	0.10 0.10	a2, a4
2-78	783100-C5-1	THRUST REVERSER CONTROL AND INDICATING DETAILED INSPECTION OF ACTUATOR ROD END ATTACHMENTS (BLOCKER DOORS DEPLOYED)	24 MO OR 7500 FH	1 1 1 1	0.08 0.08 0.08 0.08	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
2-78	783100-C6-1	THRUST REVERSER CONTROL AND INDICATING OPERATIONAL CHECK OF ACTUATOR SECONDARY LOCK MECHANISM	180 MO OR 8000 FC OR 24000 FH	1 1	0.20 0.20	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure A.9: Powerplant MPD tasks selected page 4

2-78	783100-C7-1	THRUST REVERSER CONTROL AND INDICATING GENERAL VISUAL INSPECTION OF PRIMARY LATCH MECHANISM (BLOCKER DOORS DEPLOYED)	72 MO OR 7500 FH	1 1 1 1	0.15 0.15 0.15 0.15	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
2-78	783100-C8-1	THRUST REVERSER CONTROL AND INDICATING GENERAL VISUAL INSPECTION OF ACTUATOR ROD END ATTACHMENTS (BLOCKER DOORS DEPLOYED)	108 MO OR 12000 FH	1 1 1 1	0.08 0.08 0.08 0.08	c2, c4, c6, c8, c10, c12, c14, c16
2-80	801110-C1-1	STARTER CHECK CHIP DETECTOR	12 MO OR 1000 FH	1 1	0.30 0.30	a2, a4
2-80	801110-C2-1	STARTER REPLENISH OIL SYSTEM	6 MO OR 600 FH	1 1	0.20 0.20	a1, a2, a3, a4
2-80	801110-C3-1	STARTER DRAIN AND REPLENISH OIL SYSTEM	12 MO OR 1200 FH	1 1	0.30 0.30	a2, a4
3-71	711300-01-2	FAN COWL DOOR HINGE FITTINGS GENERAL VISUAL INSPECTION OF FAN COWL DOOR HINGE FITTINGS AND SURROUNDING STRUCTURE. NOTE: PLANNING: - CREDIT CAN BE TAKEN FROM PREVIOUS ACCOMPLISHMENT OF TASK 711300-01-1.	7500 FC	1 1 1 1	0.20 0.20 0.20 0.20	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
3-71	712111-01-1	FORWARD ENGINE MOUNT DETAILED INSPECTION OF FORWARD ENGINE MOUNT INSTALLATION	3 YE OR 2200 FC OR 4500 FH	1 1 1 1 1 1	0.10 0.10 0.10 0.10 0.10 0.10	a2, a4

Figure A.10: Powerplant MPD tasks selected page 5

3-71	712111-02-1	FORWARD ENGINE MOUNT DETAILED INSPECTION OF DISASSEMBLED FORWARD ENGINE MOUNT INSTALLATION INCLUDING MATING SURFACES.	12 YE	1 1 1 1 1 1	0.50 0.50 0.50 0.50 0.50 0.50	c8, c16
3-71	712111-05-4	FORWARD ENGINE MOUNT SPECIAL DETAILED INSPECTION (TC) OF FORWARD ENGINE MOUNT PYLON BOLTS	7500 FC OR 15000 FH	1 1	0.58 0.58	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
3-71	712112-01-1	FORWARD ENGINE MOUNT SPECIAL DETAILED INSPECTION (ENDOSCOPE) OF FORWARD ENGINE MOUNT LINK LUGS	7500 FC OR 15000 FH	1 1	0.55 0.55	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
3-71	712211-01-1	AFT ENGINE MOUNT DETAILED INSPECTION OF DISASSEMBLED AFT ENGINE MOUNT INSTALLATION INCLUDING MATING SURFACES.	12 YE	1 1 1 1 1 1	0.50 0.50 0.50 0.50 0.50 0.50	c8, c16
3-71	712211-03-1	AFT ENGINE MOUNT DETAILED INSPECTION OF AFT ENGINE MOUNT INSTALLATION	6 YE OR 7500 FC OR 15000 FH	1 1 1 1 1 1	0.10 0.10 0.10 0.10 0.10 0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
3-71	712211-05-1	AFT ENGINE MOUNT SPECIAL DETAILED INSPECTION (TC) OF AFT ENGINE MOUNT PYLON BOLTS	7500 FC OR 15000 FH	1 1	0.50 0.50	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure A.11: Powerplant MPD tasks selected page 6

3-71	712212-01-1	AFT ENGINE MOUNT SPECIAL DETAILED INSPECTION (ENDOSCOPE) OF AFT ENGINE MOUNT LINK LUGS	7500 FC OR 15000 FH	1 1	0.63 0.63	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
3-71	712213-01-1	AFT ENGINE MOUNT SPECIAL DETAILED INSPECTION (ENDOSCOPE) OF AFT ENGINE MOUNT PINS	7500 FC OR 15000 FH	1 1	0.80 0.80	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
3-78	783001-01-1	THRUST REV 12 O'CLOCK BEAM JUNCTION DETAILED INSPECTION OF THRUST REVERSER 12 O'CLOCK BEAM JUNCTION WITH THE FORWARD FRAME	12 YE OR 15000 FC	1 1 1 1	0.20 0.20 0.20 0.20	c3, c6, c14, c9, c12, c15
3-78	783002-01-1	THRUST REVERSER FORWARD FRAME DETAILED INSPECTION OF THRUST REVERSER FORWARD FRAME TO 6 O'CLOCK BEAM JOINT	12 YE OR 15000 FC	1 1 1 1	0.20 0.20 0.20 0.20	c3, c6, c14, c9, c12, c15
3-78	783003-01-1	THRUST REVERSER FORWARD FRAME DETAILED INSPECTION OF THRUST REVERSER FORWARD FRAME TO 3/9 O'CLOCK BEAM JOINT	12 YE OR 15000 FC	1 1 1 1	0.20 0.20 0.20 0.20	c3, c6, c14, c9, c12, c15
3-78	783004-01-1	THRUST REVERSER FORWARD FRAME SPECIAL DETAILED INSPECTION (HFEC) OF THRUST REVERSER FORWARD FRAME AT ACTUATOR ATTACHMENT	15000 FC	1 1 1 1	0.67 0.67 0.67 0.67	c3, c6, c14, c9, c12, c15

Figure A.12: Powerplant MPD tasks selected page 7

3-78	783004- 02-1	THRUST REVERSER FORWARD FRAME DETAILED INSPECTION OF THRUST REVERSER FORWARD FRAME AT ACTUATOR ATTACHMENT	12 YE	1 1 1 1	0.20 0.20 0.20 0.20	c8, c16
3-78	783200- 01-1	"C" DUCT HINGE FITTING GENERAL VISUAL INSPECTION OF "C" DUCT HINGE FITTINGS AND SURROUNDING STRUCTURE.	7500 FC	1 1 1 1	0.15 0.15 0.15 0.15	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
3-78	783200- 02-1	"C" DUCT HINGE FITTING DETAILED INSPECTION OF "C" DUCT HINGE FITTINGS AND SURROUNDING STRUCTURE.	12 YE	1 1 1 1 1 1	0.49 0.49 0.49 0.49 0.49 0.49	c8, c16
3-78	783209- 01-1	THRUST REVERSER DETAILED INSPECTION OF THRUST REVERSER V-GROOVE ADAPTER RING.	6 YE OR 7500 FC	1 1 1 1	TBD TBD TBD TBD	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
4-ZL- 400	ZL-400- 02-1	POWERPLANTS, NACELLES AND PYLONS GENERAL VISUAL INSPECTION OF POWERPLANTS, NACELLES AND PYLONS	12 MO	1	0.2	a2, a4
4-ZL- 400	ZL-411- 01-3	UPPER FORWARD PYLON GENERAL VISUAL INSPECTION OF UPPER FORWARD PYLON (EWIS)	24 MO	1 1 1 1 1 1	0.03 0.03 0.03 0.03 0.03 0.03	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure A.13: Powerplant MPD tasks selected page 8

4-ZL-400	ZL-415-01-1	LOWER PYLON GENERAL VISUAL INSPECTION OF LOWER PYLON (EWIS)	48 MO	1 1	0.20 0.20	c2, c4, c6, c8, c10, c12, c14, c16
4-ZL-400	ZL-433-01-1	AIR INTAKE LIP GENERAL VISUAL INSPECTION OF AIR INTAKE LIP (EWIS)	72 MO OR 24000 FH	1 1 1 1	0.15 0.15 0.15 0.15	c4, c8, c12, c16
4-ZL-400	ZL-435-01-1	FAN AND ACCESSORY GEAR BOX GENERAL VISUAL INSPECTION OF FAN AND ACCESSORY GEAR BOX (EWIS)	12 MO	1 1 1 1	0.10 0.10 0.10 0.10	a2, a4
4-ZL-400	ZL-437-01-1	FAN COWL GENERAL VISUAL INSPECTION OF FAN COWL (EWIS)	24 MO	1 1 1 1	0.10 0.10 0.10 0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
4-ZL-400	ZL-451-01-1	THRUST REVERSER GENERAL VISUAL INSPECTION OF THRUST REVERSER (EWIS)	24 MO	1 1 1 1	0.10 0.10 0.10 0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
4-ZL-400	ZL-453-01-1	HOT SECTION GENERAL VISUAL INSPECTION OF HOT SECTION (EWIS)	24 MO	1 1 1 1	0.10 0.10 0.10 0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure A.14: Powerplant MPD tasks selected page 9

4-ZL-400	ZL-471-01-4	PYLON LEADING EDGE AND LOWER FAIRING GENERAL VISUAL INSPECTION OF PYLON LEADING EDGE AND LOWER FAIRING (EWIS)	24 MO	1 1 1 1 1 1 1 1 1 1 1 1	0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure A.15: Powerplant MPD tasks selected page 10

A.4 ATR72 MPD powerplant tasks

Appendix B

New tasks collection

B.1 TP-PHEP

Component	No.	Task Code	Task Description	Interval MTBF based (FH)	Interval from MPDs	Task MH	Task allocation
Propeller unit	4	OPC	Operational check of pitch mechanism	3615.698	-	0.64	a4
	4	RST	Restoration / Overhaul of the propeller blades & hub	13890.902	10,500 FH	18	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	4	GVI	General visual inspection of propeller blades, hub and spinner for cracks in material and proper mounting	10150.4	1,500 FH or 9 MO	0.4	a2, a4
	4	SRV	Cleaning of blade surface	7488.821	-	8	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	4	SRV	Check of Propeller Oil Level	7488.821	3,000 FH or 18 MO	1.6	a4
	4	OPC	Operational Check of Propeller Anti-Icing System	3615.698	750 FH or 4,5 MO	1.2	a1, a2, a3, a4
	4	GVI	Removal of Propeller Anti-Icing System for General Visual Inspection and Cleaning	10150.4	500 FH	4	a1, a2, a3, a4
Propeller control unit	--	FNC	Functional Check of Propeller Electronic Control Unit (PEC) through BITE		8,000 FH	0.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Gearbox	4	SRV	Checking oil level of gearbox	9285.3287	72 MO or 6,000 FH	1.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	4	SDI	Special detailed inspection of gearbox (Endoscope)	11651.58		10.00	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	4	SRV	Lubrication of gearbox	9285.3287	144 MO or 18,000 FH	2	c3, c6, c9, c12, c15

Figure B.1: New tasks introduced TP-PHEP page 1

TMS gearbox - Pump	6	FNC	Functional check of the cooling pump (Water-mixture)	5213.3083	72 MO or 10,000 FH	1	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS gearbox - Heat exchanger	4	RST	Remove heat exchangers for in-shop cleaning (Oil & Water-mixture)	7706.2458	108 MO or 12,000 FH	1	c2, c4, c6, c8, c10, c12, c14, c16
TMS gearbox - Piping	2	FNC	Functional check for leakage of TMS piping system	61396.617	6,300 FH	1.8	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS gearbox - Coolant filter	4	DIS	Discard of filter for cooling fluid (Oil & Water-mixture)	273147.82	5,000 FH	0.10	a4
TMS gearbox - Coolant	1	SRV	Check of coolant level (Water mixture)		72 MO or 6,000 FH	0.3	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	1	SRV	Exchange of coolant (Water mixture)		48 MO	0.5	c2, c4, c6, c8, c10, c12, c14, c16
TMS motor - all components	1	VCK	Visual check of TMS components for leaks	-	108 MO or 12,000 FH	0.05	c2, c4, c6, c8, c10, c12, c14, c16
Electric Motor + Inverter	20	RST	In-Shop restoration of motor unit (LLPs - Bearing / Windings) - calibration of motor sensors	8496.3036	-		c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	20	FNC	Functional check of motor unit including inverter (BITE)	5747.7858	-	0.10	a4
Mounting	2	VCK	Visual Check of mounting system and other load-bearing structural parts	10932.49	36 MO or 5,200 FC	2.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	2	SDI	Special detailed inspection of mounting system and other load-bearing structural parts (Endoscope)	29193.102	7,500 FC or 15,000 FH	2.68	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure B.2: New tasks introduced TP-PHEP page 2

TMS motor - Pump	6	FNC	Functional check of the cooling pump (Water-mixture)	5213.3083	72 MO or 10,000 FH	1	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS motor - Heat exchanger	4	RST	Remove heat exchangers for in-shop cleaning (Oil & Water-mixture)	23836.557	108 MO or 12,000 FH	1	c2, c4, c6, c8, c10, c12, c14, c16
TMS motor - Piping	2	FNC	Functional check for leakage of TMS piping system	61396.617	3,000 FH	1.8	a4
TMS motor - Coolant filter	4	DIS	Discard of filter for cooling fluid (Oil & Water-mixture)	273147.82	5,000 FH	0.05	a4
TMS motor - Ion filter	2	DIS	Discard of ion filter (Water-mixture)	273147.82	5,000 FH	0.05	a4
TMS motor - Coolant	1	SRV	Check of coolant level (Water mixture)		72 MO or 6,000 FH	0.3	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	1	SRV	Exchange of coolant (Water mixture)		48 MO	0.5	c2, c4, c6, c8, c10, c12, c14, c16
TMS motor - all components	1	VCK	Visual check of TMS components for leaks	-	108 MO or 12,000 FH	0.05	c2, c4, c6, c8, c10, c12, c14, c16
Sensoring	--	FNC	Functional check of sensoring for TMS and components (motor, inverter and gearbox)	129371.99	72 MO or 7500 FH	0.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Circuit Breaker	--	FNC	Functional check of circuit breaker	13351.39	-	0.1	c2, c4, c6, c8, c10, c12, c14, c16
	--	OPC	Operational check of circuit breaker	5137.0955	72 MO or 7,500 FH	0.15	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Battery	2	FNC	Functional Check of battery pack and checking of degradation status through BITE	9851.1067	6 MO	0.2	a1, a2, a3, a4
	2	DIS	Replacement of battery pack with new unit and calibration of sensors	24637.842	3000 FC	0.3	a4
Converter	--	FNC	Functional Check of biderictional converter through BITE	15949.976	750 FH	0.1	a1, a2, a3, a4

Figure B.3: New tasks introduced TP-PHEP page 3

BMS	9	FNC	Functional Check of BMS, sensors and communication lines through BITE	33084.743	12 MO or 1,000 FH	0.1	a2, a4
TMS battery - Coolant	1	SRV	Check of TMS coolant level		72 MO or 6,000 FH	0.03	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	1	SRV	Drain and refill of TMS cooling fluid		48 MO	0.5	c2, c4, c6, c8, c10, c12, c14, c16
TMS battery - Piping	3	FNC	Functional check for leakage of TMS piping system	61396.617	6,300 FH	1.8	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS battery - Pump	9	FNC	Functional check of TMS pump	5213.3083	72 MO or 10,000 FH	1	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS battery - Heat Exchanger	3	RST	Remove TMS heat-exchanger for in-shop cleaning	23836.557	108 MO or 12,000 FH	1	c2, c4, c6, c8, c10, c12, c14, c16
TMS battery - Condenser	3	RST	Remove TMS condenser for in-shop cleaning and for in-shop leake test	29081.51	144 MO or 18,000 FH	1	c3, c6, c9, c12, c15
TMS battery - Coolant filter	3	DIS	Discard of TMS filter for cooling fluid	273147.82	5,000 FH	0.05	a4
TMS battery - Expansion Vessel	3	SDI	Special detailed inspection of the Expansion Vessel (membran and leakage)	26026.545	144 MO or 18,000 FH	1	c3, c6, c9, c12, c15
TMS battery - Heating Element	3	FNC	Functional check of TMS heating element	45501.07		0.2	c7, c14
	3	RST	Remove heating element for in-shop cleaning	48276.249	108 MO or 12,000 FH	0.42	c2, c4, c6, c8, c10, c12, c14, c16
TMS battery - Ion filter	3	DIS	Discard of TMS ion exchange filter	273147.82	5,000 FH	0.05	a4
TMS battery - Sensoring	3	FNC	Functional check of sensoring for TMS	129371.99	72 MO or 7500 FH	0.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure B.4: New tasks introduced TP-PHEP page 4

TMS all components	1	VCK	Visual check of TMS components for leaks	-	108 MO or 12,000 FH	0.05	c2, c4, c6, c8, c10, c12, c14, c16
Mounting Battery	2	VCK	Visual Check of mounting system and other load-bearing structural parts	23264.445	36 MO or 5,200 FC	1.100	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	2	SDI	Special detailed inspection of mounting system and other load-bearing structural parts	23264.445	7,500 FC or 15,000 FH	1.340	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Casing Battery	2	VCK	Visual Check of battery safety casing		4 MO	0.8	a1, a2, a3, a4
	2	SDI	Special detailed inspection of battery safety casing		10000 FC	3.36	c2, c4, c6, c8, c10, c12, c14, c16
Burst disk battery	2	GVI	Generalvisual inspection of battery safety venting system (burst disc)		24 MO or 2,000 FH	0.1	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	2	DIS	Discard of safety battery safety venting system (burst disc)		120 MO	0.65	c6, c12
Wiring	1	GVI	General visual inspection of Wiring and Connectors	692125.91	12 MO	0.1	a2, a4
	1	DET	Detailed inspection of the wiring and connectors	640771.13	24 MO	0.13	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Control unit	3	FNC	Functional Check of control unit for electric distribution	9893.182	12 MO or 1,000 FH	0.1	a2, a4
Communication lines	1	DET	Detailed inspection of communication lines	640771.13	12 MO	0.1	a2, a4
	1	GVI	General visual inspection of communication lines	692125.91	24 MO	0.13	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
		FNC	Functional check of circuit breaker	13351.39		0.1	c2, c4, c6, c8, c10, c12, c14, c16

Figure B.5: New tasks introduced TP-PHEP page 5

Circuit Breaker	--	OPC	Operational Check of circuit breaker	5137.0955	72 MO or 7,500 FH	0.15	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure B.6: New tasks introduced TP-PHEP page 6

B.2 MHEP configurations

Component	No.	Task Code	Task Description	Interval MTBF based (FH)	Interval from MPDs	Task MH	Task allocation
Propeller unit	2	OPC	Operational check of pitch mechanism	3615.698	-	0.32	a4
	2	RST	Restoration / Overhaul of the propeller blades & hub	13890.902	10,500 FH	9.00	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	2	GVI	General visual inspection of propeller blades, hub and spinner for cracks in material and proper mounting	10150.4	1,500 FH or 9 MO	0.20	a2, a4
	2	SRV	Cleaning of blade surface	7488.821	-	4.00	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	2	SRV	Check of Propeller Oil Level	7488.821	3,000 FH or 18 MO	0.80	a4
	2	OPC	Operational Check of Propeller Anti-Icing System	3615.698	750 FH or 4,5 MO	0.60	a1, a2, a3, a4
	2	GVI	Removal of Propeller Anti-Icing System for General Visual Inspection and Cleaning	10150.4	500 FH	2.00	a1, a2, a3, a4
Propeller control unit	--	FNC	Functional Check of Propeller Electronic Control Unit (PEC) through BITE		8,000 FH	0.20	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Fan	2	GVI	General visual inspection of fan and accessory gear box		12 MO	0.20	a2, a4
Gearbox	2	SRV	Checking oil level of gearbox	9285.3287	36 MO or 3,000 FH	0.60	a4
	2	SDI	Special detailed inspection of gearbox (Endoscope)	11651.58	-	5.00	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	2	SRV	Lubrication of gearbox	9285.3287	144 MO or 18,000 FH	1.00	c3, c6, c9, c12, c15

Figure B.7: New tasks introduced MHEP page 1

TMS gearbox - Pump	6	FNC	Functional check of the cooling pump (Water-mixture)	5213.3083	72 MO or 10,000 FH	1.000	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS gearbox - Heat exchanger	4	RST	Remove heat exchangers for in-shop cleaning (Oil & Water-mixture)	23836.557	108 MO or 12,000 FH	1.000	c2, c4, c6, c8, c10, c12, c14, c16
TMS gearbox - Piping	2	FNC	Functional check for leakage of TMS piping system	61396.617	6,300 FH	1.800	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS gearbox - Coolant filter	4	DIS	Discard of filter for cooling fluid (Oil & Water-mixture)	273147.82	5,000 FH	0.05	a4
TMS gearbox - Coolant	1	SRV	Check of coolant level (Water mixture)		72 MO or 6,000 FH	0.03	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11
	1	SRV	Exchange of coolant (Water mixture)		48 MO	0.50	c2, c4, c6, c8, c10, c12, c14, c16
TMS motor - all components	1	VCK	Visual check of TMS components for leaks	-	108 MO or 12,000 FH	0.050	c2, c4, c6, c8, c10, c12, c14, c16
Electric Motor	--	RST	In-Shop restoration of motor unit (LLPs - Bearing / Windings) - calibration of motor sensors	8496.3036	-		c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	--	FNC	Functional check of motor unit including inverter (BITE)	5747.7858	-	0.10	a4
Mounting	2	VCK	Visual Check of mounting system and other load-bearing structural parts	10932.49	36 MO or 5,200 FC	1.100	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	2	SDI	Special detailed inspection of mounting system and other load-bearing structural parts (Endoscope)	29193.102	7,500 FC or 15,000 FH	1.340	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure B.8: New tasks introduced MHEP page 2

TMS motor - Pump	6	FNC	Functional check of the cooling pump (Water-mixture)	5213.3083	72 MO or 10,000 FH	1.000	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS motor - Heat exchanger	4	RST	Remove heat exchangers for in-shop cleaning (Oil & Water-mixture)	23836.557	108 MO or 12,000 FH	1.000	c2, c4, c6, c8, c10, c12, c14, c16
TMS motor - Piping	2	FNC	Functional check for leakage of TMS piping system	61396.617	6,300 FH	1.800	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS motor - Coolant filter	4	DIS	Discard of filter for cooling fluid (Oil & Water-mixture)	273147.82	5,000 FH	0.050	a4
TMS motor - Ion filter	2	DIS	Discard of ion filter (Water-mixture)	273147.82	5,000 FH	0.050	a4
TMS motor - Coolant	1	SRV	Check of coolant level (Water mixture)	6231.4835	72 MO or 6,000 FH	0.06	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	1	SRV	Exchange of coolant (Water mixture)		48 MO	0.50	c2, c4, c6, c8, c10, c12, c14, c16
TMS motor - all components	1	VCK	Visual check of TMS components for leaks	-	108 MO or 12,000 FH	0.050	c2, c4, c6, c8, c10, c12, c14, c16
Sensoring	--	FNC	Functional check of sensoring for TMS and components (motor, inverter and gearbox)	129371.99	72 MO or 7,500 FH	0.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Circuit Breaker	--	FNC	Functional check of circuit breaker	13351.39	-	0.1	c2, c4, c6, c8, c10, c12, c14, c16
	--	OPC	Operational check of circuit breaker	5137.0955	-	0.100	a4
Battery	2	FNC	Functional Check of battery pack and checking of degradation status through BITE	9851.1067	6 MO	0.2	a1, a2, a3, a4
	2	DIS	Replacement of battery pack with new unit and calibration of sensors	24637.842	3000 FC	0.300	a4
Converter	--	FNC	Functional Check of biderictional converter through BITE	15949.976	750 FH	0.100	a1, a2, a3, a4

Figure B.9: New tasks introduced MHEP page 3

BMS	2	FNC	Functional Check of BMS, sensors and communication lines through BITE	33084.743	12 MO or 1,000 FH	0.100	a2, a4
TMS battery - Coolant	2	SRV	Check of TMS coolant level		72 MO or 6,000 FH	0.030	c1, c2, c3, c4, c5, c6, c7, c8
	2	SRV	Drain and refill of TMS cooling fluid		48 MO	0.50	c2, c4, c6, c8, c10, c12, c14, c16
TMS battery - Piping	2	GVI	General visual inspection of TMS piping system	66317.265	6,300 FH	1.800	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS battery - Pump	2	FNC	Functional check of TMS pump	5213.3083	72 MO or 10,000 FH	1.000	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS battery - Heat Exchanger	2	RST	Remove TMS heat-exchanger for in-shop cleaning	23836.557	108 MO or 12,000 FH	1.000	c2, c4, c6, c8, c10, c12, c14, c16
TMS battery - Coolant filter	2	DIS	Discard of TMS filter for cooling fluid	273147.82	5,000 FH	0.050	a4
TMS battery - Heating Element	2	FNC	Functional check of TMS heating element	45501.07		0.2	c7, c15
	2	RST	Remove heating element for in-shop cleaning	67259.1	108 MO or 12,000 FH	0.420	c2, c4, c6, c8, c10, c12, c14, c16
TMS battery - Ion filter	2	DIS	Discard of TMS ion exchange filter	273147.82	5,000 FH	0.050	a4
TMS battery - Sensoring	2	FNC	Functional check of sensoring for TMS	129371.99	72 MO or 7500 FH	0.200	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS all components	-	VCK	Visual check of TMS components for leaks	-	108 MO or 12,000 FH	0.050	c2, c4, c6, c8, c10, c12, c14, c16
Mounting Battery	2	VCK	Visual Check of mounting system and other load-bearing structural parts	10932.49	36 MO or 5,200 FC	0.550	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure B.10: New tasks introduced MHEP page 4

		SDI	Special detailed inspection of mounting system and other load-bearing structural parts	29193.102	7,500 FC or 15,000 FH	0.670	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Casing Battery	2	VCK	Visual Check of battery safety casing			0.4	a1, a2, a3, a4
		SDI	Special detailed inspection of battery safety casing			1.68	c2, c4, c6, c8, c10, c12, c14, c16
Burst disk battery	2	GVI	Generalvisual inspection of battery safety venting system (burst disc)		24 MO or 2,000 FH	0.100	a4
	2	DIS	Discard of safety battery safety venting system (burst disc)		120 MO	0.650	c6, c12
Wiring	1	GVI	General visual inspection of Wiring and Connectors	692125.91	12 MO	0.100	a2, a4
	1	DET	Detailed inspection of the wiring and connectors	640771.13	24 MO	0.130	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Control unit	3	FNC	Functional Check of control unit for electric distribution	9893.182	12 MO or 1,000 FH	0.100	a2, a4
Communication lines	1	DET	Detailed inspection of communication lines	640771.13	12 MO	0.100	a2, a4
	1	GVI	General visual inspection of communication lines	692125.91	24 MO	0.130	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Circuit Breaker	--	FNC	Functional check of circuit breaker	13351.39		0.1	c2, c4, c6, c8, c10, c12, c14, c16
	--	OPC	Operational Check of circuit breaker	5137.0955	72 MO or 7,500 FH	0.15	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Tank	2	SDI	Special detailed inspection (NDT) of the inner tank to detect damges	11276.706	120 MO or 10,000 FC	2.00	c2, c4, c6, c8, c10, c12, c14, c16
	2	FNC	Functional check of the tank isolation	11276.706	10,000 FC	2.00	c2, c4, c6, c8, c10, c12, c14, c16

Figure B.11: New tasks introduced MHEP page 5

	2	GVI	General visual inspection of the outer tank to detect damages and leakages	12180.48	10,000 FC	1.16	c2, c4, c6, c8, c10, c12, c14, c16
Tank Shut off Valve	2	OPC	Operational check of the LH2 tank shut off valve by BITE	36099.041	108 MO or 15,000 FH	0.10	c3, c6, c9, c12, c15
	2	FNC	Removal of the LH2 tank shut off valve for in-shop Functional Check including cleaning	93821.963	180 MO or 24,000 FH	0.20	c4, c8, c12, c16
Tank, piping, valves, pumps, evaporators, heat exchangers	1	SDI	Lekage inspection via lekage/ pressure test of the tank and distribution system with a substitute gas (Helium, Nitrogen)	-	108 MO or 12,000 FH	0.05	c2, c4, c6, c8, c10, c12, c14, c16
	1	FNC	Functional check of the piping system	-	3,000 FH	1.80	a4
Distribution valves	10	FNC	Removal of all valves in the distribution system for in-shop Functional Check including cleaning	248574.51	144 MO or 36,000 FH	0.30	c6, c12
	10	OPC	Operational check of all valves in the distribution system by BITE	95641.798	72 MO or 10,000 FH	0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Safety (Venting Valve)	14	FNC	Removal of the safety (venting) valve for in-shop Functional Check	99642.48	80 MO or 24,000 FH	0.83	c4, c8, c12, c16
Burst Disk	4	GVI	General visual inspection of burst disk		24 MO or 2,000 FH	0.10	a4
	4	DIS	Discard of the burst disk		60 MO	0.65	c3, c6, c9, c12, c15
Check Valve	6	FNC	Removal of the check valves for in-shop Functional Check including cleaning	552813.19	180 MO	1.49	c10
	6	OPC	Operational check of the check valves by BITE	212701	72 MO	0.20	c4, c8, c12, c16
Electric Evaporator (Tank)	2	FNC	Functional check of the electric vaporizer (hydrogen recirculation)	10781.378	108 MO or 12,000 FH	1.00	c2, c4, c6, c8, c10, c12, c14, c16
Electric Evaporator (Fuel Cell)	2	FNC	Functional check of the electric vaporizer (fuel cell)	10781.378	108 MO or 12,000 FH	1.00	c2, c4, c6, c8, c10, c12, c14, c16
Boost Pump	6	FNC	Functional check of the boost pump	6811.2019	72 MO or 10,000 FH	1.00	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure B.12: New tasks introduced MHEP page 6

High Pressure Pump	4	FNC	Functional check of the high pressure pump	6811.2019	72 MO or 10,000 FH	1.00	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Vacuum Box (Boost pumps)	2	FNC	Functional check of the vacuum box for the boost pumps		6,300 FH	0.83	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Vacuum Box (High-pressure pumps)	2	FNC	Functional check of the vacuum box for the boost pumps		6,300 FH	0.83	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Crossfeed Valve	2	OPC	Operational check of the crossfeed valve by BITE	95641.798	72 MO or 6,000 FH	0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	2	FNC	Removal of the crossfeed valve for Functional Check including cleaning	248574.51	108 MO or 12,000 FH	0.65	c2, c4, c6, c8, c10, c12, c14, c16
Hydrogen Filter	4	RST	Inspection and cleaning of hydrogen filter	161439.4	72 MO or 8,500 FH	0.15	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	4	VCK	Visual Check of hydrogen filter for clogging indicators	40899.588	24 MO or 2000 FH	0.06	a4
Hydrogen Condition Sensoring	--	FNC	Inspection and callibration of the sensoric	30170.981	72 MO or 7500 FH	0.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Hydrogen Detection Sensoring	--	FNC	Inspection and callibration of the hydrogen sensors	351157.21	72 MO or 7500 FH	0.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Ventilation	--	OPC	Operational check of the ventilation system		16,000 FH	0.60	c2, c4, c6, c8, c10, c12, c14, c16

Figure B.13: New tasks introduced MHEP page 7

Mounting	1	SDI	Special detailed inspection of the mounting system and other load-bearing structural parts (Endoscope)	29193.102	7,500 FC or 15,000 FH	0.10	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	1	VCK	Visual Check of mounting system and other load-bearing structural parts	10932.49	36 MO or 5,200 FC	0.55	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Engine Shut off Valve	2	OPC	Operational check of the LH2 engine shut off valve by BITE	36099.041	108 MO or 15,000 FH	0.10	c3, c6, c9, c12, c15
	2	FNC	Functional check of the LH2 engine shut off valve, including testing and cleaning	93821.963	180 MO or 24,000 FH	0.20	c4, c8, c12, c16
PEMFC Stack	4	DIS	Exchange of PEM Stacks after EoL	6388.5964	10000 FH	24	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	4	FNC	Functional check of PEMFC to determine SoH via BITE / EIS	2554.3935		0.20	a4
Control unit	8	FNC	Functional check of the control units via BITE	11023.315	12 MO or 1,000 FH	0.100	a2, a4
Air flow meter including sensors (flow, humidity, temperature, pressure)	4	FNC	Functional check of air flow meter including calibration of sensors	30170.981	12 MO or 1,000 FH	0.100	a2, a4
H2 flow meter including sensors (flow, humidity, temperature, pressure)	4	FNC	Functional check of hydrogen flow meter including calibration of sensors	30170.981	12 MO or 1,000 FH	0.100	a2, a4
H2 shut off valve	4	FNC	Removal of the hydrogen shut off valve for in-shop functional check including cleaning	93821.972	180 MO or 24,000 FH	0.20	c4, c8, c12, c16
	4	OPC	Operational check of the hydrogen shut off valve by BITE	36099.044	108 MO or 15,000 FH	0.10	c3, c6, c9, c12, c15

Figure B.14: New tasks introduced MHEP page 8

H2 purge valve	4	FNC	Removal of the hydrogen purge valve for in-shop functional check including cleaning	93821.972	210 MO or 50,000 FH	0.65	c4, c8, c12, c16
	4	OPC	Operational check of the hydrogen purge valve by BITE	36099.044	108 MO or 12,000 FH	0.2	c2, c4, c6, c8, c10, c12, c14, c16
H2 pressure regulator valve	4	FNC	Removal of the hydrogen pressure regulator valve for in-shop functional check including cleaning	6109.4046	210 MO or 50,000 FH	0.65	c4, c8, c12, c16
	4	OPC	Operational check of the pressure regulator valve via bite	2350.6612	108 MO or 12,000 FH	0.2	c2, c4, c6, c8, c10, c12, c14, c16
H2 recirculation pump	4	FNC	Functional check of the hydrogen recirculation pump	6775.1905	72 MO or 10,000 FH	1.00	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
H2 filter	4	VCK	Visual Check of hydrogen filter for clogging indicators	31467.582	24 MO or 2,000 FH	0.06	a4
	4	RST	Inspection and cleaning of hydrogen filter	124209.26	72 MO or 8,500 FH	0.15	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Air filter	4	DIS	Discard of the air filter	62324.725	108 MO or 15,000 FH	0.25	c3, c6, c9, c12, c15
Air compressor	4	FNC	Functional check of the air compressor	9304.7144	36 MO or 3,000 FH	0.1	a4
Air humidifier	4	FNC	Functional check of the air humidifier	18617.68	144 MO or 18,000 FH	1	c3, c6, c9, c12, c15
Air mixing (bypass) valve	4	FNC	Removal of the air mixing (bypass) valve for in-shop functional check including cleaning	6192.7718	144 MO	0.40	c8, c16
	4	OPC	Operational check of the air mixing (bypass) valve via bite	2382.7376	24 MO	0.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Air intercooler	4	RST	Remove air intercooler for in-shop cleaning	23836.91	252 MO or 36,000 FH	0.2	c6, c12
Air pressure regulator valve	4	FNC	Removal of the air pressure regulator valve for in-shop functional check including cleaning	6109.4046	210 MO or 50,000 FH	0.65	c4, c8, c12, c16

Figure B.15: New tasks introduced MHEP page 9

	4	OPC	Operational check of the pressure regulator valve via bite	2350.6612	108 MO or 12,000 FH	0.2	c2, c4, c6, c8, c10, c12, c14, c16
H2 ventilation system (fan + motor)	4	OPC	Operational check of the ventilation system (motor + fan)		36 MO or 3,000 FH	0.1	a4
	4	FNC	Functional check of the ventilation system (motor + fan)			0.5	
H2 leakage detection system	4	OPC	Operational check of the hydrogen leakage detection system		36 MO or 3000 FH	0.1	a4
	4	RST	Remove leakage detection system for in-sop cleaning including calibration of sensors		108 MO or 12,000 FH	0.3	c2, c4, c6, c8, c10, c12, c14, c16
TMS - Coolant pump	4	FNC	Functional check of the cooling pump (TMS)	5213.3074	72 MO or 10,000 FH	1.000	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
TMS - Valves	--	FNC	Removal of the TMS valves for in-shop functional check including cleaning	201225.97	144 MO	0.4	c8, c16
	--	OPC	Operational check of the TMS valves by BITE	77423.922	108 MO or 12,000 FH	0.1	c2, c4, c6, c8, c10, c12, c14, c16
TMS - Coolant	1	SRV	Check of coolant level		72 MO or 6,000 FH	0.30	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	1	SRV	Exchange of the coolant (TMS)		48 MO	0.50	c2, c4, c6, c8, c10, c12, c14, c16
TMS - Coolant filter	4	DIS	Discard of the filter for cooling fluid (TMS)	273147.76	5,000 FH	0.050	a4
TMS - Ion exchange filter	4	DIS	Discard of the ion exchange filter (TMS)	273147.76	5,000 FH	0.050	a4
TMS - Heat exchanger	12	RST	Remove heat exchangers for in-shop cleaning (TMS)	23836.557	108 MO or 12,000 FH	1.000	c2, c4, c6, c8, c10, c12, c14, c16
TMS - Heating element	4	RST	Remove heating element for in-shop cleaning (TMS)	67259.083	108 MO or 12,000 FH	0.42	c2, c4, c6, c8, c10, c12, c14, c16
TMS - Expansion vessel	4	GVI	Check pressure gauge and check for leakage of the expansion vessel (TMS)	35276.56		0.2	c5, c10, c15

Figure B.16: New tasks introduced MHEP page 10

TMS - Temperature sensors	4	FNC	Functional check of sensoring for TMS including calibration	129372	72 MO or 7500 FH	0.2	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
Circuit breaker	8	OPC	Operational Check of the circuit breaker units	5137.0955	72 MO or 7,500 FH	0.15	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	8	FNC	Functional check of the circuit breaker units	13351.39		0.1	c2, c4, c6, c8, c10, c12, c14, c16
Mounting	4	VCK	Visual Check of mounting system and other load-bearing structural parts	10932.493	36 MO or 5,200 FC	0.550	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
	4	SDI	Special detailed inspection of the mounting system and other load-bearing structural parts (Endoscope)	29193.109	7,500 FC or 15,000 FH	0.670	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16
FC exhaust	4	GVI	General visual inspection of the exhaust for blockage	174030.14	72 MO	0.15	c4, c8, c12, c16
FC system	4	SDI	Leakage inspection via leakage/pressure test of the distribution systems with air (cathode path) and substitute gas (anode path) and the FC stack		108 MO or 12,000 FH	0.05	c2, c4, c6, c8, c10, c12, c14, c16
	4	VCK	Check the FC system for defects and leackages		6,300 FH	1.8	c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15, c16

Figure B.17: New tasks introduced MHEP page 11

Appendix C

MHEP Configurations Maintenance Plans

C.1 TP-MHEP

Check	Downtime	Interval (FH)	Interval (FC)	Interval (DY)	Material cost	MH	Labor Rate	Fixed cost	Fiscal Year
Transit	0,6	0	1	0	7,4	3,2	70	0	2006
Pre Flight	1,0	0	0	1	7,4	0,5	70	0	2006
Daily	1,0	0	0	1,5	525,0	4,5	70	0	2006
Weekly	2,0	0	0	7	809,5	12,7	70	0	2006
A1	48,6	500	750	120	9805,1	427,6	70	0	2011
A2	48,3	1000	1500	240	9731,6	425,1	70	0	2011
A3	48,6	1500	2250	360	9805,1	427,6	70	0	2011
A4	54,8	2000	3000	480	13732,1	481,9	70	0	2011
C1	126,1	6000	4500	540	228876,3	3152,0	60	0	2011
C2	202,6	12000	9000	1080	266493,3	5065,6	60	0	2011
C3	188,5	18000	13500	1620	259124,6	4713,2	60	0	2011
C4	568,4	24000	18000	2160	476687,8	14209,6	60	0	2011
C5	149,5	30000	22500	2700	239591,1	3738,2	60	0	2011
C6	235,1	36000	27000	3240	281646,7	5877,7	60	0	2011
C7	201,8	42000	31500	3780	265471,2	5044,8	60	0	2011
C8	910,4	48000	36000	4320	740756,6	22759,5	60	0	2011
C9	155,0	54000	40500	4860	241952,1	3873,9	60	0	2011
C10	245,1	60000	45000	5400	286437,5	6126,5	60	0	2011
C11	210,3	66000	49500	5940	269489,7	5258,3	60	0	2011
C12	639,1	72000	54000	6480	551063,4	15976,7	60	0	2011
C13	161,2	78000	58500	7020	244919,7	4029,8	60	0	2011
C14	248,3	84000	63000	7560	287907,7	6207,1	60	0	2011
C15	214,3	90000	67500	8100	271233,9	5357,4	60	0	2011
C16	954,5	96000	72000	8640	896669,7	23863,6	60	0	2011
Main Tyre Retread	1,0	0	300	0	0,0	0,0	50	2400	2006
Main Tyre Replacement	1,0	0	1500	0	0,0	0,0	50	6400	2006
Nose Tyre Retread	1,0	0	200	0	0,0	0,0	50	600	2006
Nose Tyre Replacement	1,0	0	1000	0	0,0	0,0	50	800	2006
Brakes	1,0	0	2100	0	0,0	0,0	50	132000	2006
Landing Gear	1,0	28000	18350	0	0,0	0,0	50	340000	2006
Main Tyre Inspection	1,0	0	300	0	0,0	0,0	50	1800	2006
Nose Tyre Inspection	1,0	0	1500	0	0,0	0,0	50	500	2006
ESV	1,0	0	5000	0	0,0	0,0	70	1200000	2007

Figure C.1: Maintenance plan TP-MHEP page 12

C.2 TF-MHEP

Check	Downtime	Interval (FH)	Interval (FC)	Interval (DY)	Material cost	MH	Labor Rate	Fixed cost	Fiscal Year
Transit	0,6	0	1	0	7,4	3,2	70	0	2006
Pre Flight	1,0	0	0	1	7,4	0,5	70	0	2006
Daily	1,0	0	0	1,5	525,0	4,5	70	0	2006
Weekly	2,0	0	0	7	649,1	10,2	70	0	2006
A1	47,8	500	750	120	9797,3	420,3	70	0	2011
A2	48,0	1000	1500	240	9778,0	422,5	70	0	2011
A3	47,8	1500	2250	360	9797,3	420,3	70	0	2011
A4	49,5	2000	3000	480	12775,3	435,7	70	0	2011
C1	123,8	6000	4500	540	96033,4	3094,9	60	0	2011
C2	200,7	12000	9000	1080	133895,2	5016,8	60	0	2011
C3	186,5	18000	13500	1620	126558,8	4663,0	60	0	2011
C4	566,1	24000	18000	2160	344132,1	14152,7	60	0	2011
C5	146,5	30000	22500	2700	106650,3	3661,5	60	0	2011
C6	233,6	36000	27000	3240	149368,5	5840,9	60	0	2011
C7	198,6	42000	31500	3780	132521,5	4963,8	60	0	2011
C8	909,9	48000	36000	4320	609524,1	22746,5	60	0	2011
C9	152,8	54000	40500	4860	109393,0	3818,8	60	0	2011
C10	242,4	60000	45000	5400	153664,4	6060,2	60	0	2011
C11	206,9	66000	49500	5940	136543,1	5172,6	60	0	2011
C12	637,4	72000	54000	6480	418970,4	15936,0	60	0	2011
C13	157,8	78000	58500	7020	111973,1	3944,1	60	0	2011
C14	246,7	84000	63000	7560	155872,6	6166,9	60	0	2011
C15	211,9	90000	67500	8100	138626,1	5296,9	60	0	2011
C16	954,0	96000	72000	8640	765834,6	23849,8	60	0	2011
Main Tyre Retread	1,0	0	300	0	0	0	50	2400	2006
Main Tyre Replacement	1,0	0	1500	0	0	0	50	6400	2006
Nose Tyre Retread	1,0	0	200	0	0	0	50	600	2006
Nose Tyre Replacement	1,0	0	1000	0	0	0	50	800	2006
Brakes	1,0	0	2100	0	0	0	50	132000	2006
Landing Gear	1,0	28000	18350	0	0	0	50	340000	2006
Thrust Reversers	1,0	0	12000	0	0	0	50	340000	2006
Main Tyre Inspection	1,0	0	300	0	0	0	50	1800	2006
Nose Tyre Inspection	1,0	0	1500	0	0	0	50	500	2006
ESV1	1,0	0	15000	0	0	0	70	10800000	2014
ESV2	1,0	0	25000	0	0	0	70	7200000	2014
ESV3	1,0	0	35000	0	0	0	70	7200000	2014

Figure C.2: Maintenance plan TF-MHEP

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