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Estimation of scheduled, routine maintenance implication for a battery-electric propulsion system

Diplomarbeit

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Abstract

High emissions, an increase of annual air travel and the requirement of a sustainable, zero emission aviation within the next few decades, sets major challenges to aircraft manufacturers and operators. Due to high technological maturity of conventional propulsion systems, no significant potential for optimization to achieve these ambitious climate targets can be expected. Thus, new propulsion concepts moving into focus, such as the battery driven electric propulsion system. However, currently there is no corresponding system design used in commercial aviation, which may be, among other more decisive reasons, caused by high uncertainties regarding the impact on maintenance. As the costs for maintaining an aircraft significantly contribute to the overall operating costs and the change depending on the conversion from a conventional propulsion system to an Electric Propulsion System (EPS) is not yet determined, it is an important aspect in the development of sustainable propulsion concepts. Within this work, an estimation regarding this change is addressed, whereby a first draft of upcoming maintenance is developed, assuming a complete replacement of the conventional kerosene-based system of an A320, by a battery-electrical one. From an initial system design layout, necessary maintenance implications are derived, using the MSG-3 analysis, examined and subsequently compared to those of the conventional system. The investigation of this work shows that operating an aircraft with a battery-based EPS, a reduction of the maintenance effort, compared to its conventional counterpart, by about 37% within an average utilization can be expected. This is mainly attributed to the amount of replaced systems and components of the conventional system, but as well to the increase of those maintenance tasks, that are intended to determine the condition and functionality of the system and its components, thus are consequently less elaborate. Results of this work can serve as a first approach on a more detailed design and development process of an electric drive system, considering maintenance implications in an early design stage. Further, the examined tendencies can be used as a solid base for future assessments regarding cost efficiency.

Kurzfassung

Hohe Emissionen, ein jährlicher Anstieg des Flugaufkommens und die Forderung einer nachhaltigen und emissionsfreien Luftfahrt innerhalb der nächsten Jahrzehnte, führen zu großen Herausforderungen für Luftfahrzeughersteller und Betreiber. Aufgrund technologisch ausgereifter, konventioneller Antriebe, können signifikante Verbesserungen zur Erreichung der ambitionierten Klimaziele nicht mehr erwartet werden. Somit rücken neue Antriebskonzepte in den Fokus, wie zum Beispiel, batteriebetriebene elektrische Antriebe. Aktuell werden keine entsprechenden Systeme in der kommerziellen Luftfahrt genutzt, was, neben anderen entscheidenderen Gründen, mit der damit verbundenen Unsicherheit bezüglich des zu erwartenden Wartungsumfangs zusammenhängt. Da die Kosten für die Instandhaltung eines Luftfahrzeugs maßgeblich zu den gesamten Betriebskosten beitragen und deren Veränderung durch die Umstellung von einem konventionellen Antrieb auf ein elektrisches System derzeit noch nicht abschätzbar ist, sind die Instandhaltungskosten ein wichtiger Aspekt in der Entwicklung nachhaltiger Antriebskonzepte. Mit dieser Arbeit soll eine Abschätzung dieser, aus der Systemumstellung resultierenden, Änderung des Wartungsaufwandes getroffen werden, wobei ein erster Entwurf der aufkommenden Instandhaltungsmaßnahmen entwickelt wird, unter der Annahme, dass das gesamte konventionelle, kerosinbasierte System eines A320 durch einen batteriebetriebenen Antrieb getauscht wird. Von einem initialen Systemlayout sollen, mithilfe der MSG-3 Analyse, notwendige Wartungsaufgaben abgeleitet werden und im Anschluss untersucht und mit denen eines konventionellen Systems verglichen werden. Die Untersuchung dieser Arbeit stellt fest, dass während des Betriebes, bei einer durchschnittlichen Auslastung, eines batterieelektrischen Antriebssystems, verglichen zum konventionellen System, eine Reduktion des Instandhaltungsaufwands von etwa 37% erwartet werden kann. Dies lässt sich hauptsächlich auf den Umfang der ersetzten Systeme und Komponenten des konventionellen Systems zurückführen. Allerdings auch auf den Anstieg von Wartungsarbeiten, die den Zustand und die Funktionsfähigkeit des Systems und dessen Komponenten feststellen sollen und daher weniger aufwendig sind. Ergebnisse dieser Arbeit können als Anhaltspunkt für ein detaillierteres Design und weitere Entwicklungsprozesse elektrischer Antriebe genutzt werden, die den Einfluss von Instandhaltung in frühen Designstadien berücksichtigen. Darüber hinaus, können mit den hierin festgestellten Tendenzen, bezüglich Wartungsaufkommen, Bewertungen für künftige Kostenabschätzungen vorgenommen werden.

Contents

Nomenclature

Symbols

λ	h^{-1}	Failure Rate

Acronyms

A4A	Airlines for America
ACARE	Advisory Council for Aviation Research and Innovation in Europe
ADJ	Adjustment
AHM	Aircraft Health Monitoring
AMP	Aircraft Maintenance Program
APU	Auxilary Power Unit
APUC	APU Cycles
APUH	APU Hours
ATA	Air Transport Association of America
AVG	Average Utilization Rate
BAT	Battery
BITE	Built-In Test Equipment
BM	Base Maintenance
BMS	Battery Management System
CB	Circuit Breaker
CCU	Coolant Control Unit
CLN	Cleaning
CMR	Certification Maintenance Requirement
CONV	DC/DC Converter
CP	Coolant Pump
DET	Detailed Inspection
DIS	Discard
DMC	Direct Maintenance Costs
DOC	Direct Operating Costs
EAR	Easy Access Rules
EASA	European Aviation Safety Agency
ECAM	Electronic Centralized Aircraft Monitoring
EDS	Electric Drive System
ENG	Engine
EOL	End of Life
EPS	Electric Propulsion System
ESD	Energy Storage and Distribution
F	Filter
FAA	Federal Aviation Agency
FC	Flight Cycles
FEC	Failure Effects Category
FFI	Failure Finding Interval
FH	Flight Hours
FMEA	Failure Mode and Effects Analysis

FNC	Functional Check
GVI	General Visual Check
HEX	Heat Exchanger
HUR	High Utilization Rate
IMC	Indirect Maintenance Costs
INV	DC/AC Inverter
IOC	Indirect Operating Costs
ISC	Industry Steering Committee
LCK	Leak Check
LFS	Long Flight Segment
LIB	Lithium Ion Battery
LM	Line Maintenance
LUB	Lubrication
LUR	Low Utilization Rate
M	Electrical Motor
MCF	Motor Cooling Fan
MCU	Motor Control Unit
MMH	Maintenance Man Hour
MO	Month
MPD	Maintenance Planning Document
MPP	Maintenance Program Proposal
MRB	Maintenance Review Board
MRBR	Maintenance Review Board Report
MRO	Maintenance Repair and Overhaul
MSG	Maintenance Steering Group
MSI	Maintenance Significant Item
MTBF	Mean Time Between Failure
N/A	Not Applicable
NDT	Non-Destructive Testing
OPC	Operational Check
PTU	Power Transfer Unit
RCM	Reliability Centered Maintenance
RES	Coolant Reservoir
RST	Restoration
SDI	Special Detailed Inspection
SFS	Short Flight Segment
SOC	State of Charge
SOP	State of Power
SOV	Shut-off Valve
SSA	System safety Analysis
SVC	Servicing
TMS	Thermal Management System
TOC	Total Operating Costs
VCK	Visual Check
VDI	Verein Deutscher Ingenieure

1 Introduction

The global aviation sector contributes about 2% of the total CO_2 emissions [21] and this proportion will increase due to annual growth of air travel [65]. To address the global climate change, in June 2022 the Advisory Council for Aviation Research and Innovation in Europe (ACARE) presented the *´´Fly the Green Deal* - Vision" (which succeeds the former *Flightpath 2050*) to support the Green Deal of the European Commission towards sustainable aviation [3]. Herein, ambitious goals for emission reduction and the need for technical improvement of propulsion systems are formulated.

During the last years, high effort was spent to improve the efficiency of aircraft engines and reduce their emissions, even though, due to high level of maturity of the engines, only small efficiency gains had been achieved [48]. Accordingly, the aviation industry is considering novel propulsion and aircraft concepts that promise a drastic reduction of their associated emission levels. One of the promising technologies to provide the CO_2-free, sustainable energy demand is a fully battery-electric propulsion system. This includes the storage of necessary energy for a certain flight profile, as well as the distribution and conversion to generate thrust. However, the transfer to another propulsion technology will lead to a tremendous change of the system design, which will also affect the costs related to Maintenance, Repair and Overhaul (MRO) and consequently on operating costs. According their significant contribution to these costs, the reduction of upcoming maintenance, especially in context of new technologies, is a main concern of customers. Hence, a battery-based Electric Propulsion System (EPS) for future carbon-free aircraft shall be investigated, towards its potential maintenance effort and the corresponding implications on complexity.

This work focuses on identification of potential failures depending on certain degradation patterns of those components, incorporated in the system design developed in the author's previous work. According the established method of the MSG-3 logic, an appropriate maintenance plan shall be derived. Subsequently, based on the reference aircraft, the A320, a comparative analysis regarding their corresponding maintenance implications shall be made.

Aim of this work is to elaborate the maintenance requirements for a new Battery-Electric Propulsion System (EPS) and its associated changes compared to a Kerosene-based Propulsion System (*legacy system*). Following research questions will be addressed.

1. **What are the maintenance requirements of a Battery Electric Propulsion System (EPS)?**

2. **How does the maintenance effort, resulting from conversion to a battery based propulsion system, change and is there a best case utilization scenario?**

3. **What does the scope of maintenance consist of and is there a dominant usage parameter or specific kind of task driving the maintenance effort?**

The results of this work will provide a first overview of the potential maintenance requirements of an EPS and it's change regarding necessary effort, task distribution and most affected components. Further, this work delivers a potential approach for design aspects of several components and improvement of the system's structure to reduce maintenance implications.

This work is structured as follows. Chapter 2 will explain the necessary fundamentals, wherein basics of maintenance and the development of its extent are outlined. Further, the conventional kerosene-based and the new EPS are displayed and discussed. Subsequently, chapter 3 describes the methodology for developing a maintenance schedule for a new system design, which is then conducted within chapter 4. The 5^{th} chapter discusses the maintenance implications developed in the previous chapter and compares the conventional and the electrical system's maintenance effort, whereby the influence of different utilization parameters is investigated. Finally, chapter 6 summarizes the results of both, resulting maintenance implications of the new system design and its changes compared to the conventional system. Additionally, an assessment of the results and a brief outlook on future work is given.

2 Fundamentals

Within chapter 2 the basics of Maintenance Repair and Overhaul (MRO) shall be outlined and described. This includes the current state of the art of conducting maintenance as well as future tendencies. Moreover, the standardized process for evaluating the needs of particular maintenance tasks will be described. In a short overview it shall be displayed how the results of this process are summarized. Further, the system design on which this work is based, will be explained, the components it includes were investigated according their potential degradation behavior. Additionally, a brief overview of the legacy system, utilized for comparison is given.

2.1 Basics of Maintenance Repair and Overhaul (MRO)

Maintenance is a major part while operating an aircraft. Reliably and regularly performed maintenance contributes to sustainable safety and functionality by reducing the risk of failures and ensuring the continuous usage of components. Accordingly, this sub chapter is intended to present a general overview of the requirements for defining an appropriate maintenance schedule of an aircraft and what strategies therefore can be used.

To understand what maintenance is, Verein Deutscher Ingenieure (VDI) provides a short definition:

> "*Maintenance are measures taken to maintain the designed condition of a product (service), to determine and evaluate the actual condition (inspection) of a product, and to restore (repair) the product to its designed condition. Service, inspection and repair are sub terms for the maintenance.*" [60]

Further, maintenance can be grouped into four aspects, which shall be clarified as follows. [16]

Maintenance: includes all measures to reduce degradation and wear of an item, conducted during its usage, like: Cleaning (CLN), Lubrication (LUB) or Adjustment (ADJ). In general, these tasks are understood as servicing.

Inspection: Inspections are used to determine and evaluate the current condition of an item. Herein, degradation causes are investigated to derive appropriate counter actions.

Modification: Administrative, technical or economical measures are taken to improve reliability, safety or maintainability, whereby the item's functionality is unchanged.

Restoration: is intended to restore, or repair, the functionality of a faulty unit, which is either repaired or replaced.

With regard to aviation, the objectives of maintenance are ensuring and restoring safety and reliability of an aircraft at minimum costs as well as obtaining information to improve the design. Maintenance aims on identifying failures and to prevent deterioration [10].

Maintenance can be differentiated by various criteria. In first place a distinction can be made between *scheduled* and *unscheduled* maintenance, whereby scheduled maintenance contains all measures which are performed according a prescribed time or usage parameters. They are planned, unlike the unscheduled maintenance, which is performed after impairment has been detected. Actions, defined by the scheduled maintenance, can be inspection tasks, monitoring, calibration or even discard tasks [30]. In addition, scheduled maintenance can be further divided into *Routine* and *Non-Routine*. Routine tasks are those, performed periodically according the defined maintenance program, for example regular lubrication or inspection, whereas non-routine tasks with predictive character can be planned based on statistical failure rates or on the condition determined within scheduled investigations. Non-routine maintenance is otherwise unplanned with corrective character depending on determined failure [30]. A graphical overview is displayed in Fig. 2.1.

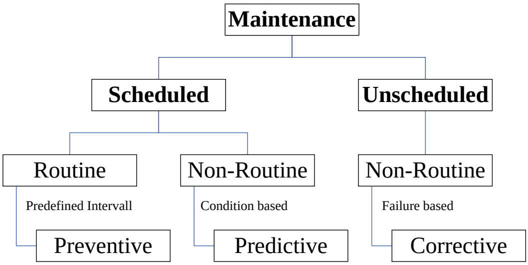


Figure 2.1 Graphical overview of maintenance differentiation according planning level

Next to the planning aspect, maintenance can also be divided by the organizational degree responsible for conduction, which can be Line Maintenance (LM) or Base Maintenance (BM). They differ in terms of operational conduction, material requirements, and staff qualification. LM is performed during normal operation, possible to conduct during the regular ground time, without need of any specialized tooling or high degree of deinstallation. BM is more complex and requires a hangar or a repair station as well as specialized tooling. [28]

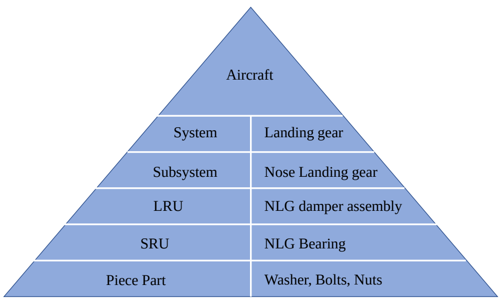


Figure 2.2 System differentiation

To analyze maintenance on a system or component level, a further classification must be made regarding the aircraft structure. Hereby, the aircraft is divided into several systems, of which each has it's own functionality and consist of a certain amount of subsystems, depicted as the two top layers in Fig. 2.2. Exemplary, the division into the sub groups is demonstrated for a nose landing gear (NLG), whereby the NLG is a subsystem of aircraft's landing gears. The next lower level describes the Line-replaceable units (LRU), which can be replaced on-wing during the LM. An example for this layer is the NLGs damper assembly. The LRUs consist of shop-replaceable units and piece parts, depicted as the two lowest levels. In case of need for repair or restoration, the SRUs are removed as part of the LRUs and send to a repair station or shop for off-wing BM. Within this work the focus is on the component level, which means LRUs and SRUs.

To enumerate the structure of the systems and the sub-grouped components and units as described above, the Air Transport Association of America (ATA)-systematic is used. Within around 100 chapters, technical devices are grouped according their function and system affiliation.

2.1.1 Maintenance Strategies

Basically a maintenance strategy describes how maintenance can be performed to ensure either the proper function of the corresponding system or that the equipment reaches or exceeds it's design life [56]. A definition given by the VDI, states these strategies are determinations whether, where, and what is to be performed by whom, how and when. They are oriented by the technical conditions of the considered component. [60]

Fig. 2.3 displays the different approaches, mainly focused in aviation.

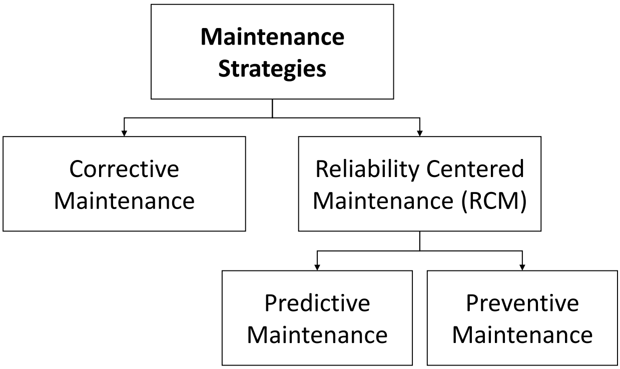


Figure 2.3 Maintenance Strategies in aviation

Corrective maintenance focuses on failure rectification, resulting either from not preventively maintained components or unexpected failures prior to the next planned task. It aims on restoring a component to its design condition after its functions decreased below minimum [33]. The corrective, or reactive maintenance approach spends no effort, neither costs nor labour, to maintain the corresponding equipment or decrease the wear. Actions are taken as soon as the component or system is inoperable or damaged. Advantages like low costs in a first place and low staff requirement are negligible compared with those costs arising for repair or replacement and unplanned downtime [56].

The second approach is the **Reliability Centered Maintenance (RCM)**, which can be described as a systematic, risk based method to develop a cost-effective maintenance plan. Herein, components and especially their failure modes are addressed to develop or optimize preventive maintenance tasks and inspection requirements. These failure modes are prioritized according their severity of consequences and impact on safety and reliability [49] [5] [56]. In advance, Sullivan et al. [56] stated, RCM takes the maintenance facility's resources into account, to prioritize and optimize their usage.

RCM can be divided in two additional strategies, as depicted in Fig. 2.3 and described as follows.

Preventive maintenance follows the proactive approach that maintenance actions are performed, based on a schedule defined by utilization parameters (FH,FC) of the corresponding system/ equipment or, if the reserve of wear-out is measurable, on condition monitoring prior to fail or damage [33] [56]. The maintenance program is intended to detect or mitigate degradation and preclude possible failures aiming to sustain or extend the useful life. Conducting this maintenance schedule provides the advantages of an increasing reliability, saving costs and additionally reducing downtime. Nevertheless, it contains the possibility of performing unneeded maintenance and the corresponding risk of incidental damage [56].

As a predefined schedule does not necessarily meet the optimal point in time, the **Predictive maintenance** concept is based on continuously monitoring and assessing a system's current state, so that with the help of diagnostic and prognostic tools it can be derived whether and when maintenance actions are necessary [33]. Monitoring can be understood as measurement that detects the onset of degradation [56]. Accordingly, the components failure behavior needs to be understood, as well as failure mechanisms and characteristics. Thus, appropriate and effective measures to identify the dominant failure modes of a specific component/ system can be integrated. Sullivan et al. [56] summarized, that predictive maintenance differs from preventive maintenance by performing tasks based on the condition of the corresponding equipment instead of a defined schedule.

The predictive maintenance concept is expected to improve operational and resource planning [33], so increased availability and quality, decreased downtime and costs are just a few of the many advantages of this method. However, in contrast there is a demand for increased investments towards maintenance equipment and staff training [56].

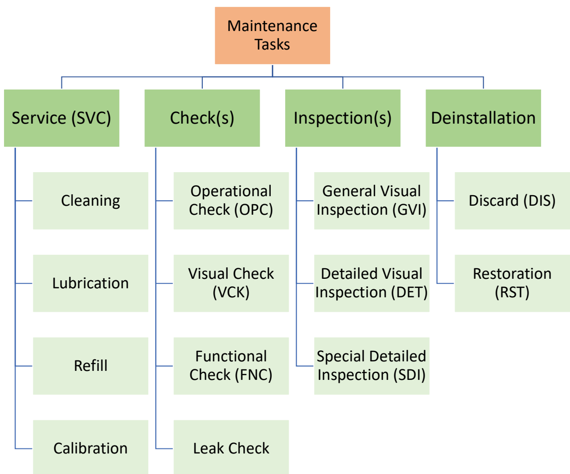


Figure 2.4 Maintenance tasks in aviation

Fig. 2.4 provides an overview of tasks, commonly applied in aircraft maintenance. Each task focuses on a specific aspect, either on identification or finding of potential impairment, on a certain quantification of its extent or to resolve the inappropriate condition.

With following explanations of the different task groups a basic understanding of their purpose and extent shall be provided [39]:

- Lubrication (LUB)/Servicing (SVC): intended to maintain inherent design capabilities by replenishing consumables to reduce the rate of functional deterioration
- Operational Check (OPC)/Visual Check (VCK): addresses the determination of an item fulfilling its intended purpose without consideration of quantitative tolerances, only to identify a failure
- General Visual Check (GVI)/Detailed Inspection (DET)/Special Detailed Inspection (SDI): used to detect damage, failure or impairing; three types with different levels of examination; for a deeper investigation specialized equipment can be used
- Functional Check (FNC): conducted to determine if the function(s) perform within specified limits, accordingly a quantitative approach
- Restoration (RST): intended to return an item to its design specification after functional degradation
- Discard (DIS): removing an item from service after a specified life limit, even without obvious functional degradation

An effective Aircraft Maintenance Program (AMP) does not necessarily include each of them, only those to be found effective to increase safety and reliability [10].

For future maintenance scheduling there will be an additional concept - Aircraft Health Monitoring (AHM). It can be considered as a method to optimize aircraft's operation and maintenance by assessing the fleet health data and determine an appropriate time for maintenance. Hereby, health monitoring mechanisms are used to support the predictive maintenance approach, wherefore it utilizes various approaches (data-driven, models-based, etc.). Further, it shall enable a live communication of failure data with ground support. Thus, AHM consists of several fields, from sensing via data processing to analyze and act. AHM promises to save huge maintenance costs, increase reliability and reduce downtime [36].

2.1.2 Maintenance Evaluation Metrics

To assess the results of this maintenance evaluation in regard to the changes of operating costs, in this section an overview of all cost for an aircraft shall be given.

The Total Operating Costs (TOC) summarizing all costs connected to usage and continuing operation, whereby they can be divided into Indirect Operating Costs (IOC) and Direct Operating Costs (DOC) [30]. DOC significantly depending on the design and usage parameters of the aircraft, so that their amount is defined during the early design phases of the aircraft. They include the costs for fuel, maintenance, flight crews and fees (navigation, airport). Determination of their amount is of great importance to operators, as the efficiency evaluation of an aircraft is conducted based on these values. IOC on the other hand, do not depend on the aircraft, but on their specific operational conditions, such as costs for ground support, management, and passenger handling.

Assuming an annually utilization of 1095 FHs, the average operation costs of an A320 would arise to 10.800 € per FH [25]. Fig. 2.5 provides an percentage allocation of DOC for an A320 rounded to whole numbers. As displayed, the major part are fuel costs, but with 17% maintenance costs are the second most share, so that it can easily be understood, that maintenance has a high influence. Moreover, it is not just responsible for the direct costs, but as well has an indirect influence on the operation efficiency. Due to scheduled or unscheduled maintenance and corresponding downtime, it can cause delays and accordingly a decreased availability of the aircraft. This means costs resulting from penalties, compensations or fees

[30]. In consequence, it is necessary to predict the downtime and the corresponding costs caused by maintenance at an early design phase, especially for new design concepts.

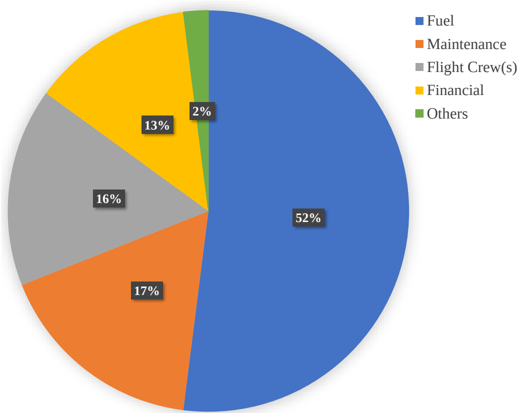


Figure 2.5 Breakdown of Direct Operating Costs (DOC) of an A320 [30]

Maintenance costs can be divided as well, into Direct Maintenance Costs (DMC) and Indirect Maintenance Costs (IMC). All costs directly contributing to performing maintenance, such as labour and material cost, as well as corresponding tools and equipment are summarized to DMC. Costs regarding management of the airline is the main driver for IMC. Due to lack of information regarding performance and amount of maintenance, it is not possible to make a statement towards the specific costs arising from the new EPS. Accordingly, this work will deal with the downtime to be expected, and depending on required tasks a rough estimation of Maintenance Man Hour (MMH) and corresponding costs can be made.

2.1.3 Aircraft Maintenance Program (AMP) Requirement

As every aircraft is subjected to a certain degree of degradation, so that the useful lifetime of its systems, equipment and components is limited depending on the aircraft's usage (FH, FC and Month (MO)) and operation conditions (temperature, humidity, dust, etc.). To address this wear and tear, especially fatigue-, environmental- and accidental damages, comprehensive maintenance is required. Due to complexity of modern aircraft, these measures are structured in the Aircraft Maintenance Program (AMP). [28]

The authority responsible for defining and developing regulations regarding aviation in Europe is the European Aviation Safety Agency (EASA). It defines the requirements for certification and (continuing) airworthiness. Besides, there are different other national authorities and organizations which have an influence on developing regulations and instructions, for example the Federal Aviation Agency (FAA), which is the national authority of the United States and the Airlines for America (A4A), which is an organization presenting policies and measures for safe and secure aircraft operation [9].

Due to very high safety standards in aviation, each aircraft needs to be kept in an airworthy and serviceable condition according to Regulation (EU) No 1321/2014 Article 3, issued by the European Commission [22]. The *Easy Access Rules (EAR) for Continuing Airworthiness* [17], issued by the EASA present a more detailed description of these requirements. According EAR Reg. (EU) No. 1321/2014 M.A.301 (c): "the continuing airworthiness shall be ensured by the accomplishment of all maintenance defined by the AMP". This Aircraft Maintenance

Program (AMP) is described in more detail within Reg. (EU) 1321/2014 M.A.302 and contains instructions of the competent authority and the corresponding certificate holder (usually the design organization).

For a more detailed differentiation: The AMP is the maintenance schedule for one specific aircraft. It contains the Maintenance Planning Document (MPD) and specific maintenance requirements regarding the environmental and operational conditions of the airline. Herein, the MPD is developed within the MSG-3 process as Maintenance Review Board Report (MRBR), described in Sec. 2.2, and supplemented with additional information by the design organization. This work will focus on the maintenance aspects evaluated by the MSG-3 logic.

Fig. 2.6 displays the typical layout of a Maintenance Planning Document (MPD).

TASK NUMBER	ZONE	DESCRIPTION	SAMPLE THRESHOLD (ST) SAMPLE INTERVAL (SI) THRESHOLD (T) INTERVAL (I)	SOURCE	REFERENCE	MEN	M/H	APPLICABILITY
	437 447	INTEGRATED DRIVE GENERATOR EN RST REMOVE IDG COOLER FOR IN-SHOP CLEANING NOTE: INTERVAL: - TASK MAY BE PERFORMED AT THE OPPORTUNITY OF ENGINE SHOP VISIT.	I: 252 MO OR 36000 FH NOTE	LUR MRB 6		1 1	0.20 0.20	CFM56-5
	438 448	INTEGRATED DRIVE GENERATOR EN FNC CHECK TORQUE OF QUICK-ATTACH-DETACH (QAD) TENSION BOLT ACCESS: 438AR 448AR	I: 24 MO OR 2400 FH	LUR MRB 9		1 1 * *	0.30 0.30 0.04 0.04	IAE
	438 448	INTEGRATED DRIVE GENERATOR EN SVC CHECK IDG OIL LEVEL AND DIFFERENTIAL PRESSURE INDICATOR NOTE: DEPENDING ON OPERATING ENVIRONMENT AND OPERATORS EXPERIENCE, A LESS FREQUENT OR MORE FREQUENT INITIAL INTERVAL MAY BE USED. ACCESS: 438AR 448AR	I: 2 MO OR 300 FH NOTE	LUR MRB 6		1 1 * *	0.02 0.02 0.04 0.04	IAE
	438 448	INTEGRATED DRIVE GENERATOR EN DIS - REMOVE AND DISCARD SCAVENGE FILTER ELEMENT - DRAIN AND REPLENISH OIL SYSTEM ACCESS: 438AR 448AR	I: 6 MO OR 800 FH	CMP LUR MRB 6		1 1 * *	0.40 0.40 0.04 0.04	IAE PRE
	438 448	INTEGRATED DRIVE GENERATOR EN OPC OPERATIONAL CHECK OF INTEGRATED DRIVE GENERATOR (IDG) * * * * * C O N T I N U E D * * * * *	I: NOTE	MRB 9		2 2	0.20 0.20	IAE
SECTION SYSTEMS : ELECTRICAL POWER					SECTION: 2-24			PAGE 4

Figure 2.6 Extract of an A320 Maintenance Planning Document (MPD)

2.2 Historical Background of Reliability Centered Maintenance (RCM)

The increasing complexity of modern aircraft and taking into account that airlines focus on the economical aspect of maintaining the airworthiness of an aircraft, leads to the demand of early definition of maintenance requirements and its extent. Thus, a decision logic considering both, safety and economical aspects, to determine the maintenance needs during the design phase is necessary. Therefore, in the 1980's the MSG-3 Analysis has been developed as a part of the Maintenance Review Board (MRB).

The MRB is a committee of different authorities and is supported by the Industry Steering Committee (ISC), which consist of different manufacturers, suppliers, and experts from airlines and maintenance facilities. They are in charge of developing a general maintenance document, for which they appoint *Maintenance-Working-Groups*. These groups, consisting of experts of the specific areas and elaborate the initial minimum requirements based on the MSG-3 process [29] [10].

Results of this process are summarized and published as MRBR, which can be considered as the basis for the Maintenance Planning Document (MPD) [28]. Additional adjustments to address operational or environmental conditions may be necessary and are defined by the operator [10].

The development of today's established *MSG-3 Logic* started back in the late 1960's with the preparation of the Apollo-Space missions. Herein, theoretical and actual failure rates were brought into connection with intensity of maintenance to develop an analyzing approach, which has been used the first time in aviation for the development of Boeing's 747. This approach had been named *Maintenance Steering Group (MSG)-1* (1^{st} generation). Until then, each airline defined the maintenance program individually for each aircraft.

The MSG-1 focused on failure rates and degradation mechanisms only, without considering the influence of a single failure to the whole system, a so called Bottom-Up Approach. Further, the approach only takes into account applicability but not the effectiveness. Accordingly, the MSG-1 Analysis only differentiates between On-Condition and Hard Time maintenance.

With demand for a generally applicable approach (not only based on B747), an improved approach, the MSG-2 Analysis, has been established as a specification document during the late 1970's.

Only a few years later, the ATA issued a new revision, the MSG-3 Approach, which from now on shall address economical needs next to safety aspects. Additionally, the decision-making process has been significantly adapted and shall be processed as Top-Down Approach. Not just the failure, but it's consequences on flight operation are now in focus of investigation. Another novelty is the task orientation of maintenance, whereby specific maintenance tasks are defined for each aircraft part. [29]

The MSG-3 Process can be divided into the following 5 steps [29]:

- Definition of Equipment/ System for investigation with corresponding function(s)
- Functional failures
- Consequences and causes of failures
- Risk assessment of failures
- Methods of failure prevention

Identifying the intended functions, their related functional failures and corresponding failure effects with the associated causes, which is addressed by step 2 and 3 can be summarized in a specific analysis - the Failure Mode and Effects Analysis (FMEA). Step 4 and 5 are MSG-specific assessments and will be conducted separately according their decision-trees. In the context of the MSG-3 logic these steps are defined as *Level 1* and *Level 2*. For reasons of continuity, the FMEA is defined herein as *Level 0*.

A more detailed description and a graphical overview is given in chapter 3 and the herein displayed Fig. 3.1

All tasks identified as efficient and applicable within the MSG-3 logic are summarized for validations and approval by the ISC as the *Maintenance Program Proposal (MPP)* [29]. Items, for which the MSG-process can not identify appropriate maintenance tasks can be monitored by the AHM or an operator's reliability program [10]. After approval of the MPP, the document will be published by the aircraft manufacturer as MRBR [29].

2.3 Legacy system

2.3.1 Kerosene-based propulsion system

For a comparative analysis in chapter 5, the state-of-the-art (kerosene-based) propulsion system, which is referenced in this work as *legacy system*, of an A320, will be used. This section is intended to describe its extent and operating principle.

The basic Airbus A320 belongs to the class of narrow body aircraft and is equipped with two conventional turbofan engines. Mainly, the aircraft is used on short- and medium range with a global average flight time of 1.8 Flight Hours (FH) per Flight Cycles (FC) [8]. Depending on the cabin design, the A320 can transport up to 180 passengers at a maximum take-off weight of 73.500 kg [1] [18]. Most A320's currently in operation are equipped with CFM International's CFM56-5B4 Engine, which provides up to around 120 kN thrust [8]. Additionally, the A320is equipped with an Auxilary Power Unit (APU), which is for comparative reasons in this work defined as APS3200 by Pratt & Whitney.

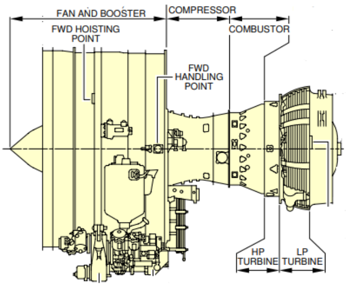
Even though a battery-electric propulsion system for an A320 seems unrealistic due to insufficient energy density of current Lithium Ion Batterys (LIBs) [11], the A320 provides a excellent data basis in terms of maintenance analysis. In addition, as one of the most operated aircraft, it has a tremendous meaning for global aviation.

Consideration of the legacy system concerns various subsystems. This includes the fuel storage and distribution system, all fuel-based components and systems connected with the Engine (ENG) as well as the APU with all associated connections. A rough overview is given by Fig. 2.7a - 2.7c.

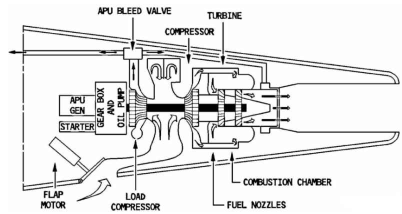
The subsystems focused within this work can be associated according their ATA-Chapter, which provides several advantages. By addressing all ATA-Chapters, subjected to a change with the new EPS, subsequently the major part of components affected are addressed. This is based on the assumption, that a profound change of the system correspondingly leads to an overall change of components belonging to the ATA-Chapter affected. Further, using these chapters, simplifies the selection of affected maintenance tasks from the MPD, as they are sorted accordingly. Another benefit is, that using this methodology, is applicable to future investigations as well.

The ATA-Chapters affected by the changes from kerosene-based system to a battery-electric driven concept are the fuel storage, distribution and ignition, which is summarized in ATA

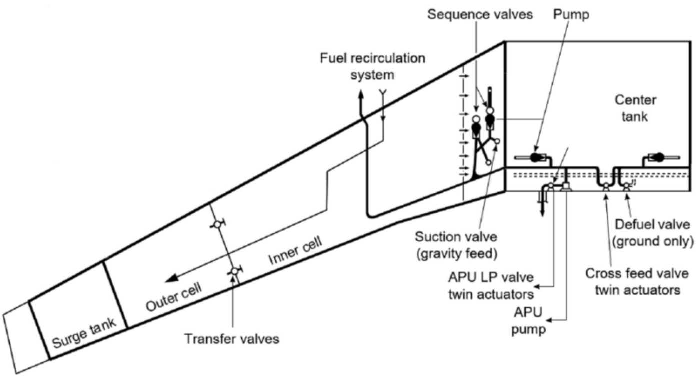
[1]based on A320-214, basic variant, no modification installed



(a) Schematic of A320 ENG CFM56 [7]



(b) Schematic of A320 APU [53]



(c) conventional fuel system [6]

Figure 2.7 conventional kerosene based system chapter 28, the APU (ATA 49) and all components and subsystems associated with the engines (ATA 70-78).

The engine, which is assumed in this work as the CFM-56, applied once at each wing has to transform the chemical energy, stored in the fuel, to shaft power and thus into thrust. Further, the engines have to provide bleed air for air conditioning and electrical energy for on-board systems in-flight.

Fig. 2.7b displays a conventional APU of an A320. It supplies (electric, hydraulic, pneumatic) power to engines and on-board systems on ground or in emergency situations [53].

The fuel infrastructure depicted in 2.7c has following functions [6]:

– storage of fuel during flight phase
– distribution and transfer
– control and supply fuel to engines and APU
– cooling of hydraulic oil

2.3.2 Built-In Test Equipment (BITE)

The increasing complexity of electronic equipment in aviation requires an in-time failure finding and condition monitoring [24]. To identify and locate possible failures, a BITE-system can be integrated in electronic items. The BITE can be understood as the interface between the technical and the support system and has significant importance in fault diagnostics [55]. According to Soederholm [55], BITE is a tool of Health Management and comprises three methodologies: Safety Check, Functional Check and Fault Localization. It focuses on a system's functions to verify the fulfillment of it's intended purpose and performance or to localize any occurred faults. The efficiency of it depends largely on test and monitoring infrastructure built into the hard- and software. Normally, the BITE is capable to reliably detect failures down to Line Replaceable Units. Another description, given by Gao et al. [24], states that the BITE-system is intended to improve the availability and ensure safety, so it is accordingly applied to complex electronic systems for automatic detection of wear and breakage. Following these descriptions, it can be understood as an on-board hardware-software diagnostic tool [46] [57] for complex electronic components, intended to identify and localize internal faults, and thus increasing safety, by using the integrated infrastructure.

Further, there are different design and usage descriptions, given as follows. Tooley [57] claims, BITE is usually designed as a signal-flow type test. Hereby, a specific signal triggers an alarm or failure message in case its flow is interrupted or deviates from a defined range. BITE can also be used to test the functionality of key circuits [46]. Therefore, three different concepts exist [46]. The interruptive BITE-concept (I-BITE), typically initiated by the operator, performs the integrated test while the system/ item is inoperative. A continuously monitoring of the system, can be performed with a continuous BITE-concept (C-BITE), whereby the system does not need to be suspended. To monitor the item periodically, a P-BITE can be used.

The BITE can be divided into direct monitoring, whereby the condition is tracked by a directly integrated sensor and indirect monitoring, which examines parameters describing the condition of the monitored component. These parameters for example can be currents, temperatures, forces or acoustic emissions. [24]

Due to constant change of the system's condition, the application of a BITE-system benefits the system's health management by monitoring of critical functions. An additional advantage is that the diagnostic of these data enables a condition based maintenance approach, and via prognostics to predict the future state of system's health. Consequently, critical functional failure can be avoided before they occur, by recommending maintenance that is not required at the moment [55].

Failure messages generated by the BITE can also be displayed in the Electronic Centralized Aircraft Monitoring (ECAM) [57].

Summarizing, an incorporated BITE-system is a method of Health Management on aircraft level.

2.3.3 Electronic Centralized Aircraft Monitoring (ECAM) System

As the propulsion system needs to be observed during its operation, the necessary data have to be visualized for the crew. The corresponding system to provide those data is the ECAM and several examples are displayed in Fig. 2.8. All data, as well as failure messages, the crew needs to know for safe handling of the system, are displayed via a screen in the cockpit. Using the ECAM has two major implications. Firstly, failures are indicated so that the crew can take appropriate actions for safe operation, and secondly - by indicating these failures to the crew, they can be considered as evident and require a different treatment within the MSG-3 Analysis [43]. In advance, the ECAM includes an interface to items equipped with BITE for fault indication. Using the ECAM, failures can easily followed up by either the flight crew or the maintenance staff [57].

Fig. 2.8a, 2.8b and 2.8c [23] depict the basic information the ECAM provides to the flight crew. Many of the displayed measures will be replaced or can be excluded completely with the new design. Also the focus on important information, necessary to be provided to the flight crew might be changing. Additionally, the ECAM does not only display engine parameters but also indicates performance data of several other systems like landing gear, flight controls and different environmental conditions [57].

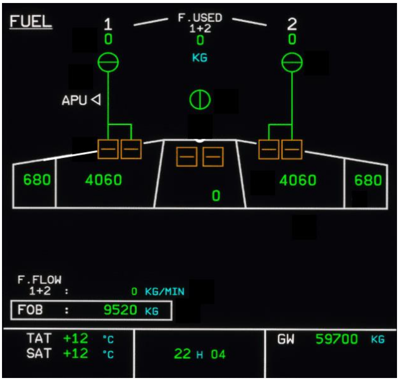
2.4 Battery-electric propulsion system

One of the many discussed approaches for sustainable aviation is the full electric, battery driven propulsion system. In the scale of an A320, there currently is no template of an appropriate system, which can be used for further analyses. Thus, this work will be based on the initial design of the author's previous work *System design and analysis of a battery-electric propulsion system* [14], wherein a first draft of the system layout has been developed in accordance with standardized procedures. The design is depicted in Fig. 2.9a and additionally the related Thermal Management System (TMS) is depicted in Fig. 2.9b. Much discussed in this context is the usage of Lithium Ion Batteries LIBs due to their characteristics, especially high energy- and power density, high operating voltage, low self-discharge, high (dis-)charging rate capability ([27], [19], [42], [52]). Accordingly, the design is based on the assumption that future EPSs will be driven by LIBs.

2.4.1 System architecture

As mentioned above, for an in-depth examination of the EPS it is necessary to have a template or an initial design of the system. Thus, the components, their amount and functions as well as their structure is known.

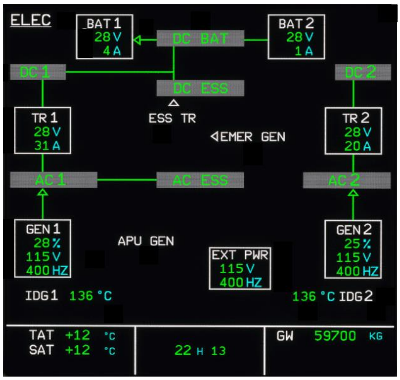
The EPS is divided in three parts, Energy Storage and Distribution (ESD), Thermal Management System (TMS) and the Electric Drive System (EDS) which is integrated two times as the aircraft has two engines. The purpose of the ESD is to store and distribute sufficient electrical energy to operate the aircraft. To convert the electric energy to shaft power and provide thrust the EDS is used. As the conversion and distribution of electrical energy generates a huge amount of heat, a TMS is integrated to dissipate this heat and protect the system from overheating.



(a) ECAM display of legacy FUEL system

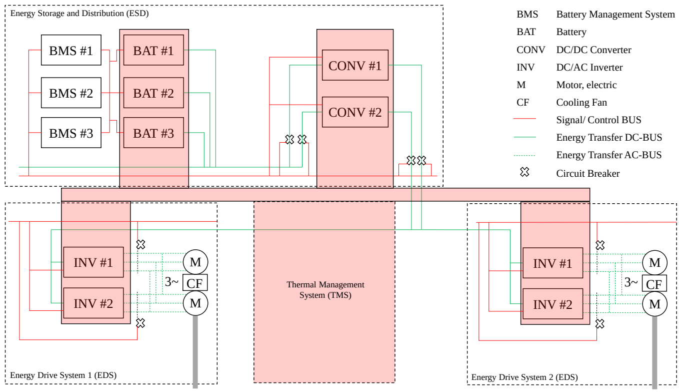
(b) ECAM display of legacy APU system

(c) ECAM display of legacy ENG system

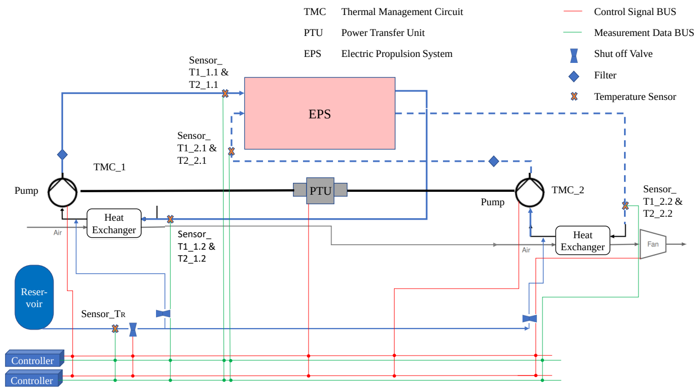


(d) ECAM display of an A320 electric system [23]

Figure 2.8 ECAM display of legacy system



(a) Electric Propulsion System (EPS) design



(b) Thermal Management System (TMS) design of Electric Propulsion System (EPS)

Figure 2.9 Layout of Electric Propulsion System (EPS) [14]

The System safety Analysis (SSA), partially conducted within the work of Dauer [14] shows the need of redundancies of several components. Further investigations can lead to additionally necessary components to support or substitute those of the initial design.

Since the electrical system takes over a major role in the operation of the new aircraft design and in advance has gone through a process of redesign, the ECAM needs to be adapted as well. Figure 2.8d shows the conventional ECAM display of the electric system of the legacy A320, after which the new layout was designed. Additionally, the EPS requires active cooling, so that the most important information of the TMS are displayed as well. The graphical layout of these cooling circuits is derived from the ECAM-display of the hydraulic system. The corresponding results of changes made, is depicted in Fig. 2.10. By using the established color code, significant failures or error messages are indicated red, while a possible impairing will be shown as amber colored. Arrow heads indicate the direction of energy flow. Following parameters have been included or extended:

– TMS data overview, including temperature, coolant flow and pump functionality

– Information bars for error messages from TMS and the electric drive train

- Component data of Electrical Motor (M), e.g. shaft vibration and temperature
- Component data of DC/AC Inverter (INV), e.g. provided voltage and frequency
- Current distribution flow

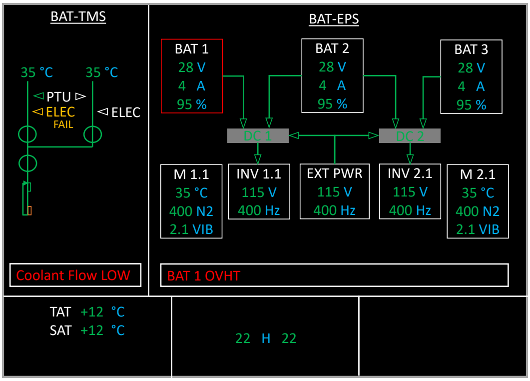


Figure 2.10 Adapted ECAM-Display for EPS

2.4.2 System degradation

Every system or item in an aircraft is subjected to a certain degree of degradation, as stated in Sec. 2.1.3, which means, that each of them needs an evaluation regarding their specific degradation behavior and the corresponding failure occurrence. Degradation mainly depends on the usage parameters and the stresses and loads the item/ system has to face as well as on the structural integrity of the item. Accordingly, each item with its unique failure behavior demands a certain treatment. In order to select adequate maintenance tasks, whether to identify or to rectify failures, their specific behavior needs to be completely understood.

The following list of parameters and loads have a major influence on the degradation behavior especially concerning electrical components:

- vibrations
- electrical (over-)loads
- temperature
- moisture
- dust
- corrosion

The following subsections shall address the main components of the EPS this work is based on. The insight in their degradation behavior and corresponding measures to detect it, provides several advantages. An early detection of degradation or potential failures, which can in consequence lead to hazardous situations, prevent the item or the whole system of failing. Further, with the knowledge of the system's current condition, an precise estimation regarding need and extent of maintenance can be made. Previously to operation, during the design process, adequate maintenance tasks can be prescribed to slow down or inhibit degradation.

The following sections shall introduce an overview of degradation mechanisms and their possible treatment in an aviation context. Thereby, only a few components are addressed to present those degradation mechanisms, that are to be expected in one form or another on the system and further to provide possible approaches to face them properly.

Lithium Ion Battery (BAT)

A battery can degrade in different ways, such as capacity fade, reducing the State of Charge (SOC) of the battery caused by chemical side reactions or loss of conductivity during the charge and discharge cycles [26] [27]. Another effect is a reduction of deliverable power of the cell, the power fade [20].

Battery's cycle life also heavily depends on its thermal control as the suitable operating temperature range of a LIB is between 20-40°C. Significant deviation heavily affects the performance of the battery and can cause safety issues, i.e. a thermal runaway. [15]

Important to mention is, that degradation mechanisms of batteries are typically not easy to observe, so the identification of observable effects is necessary [20]. Monitoring the battery with a Battery Management System (BMS) provides the possibility to mitigate failures by physical and chemical safety mechanisms [27]. A BMS integrated estimator application is used to predict batteries SOC and State of Power (SOP) as well as to cover failure cases regarding lack of capacity and demanded dis-/charge rate [61].

The End of Life (EOL) threshold of a battery is often defined as, when its remaining total capacity reaches 80% of its initial total capacity, e.g. electric vehicles [58] [42]. The cell failure limit needs to be chosen higher than the pack failure limit, to ensure that most cells do not degrade past the pack EOL of 80% [58].

With constant measurement of the battery's heat generation the maximum temperature as well as the temperature difference between cells can be observed and controlled [15]

Replacement of degraded cells of a certain battery pack is an appropriate strategy to approach battery degradation. With reaching the EOL stage of the battery pack some cells might be in a healthier state than other cells. Accordingly, replacing the entire pack instead of cells in unusable condition, is inefficient and discard of usable cells would lead to unnecessarily increased costs for the energy storage system. On the other hand, replacing single cells, requires accessibility, so that the battery pack needs to be opened during LM, which increases the risk of contamination and damage. Further, it requires a monitoring of capacity fade of each cell with a predefined threshold [58]. Moreover, integration of the necessary components increases the susceptibility to failures and consequently, can cause additional issues. An acceptable trade-off would be a restoration, whereby the battery pack is replaced as one unit, followed by an in-shop investigation and recovery to design specifications.

With integration of a liquid cooling circuit into the battery pack possible overheating and subsequent damage can be avoided [15]. Nevertheless, this cooling circuit requires observation and control of its own.

Heat Exchanger (HEX)

A liquid-to-air HEX has five major degradation mechanisms, which mainly relay on temperature gradient, fouling [2], corrosion, creep and mechanical causes like fatigue or vibration. Subsequent failures are cracks, leaks, blockage and material removal. [4] [32] [51]

Addepalli et al. [4] stated, to detect HEX damage, the component needs to be removed to perform Non-Destructive Testing (NDT). Therefore, different procedures are available, for example color penetrant, eddy current or thermography. But, a HEX suffering from fouling

[2] Fouling is caused by fluid impurities that deposit in the capillary channels of the HEX [4]

shows a reduced thermal conductivity due to increased wall thickness caused by deposition of particles. Additionally, thicker walls lead to an increase of hydraulic resistance of the fluid flow, equally as in case of blockage. Accordingly, monitoring or periodical measurement of coolant temperature and pressure can indicate the presence of degradation. [32] To reduce the effects of fouling and decreasing performance of the HEX, Kuchař et al. [37] recommends regularly cleaning while passivating the surface at the same time. Therefore two different procedures can be used, mechanical cleaning, for example with a pressure fluid or chemical cleaning [37]. Damaged HEXs can be welded, whereas defective and impaired (corroded) areas can be repaired with a weld built-up. These procedures are only applicable to carbon steel shell- and tube- HEXs [51].

DC/DC Converter (CONV) and DC/AC Inverter (INV)

As CONVs and INVs are comparable regarding their component architecture and their intended function, it can be assumed, that their degradation behavior is nearly similar. Failures in CONVs and INVs are mainly caused by temperature but also stress, humidity and mechanical vibrations, which affects the power semiconductor and the capacitor most. Thermo-mechanical fatigue is thereby the dominant failure mechanism, accelerated by temperature cycling, creep and corrosion, so that active thermal control is necessary [2]. The cooling device of a converter consists of a metal plate taking over the heat generated by the units within, connected with capillary tubes for liquid coolant [40].

Failure modes, regarding their electronic functions, are characterized by a gradual drift in power switch parameters [2]. With an included temperature measurement in the CONV or in the cooling circuit, an increase would be noticeable and thus damages or faulty behavior of the component.

This work presupposes that, due to novelty of these components in this scale, their development includes the integration of a BITE-system enabling the identification of the above mentioned degradation and failures. Additionally, the required temperature measurement can be ensured by integration of temperature sensors.

Electrical Motor (M)

In their work, Merizalde et al. [44] did a comprehensive investigation on failure causes and mechanisms regarding electrical motors. Next to various failure causes from different perspectives, such as environmental, operational and human based reasons, they investigated the failures in accordance to the components of the motor and what they are subjected to. An overview in their work displays, that the most affected components are the bearings and the stator impaired by a number of effects. This is the common sense according to other articles and papers ([12], [38]). Beyond that, they provide an allocation of failure development and its severity, which means in a first place, maintenance errors are a main contributor to failure causes. Furthermore, vibration, aging and poor lubrication mainly lead to most severe causes, mechanical breakage and insulation breakdown.

To address the above mentioned failures, Merizalde et al. [44] provided specific maintenance strategies as well, so the trend goes to continuous monitoring of the electrical equipment for remote and automatic diagnostics. Nevertheless, there is no single strategy to address all failure causes and aspects of their development. Accordingly, an overview of different techniques to monitor various faults is given, too. To prevent the degradation of mainly affected components, their work recommend some monitoring approaches, such as Motor Current Signature Analysis (MCSA), temperature and vibration measurement. Furthermore, the work provides some approaches for invasive testing, which can be used primarily to identify insulation defects, and non-invasive techniques to determine a certain damage or fault by analyzing the signal and frequency spectrum of the motor (MCSA). One of these approaches is described by [59], focusing on a model based analysis of various failure cases of motor's stator windings. For identification of the specific failure, the analysis uses Fast Fourier Transformation.

Other components

The overall EPS is not limited to above discussed degradation mechanisms as these forms concern all parts included in the propulsion system design. Wear and tear affects all rotating and moving parts due to pollution and non-ideal environment as well as aging, creep and operational conditions concern the electrical infrastructure and their intended functionality. Each item reacts on its own way to a certain degradation or impaired operation environment. Thus, for each component the measurement and detection approach of it must be designed appropriately, depending on the failure behavior the component has an affinity. Accordingly, when there are differences in failure behavior, the approach to address, postpone or avoid these failures are different as well. With performing maintenance very frequently, an increase of failures can occur, so that in future, maintenance needs to be done only when required, may it be on a safety or economical manner.

3 Methodology

Within the methodology chapter the evaluation concept shall be described in more detail. Herein the consecutive steps, their outcome and the usage of it, are described. Fig. 3.1 displays the consecutive steps of the analysis, herein named as "level 1 to 3".

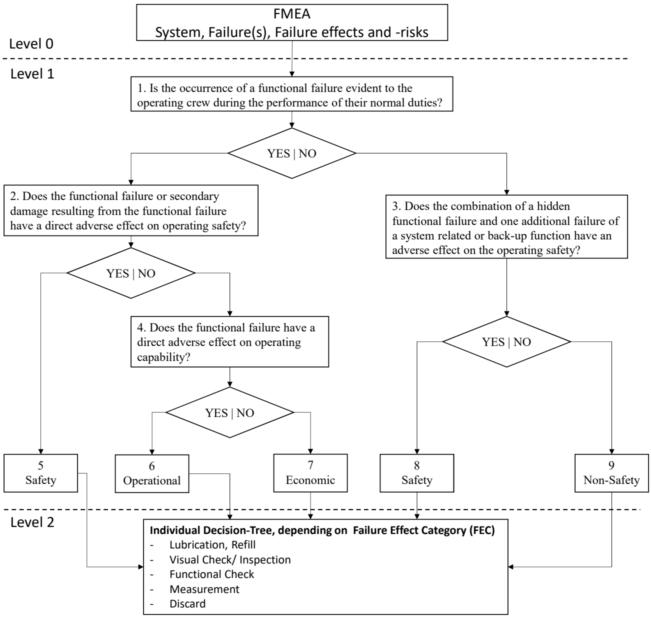


Figure 3.1 MSG-3 Evaluation process [29]

3.1 Failure Mode and Effects Analysis (FMEA)

After defining the extent of investigation focus and thus determination of the functions, now possible failures must be examined. Within system engineering there is a specific analysis, focusing on investigation of the system's architecture and its faulty behavior, the Failure Mode and Effects Analysis (FMEA). In literature, a comprehensive definition of the FMEA can be found:

> *"The FMEA is considered as a systematic approach to identify all possible ways in which a failure of a system can occur together with its causes and thus the failure's potential effect on system. The objective is to identify and document, within established ground rules, the functions, functional failures, and failure modes of an item. In addition, we can identify potential failures in a system or a process and determine how each item in the system is likely to fail and what will happen if it does."* [35, p. 5]

Accordingly, the FMEA perfectly fits the requirements to determine the system's potential failures and the subsequent consequences.

Within this work, the FMEA is a tabular listing of the functions and sub functions the EPS and its subsystems are intended to provide. In the next step, possible functional failures, faulty behavior or not fulfillment of the function's purpose are allocated to these functions. Within a third column the consequences of these failures and its effects on affected components, systems or operational condition is described. Finally, the last column identifies possible causes of the failures, whereby different causes can lead to the same failure as well as one cause can evoke several failures. Consequently, the content of the FMEA can be summarized in following key points:

- Function
- Functional Failure
- Failure Effect
- Failure Cause

For allocation reasons, the functions, their failures, effects and causes are consecutively numbered. In detail, this means: one specific function is numbered as *1*, so that one of its possible failures may be allocated as *1A*. As a failure can have different effects, one of it is addressed by *1A1* and its corresponding cause as *1A11*.

3.2 MSG-3 Analysis

Prior to the conduction of MSG-3 analysis a clear understanding of the system and its corresponding items and components is necessary. As described in Sec. 2.2 working groups are assigned for the investigation of different systems and subsystems. Their results are summarized in the MRBR.

In general the MSG-analysis is conducted for single items, the previously defined Maintenance Significant Items (MSIs) [10]. These are components of a specific (sub)system, likely to fail and thereby causing significant decrease in safety, operational availability or economical efficiency. This method is intended to decrease complexity while retain accuracy. Within this work, the complete propulsion system is considered as significant, due to the novelty of the system design. With major changes in each subsystem and correspondingly its functionality and the components it consists of, the EPS will be investigated at once.

3.2.1 Classification of failure criticality

Within Level 1 of the MSG-analysis, the failure cases are investigated and evaluated according the severity of their effects. Fig. 3.1 displays the decision logic for categorization of each failure. Herein, each failure case determined within the previously conducted FMEA, is assessed and allocated to a certain Failure Effects Category (FEC), of which each is requiring a different approach on maintaining the considered failure within level 2.

FEC 5 and 8 are safety relevant categories and require a maintenance task to prevent the occurrence of any failure, while FEC 6, 7 and 9 have only operational or economical character, which means evolving a maintenance task is optional.

The first question of the displayed logic determines the visibility of a functional failure to the crew during normal operation. This questions is answered *YES*, if the failure is noticeable by the crew. As the Aircraft Flight Manual (AFM), which describes the usual operation of flight and cabin crew, is not available in an early design stage, sometimes assumptions have to be made on which failures are evident to the crew. Herein, the crew does not necessarily notice the failure cause or its mechanism but only its occurrence. An approach to make a failure known to the crew is the ECAM-system described in Sec. 2.3.3.

In case of an evident failure (first question answered YES), the second question shall determine, whether the functional failure or secondary damage has a direct effect impairing the safety. The term *direct effect* corresponds to influencing the safety only by them self without presence of an additional failure. In case the safe continuation of the flight is impaired or passengers are seriously endangered due to the failure, the safety is considered decreased. If the question is answered with *YES* the failure is categorized as FEC 5, otherwise question four must be asked.

For a non-evident failure (question one answered NO), question three deals with investigation, whether the hidden failure in combination with another failure of a system related or of a back-up function, would decrease the operating safety. The answer must be *YES* if, comparable to question two, the safety is impaired by a combination of the hidden failure and an additional one. If so, the failure is categorized FEC 8 and requires a specific maintenance task. Otherwise, it is allocated to FEC 9, where a maintenance task is desirable to reduce the economical impact.

The fourth question, which is only asked in case of an evident failure which has no direct impact on safety, determines whether the functional failure has a negative impact on operating capability. Operation limits or emergency procedures that are necessary due to the functional failure, demand that the question is answered with *YES* and accordingly is categorized as FEC 6. Consequently, a maintenance task is desirable, if it reduces the failure risk. FEC 7 is chosen (question 4 is answered NO), if the functional failure has only economical effects, so that a task is only applied, if the costs arising by the maintenance task are lower than repair costs.

3.2.2 Evaluation of Maintenance Tasks

The failure cases and their assessed FECs are transferred to the second level and supplemented by their failure causes identified in the FMEA. Aim of this level is to allocate appropriate maintenance tasks to the failure causes, so that the failures can be corrected or the effects on operation reduced. Fig. 3.2 displays the consecutive questions to derive applicable and effective maintenance tasks. The FEC of the failure prescribes the questions to be asked.

On the left side, there is an allocation of FECs (numbers) and if the question (letter) is applicable to this FEC. In the middle block, the question is displayed. The block on the right side provides the possible tasks to be applied, as far as the question is answered *YES*.

The first question is evaluating, whether a certain servicing task or in more detail a lubrication task can be used to address the failure case. This question is applicable to all FECs. In general a lubrication task is applicable to all components suffering from wear due to movement, e.g. bearings. Servicing on the other hand, can include different task and depends on the component the task has been selected for. An example for a servicing task could simply be the cleaning of a surface or the replenishment of a reservoir.

With question two, only applicable to FEC 8 and 9 – the hidden failures – , it is determined whether an operational or visual check is applicable. Theses tasks are intended to identify the presence of a failure, but not necessarily it's extent. While the operational check shall verify the correct functionality of a specific item the visual check is intended to detect obvious damages or impairing that can lead to the loss of the component or its function.

Question three, again applicable to all FECs, shall clarify the applicability of a functional check or an inspection. Herewith, the exact fulfillment of defined function outputs or that measured values are within their tolerances shall be determined and is accordingly a more quantitative

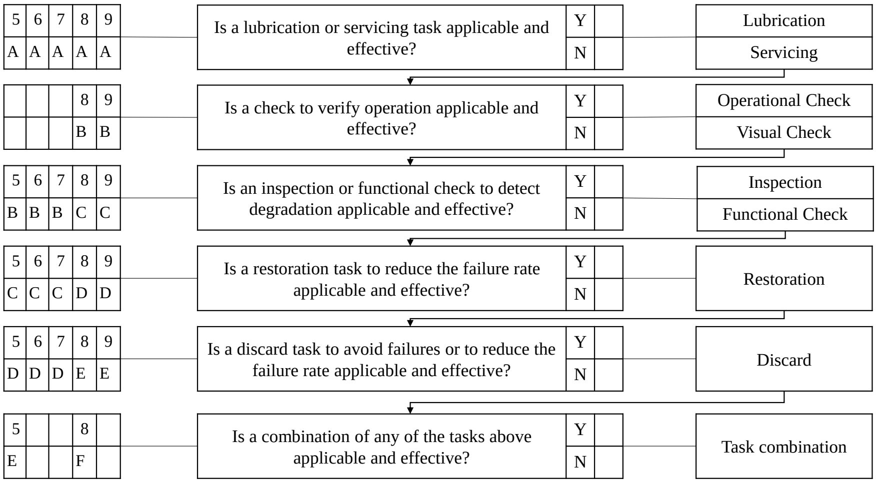


Figure 3.2 MSG-3 Level 2 Flowchart [10]

approach than question two. For usage of these tasks, sometimes it must be assumed, that it is possible to extract quantitative values.

The fourth question aims on identifying those components, a restoration task is applicable for. This requires that the impairing of the regarded component is identified and that there is a clear and defined method to restore its design functionality or to repair the unit. All FECs are concerned by this question again.

To reduce the failure rate or the risk of potential failures, question five investigates the applicability of a discard task. Hereby the corresponding component is replaced after a defined interval by a new component. Applicability herein means both, simple accessibility without impairing of surrounding items and their functionality but as well, that other tasks such as inspection or restoration would not provide any advantage on components reliability. Like question three and four, the fifth is applicable for all FECs.

The last question is only applicable to FEC 5 and 8, so that safety relevant failures are focused. Herein, it is asked for a combination of before as applicable determined tasks, that could benefit the systems reliability.

All questions and the corresponding tasks not only have to show applicability but as well be effective. Due to novelty of the system, this can only be assumed for some tasks, as it depends on many factors such as accessibility of the component itself, but as well on the specific component design, for example the integration of BITE. As of this work, effectiveness is categorized in two different aspects. The task considered, must show effective in regard to the performed task, which means, that a measurable advantage or improvement is the consequence of conducting this task and consequently reducing the risk of a failure. The second aspect is the cost effectiveness, after which, the costs arising by performance of the corresponding tasks are preferred to be as low as possible and not be more expensive than a simply run-to-failure-concept of the component and subsequently replacing the defect unit.

For clear allocation and description of these tasks refer to Sec. 2.1.1.

The next step is to consolidate and decide for necessity of those tasks, especially in regard to those failures categorized as *economical*.

3.3 Task consolidation and maintenance effort estimation

Some maintenance tasks can address several causes, so that these causes can be grouped to reduce the amount of necessary tasks. Hereby, the selection of tasks aims on the lowest amount of different tasks possible, but as many as necessary to cover all failure causes. As described in Sec. 3.2.1 not all function failures require a certain task, depending on their FEC. So, for FEC 6, 7 and 9 a task is optional and only desirable in case of Increasing availability, economical benefit or reduction of failure risk. On the other hand, a maintenance task is necessary for FEC 5 and 8. Where a maintenance task is neither applicable nor effective on these FECs, the corresponding component providing or fulfilling the function needs to be redesigned.

For subsequent investigation and comparing analysis, the selected tasks need to be defined in regard to their exact description and interval.

Intervals of maintenance tasks are given in the usage parameters Flight Hours (FH) and Flight Cycles (FC) or in Months (MOs). An exception is the APU, where the tasks are defined by APU Hours (APUH) and APU Cycles (APUC). Some maintenance tasks concerning the engine, are prescribed by engine hours and cycles. In general the task interval is selected data- or experience based. Thereby technical investigations and tests but as well customer requirements, manufacturer recommendations and in service data are considered. To avoid adverse effects on safety and reliability, a maintenance task should not be performed more often than required. [39]

Furthermore, to take into account the subsequent comparing analysis, for each task the necessary amount of MMHs must be defined. Within the MPD the corresponding workload is provided in three categories of Maintenance Man Hour (MMH), as listed below:

- MMH_{Prep} for preparatory work
- MMH_{Access} to gain necessary access
- MMH_{Task} for completion of actual task

However, since the system design is currently in its conceptual state and the exact layout is yet to be determined, any estimation of access and preparatory MMH would introduce high levels of uncertainty [43] and are accordingly not referenced within this work. A special case is the deinstallation of some components, which is described by the MMH_{Prep} for *discard*-tasks.

The definition and estimation of the selected task's MMH, is based on comparable tasks from the legacy MPD or on literature review.

3.4 Assumptions and Limits

Electrical system constrains

The battery-electric propulsion system is, due to its novelty, subjected to several assumptions, equally to the system safety analysis by Dauer [14], which is the basis for this work. Design decisions made during the system layout development had to be extended to fulfill all functions and address necessary requirements for monitoring or measurement. This means for example additional sensors to measure values and identify potential failures.

Further, it has been assumed that the design of certain components includes specific functions and capabilities, e.g. self-test equipment (BITE). In advance, all measurements and relevant system data are displayable by the ECAM system.

Legacy system constrains

To assess the developed maintenance effort of the new EPS, this work compares it to a conventional A320's maintenance effort. Therefore, within this work, the reference system is chosen as the combination of the most common used components. This includes 2 CFM56-5B engines, the APS3200 APU and an unmodified A320 aircraft structure.

Judgment

The conduction of the MSG-logic is highly based on the author's engineering judgment. Within the conduction of the first step of the MSG-3 analysis, this work focuses on a selection of major failure mechanisms, so that the first draft of the maintenance plan is not over-engineered.

Answering the questions of level 1 of the MSG-logic highly depends on the correct indication of failures to the crew and the automatically switching to redundancies. Level 2 focuses on the applicability and effectiveness of a maintenance task to a specific failure cause. This is subjected to certain assumptions regarding cost-effectiveness as well as accessibility and capability of repair or restoration.

After selection of necessary tasks, their subsequent definition is based on the models for interval determination from literature. This task definition highly relies on comparable tasks of the A320's MPD.

Comparability

For appropriate comparability of the new system design with the conventional system, within the man hour calculation, only the MMH for task conduction are used. As the system design is not yet integrated in the airframe, it can not be said, whether components are easily accessible or not, so that the required MMH for preparation and gaining access is not determinable. Further, the conduction of the comparing analysis is based on the assumption, that the new system design completely replaces all tasks related to the conventional system and its components.

4 Analysis of a battery-electric propulsion system

Chapter 4 is intended to describe the conduction of the MSG-3 process for the battery based EPS in more detail. Herein the decisions made and the processing of developed information shall be explained on specific examples for each step of the analysis.

4.1 Determination of system failures

Within the first step of investigation, as described in Sec. 3.1, the system is evaluated according functional failures, their consequences and causes. The functions, this work investigates had been transferred from the author's previous work [14] and supplemented to address additional aspects, not included in the system safety assessment.

In the first instance, for each of these functions, possible failure cases are derived. Among others, this may include, an insufficient function or a complete loss. It also depends on the regarded component and its intended function. By engineering judgment on how components or subsystems are likely to fail and based on descriptions in Sec. 2.4.2 for specific components, certain degradation mechanisms or sub items likely to fail have been identified. Tab. A1 contains the determination of these possible failure cases and displays their evaluation for the selected functions. Subsequently, within this section, the disconnection of the energy flow within the ESD and the heat rejection of the Electric Drive System (EDS) are investigated. The following examples, are intended to describe the decision process for this part of the overall analysis.

The first example, deals with the disconnection of the energy source within the ESD, which is either intended or unintended. This leads to the considered two failure cases, 6A an erroneous disconnection and 6B whereby an intended disconnection is not performed. While the first case will suffer from loss of energy supply and consequently the provision of several functions, possible damages can occur. On the other hand, assuming the disconnection is the reaction to prevent or reduce the risk of a critical failure, the failure of case 6B would mean, that this dangerous condition can not be controlled. In consequence, this will lead as well to possible damages or even a critical condition. Both effects are correspondingly referenced as 6A1 and 6B1.

The component intended to fulfill this function is the Circuit Breaker (CB), which is subjected to fail by two different major causes. As of this work, these cases are named for case 6A *fail open*, as it opens unintended and for case 6B *fail close*, as it does not close when intended. Following the reference prescription, both causes are allocated as 6A11 and 6B11.

Another example is the heat rejection from the EDS, whereby the first case, 15A, describes the total loss of heat dissipation, while the second case, 15B, addresses the incorrect performance. Each case entails an ECAM indication of a faulty condition, as the temperature of the cooling circuits and its related components is redundantly tracked during the flight. Accordingly, a significant increase of temperature will be shown and noticed via the ECAM.

Cooling circuits suffering from different causes, that can lead to damage on affected components such as clogging, leakage or defect cooling interfaces, but as well from incorrect control signals due to defect sensors. In either case, this evokes overheating or over cooling, which in consequence leads to a decrease of the regarded component's performance or even impairs its structural integrity. These effects are listed with reference 15A1 and 15B1.

With regard to the EDS, a possible damage or defect, leading to one of the failure effects, may be caused by the interfaces of the cooled component and the cooling circuit, for example the INV integrated cooling. As, per design decision, the electric motor is not liquid cooled, but connected to a motor cooling fan, the failure effect is subjected to defect or damage of this fan. Further, a lack of coolant leads to insufficient heat rejection, so that a coolant leak can as well cause overheating. Additionally, by indications of a defect sensor, an inappropriate cooling demand can be triggered, which can lead to overheating or -cooling [1], depending on sensors deviation. These causes are allocated separately to each failure effect and referenced as 15A11 to 15A14, resp. 15B11 to 15B13, which leads to the differentiation of four and three failure causes for the corresponding failure cases.

To evaluate the potential failure behavior of the system and its components, without deep diving into the physical degradation mechanisms, this work focuses on major failure causes identified via literature review, which is partially described in Sec. 2.4.2. These major failure causes are related component's failures or damages due to their most common defects.

Table 4.1 Function and Failure distribution per sub system

Distribution	ESD	EDS	TMS	Total
functions per sub system	10	6	11	27
failure causes per sub system	30	19	23	72

As depicted in Tab. 4.1, it can be seen, that the share of functions per sub system is approximately equal, only the EDS has less tasks, which can be neglected, as it is a two parted system (once per engine). Further, for a total of 27 functions, 72 possible failure causes have been determined. The major part of these failures can be allocated to the ESD sub system, while the second most failure causes are examined for the TMS.

Thus it can be seen, that the ESD is potentially, the leading driver for failures and consequently for the amount of necessary maintenance. On the other hand the EDS seems to cause less failures, but taking into consideration that there are two circuits per aircraft, potentially doubling the amount of failures, the drive system becomes the leading cause for increased maintenance. Further, the relevance of the TMS and its associated failures is indicated. So at this point, only a rough estimation regarding upcoming maintenance can be made.

4.2 Level 1 - Failure categorization

Within the second step of this work's investigation, the identified failure cases, now have to be categorized according the severity of their effects. Following the description in Sec. 3.2.1, the four questions are subsequently answered for each failure case.

Depending on the determined evidence of the failure case in the first question, the subsequent question is considering the effects on operating safety, either by itself or secondary damage, or in combination with an additional functional failure. Finally, question four addresses the effects on operating capability. Based on the author's engineering judgment, the consequences of a certain functional failure on the system's operational safety and operating capability have to be determined.

The design of Tab. A2 is used to display and evaluate all results of level one. Within the first two columns the failure case considered is addressed. Subsequently, in pairs of columns, the four questions are, answered within the first one and correspondingly justified in the

[1]Overcooling describes the significant reduction of temperature below the considered component's design temperature and accordingly has to be avoided. It can have various effects, thus like decrease of performance, icing or, due to condensation of moisture, short circuits.

second. Depending on the answer of the first question either the third or the second and fourth question are not applicable. These questions are answered with "*X*". Finally, in the last column the corresponding FEC is allocated.

Mainly, three different approaches have been used for failure categorization. To provide a general understanding of the decisions made, each approach shall be explained by one of the following three examples. They shall outline the major aspects, driving these decisions, such as evidence, the relevance of redundancy, the presence of multiple failures and their effects.

Evident failures with installed redundancy

The first example considers *failure case 6A*, erroneous disconnection of energy source within the ESD, in which the connection between energy storage and distribution is unintentionally disconnected. This disconnection does not require any indication or error message, as the consequence will be noticed by the flight crew at once and accordingly is evident. Due to disconnection, the energy supply immediately is lost and the EDS stops providing thrust. Consequently, the first question, regarding the failure's evidence can be answered *YES*. Following the schema, question two asks about the effect on operating safety. As this case has been part of the SSA, there is an additional circuit, bridging the defect Circuit Breaker (CB). This redundancy is intended to provide safe and unimpaired continuation of the flight, so that the question for an impact on safety can be negated. Justification for that is, that the system only loses its redundancy. As the failure is evident to the crew, the third question is not applicable and can be neglected. Finally, with question four the effect on operating capability must be evaluated. In case there is no automatic transfer from the defect component to its redundancy, the crew has to do it manually. By loosing the redundancy, it can be expected that after landing the defect must be investigated and corrected prior to the next flight. This means, depending on severity of failure and resulting complexity of correction, a possible increase of necessary downtime can consequently reduce the operating capabilities.

Further, the loss of a specific component can also have an impact on in-flight operations, leading to restrictions or limits. The extent of it, is defined by the manufacturers Master Minimum Equipment List (MMEL) [28]. Answering these questions, leads to one of the five FECs. Concerning the case of the first example, it is categorized as *FEC 6, Operational*. Exemplary, Fig. 4.1 displays the decision process of the failure case *6A*, which also has been discussed within step zero. The marked red lines, symbolize the decisions made within level 1 of the MSG-3 logic.

Evident failures without redundancy

Failure case 12A will serve as the second example. Herein, the loss of electric energy supply to the EDS is examined, which can, analogue to case 6A, lead to loss of thrust. With the assumption that measured values, which are caused by a functional failure are displayed via the ECAM-system to the crew, the first question is answered *YES*. This presupposes that a corresponding value is measurable, which allows to make a statement regarding the specific failure. The failure of the power distribution would cause significant impact on the aircraft's safety as, per design layout, there is no second path for distributing the electrical energy. This means a total loss of the corresponding EDS-circuit and in consequence, the loss of the engine. Accordingly, question two must be answered *YES*. Thus, for an evident failure, which leads to a safety critical condition the third and fourth question are not applicable, so that the decision logic leads to *FEC 5 - Safety*.

Hidden failures without redundancy

The third example describes the *failure case 1B*, measured values displayed via ECAM without any notice correctness, whereby the BMS delivers wrong data regarding the BAT status. Within the initial design approach, there is no data handling unit integrated, checking the measured values regarding their correctness. As of this work, this means, that all data provided to the

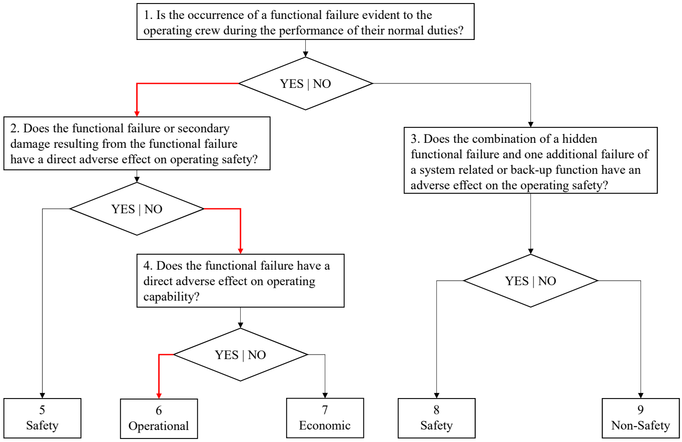


Figure 4.1 MSG-3 Level 1 Failure Case 6A

ECAM, are not necessarily showing the actual condition of the system. Consequently, there is no indication on false measurement data, so that a failure remains hidden and accordingly, the first question must be answered *NO*. Thus, question two and four are not applicable. By indicating false values, there is no impact on safety, but the third question asks as well for combinations of the considered hidden failure and an additional one. This question follows a rather theoretical approach, by combining possible functional failures of different components and the considered failure and estimating their consequences. Accordingly, this question highly depends on the authors understanding of the system next to engineering judgment. Concerning failure 1B, for example, if the battery has a functional failure as well and is not providing the full amount of stored electrical energy. By not indicating this issue, due to a faulty BMS, this condition can lead to a reduced flight range and consequently to a critical situation. The decision logic delivers *FEC 8 - Safety*.

Table 4.2 Failure Effects Category (FEC) distribution

Failure Effects Category (FEC)	FEC 5	FEC 6	FEC 7	FEC 8	FEC 9	Total
Amount of failure cases	3	21	9	3	1	37

Tab. 4.2 provides the results of the failure categorization. This distribution seems to be logical, as with a higher amount of safety critical/ relevant failures the system should be considered for a redesign. Conduction of level one delivers a severity classification of each considered functional failure, which is transferred to level two. Appendix B, Tab. A2 lists the complete conduction of the first step's failure categorization.

4.3 Level 2 - Maintenance options investigation

This part of the analysis takes over the failure causes from the FMEA and their categorization according level 1 to evaluate an appropriate maintenance approach. The description in Sec. 3.2.2 provides an understanding of the determination of applicable maintenance tasks, which have been discussed in Sec. 2.1.1. Accordingly, the questions are answered for each failure cause, so subsequently an applicable and effective task is determined.

The layout of the table, used to conduct and display the results of level 2 shall be explained as follows:

– *Ref*: Displays the number for allocation of the corresponding failure cause, refer to Tab. A1

– *Comp*: Addresses the component affected by the corresponding failure cause, simplifies the allocation of applicable tasks

– *Question*: Head of column pair, refers to the several questions for task determination within level 2

– *Ans*: Sub column, answers the question of the corresponding head of column pair (YES/ NO/ X)

– *Description*: Sub column, describes the task related to the question of the head of column pair, if applicable and effective

For each question of level two, there is a pair of columns, except for question six, as all failure causes have an allocated maintenance task. Accordingly, the last question was never necessary to be answered, so it has been excluded from the table displayed in the appendix, Tab. A3.

The conduction of level 2 shall be explained on a failure case applicable to all questions. Thus, its categorization has to be FEC 8. To address this, failure case *22A (fails to keep coolant free of contamination)* has been chosen, which is allocated to *Ref. 22A11*. Within the table mentioned above, the results are displayed.

By question one, the applicability of servicing or a lubrication task shall be determined. As the filter, considered within failure case 22A, is not a part requiring lubrication, this is not applicable. In regard to servicing, a filter can be cleaned. In order to do so, the filter must be removed from the cooling circuit, which could lead to additional contamination of the circuit, depending on the environment, the deinstallation is performed at. Consequently, the SVC task is applicable, but not necessarily (cost) effective. In advance, depending on the filter, a cleaning may not restore its properties back to 100%.

With consecutive question two, the probability of detection shall be increased by usage of a VCK or an OPC. An OPC can not be conducted for a filter, but a VCK can. Equally to the servicing task, the filter needs to be removed after opening the cooling circuit, which as well can lead to additional contamination. Moreover, regularly checking the filter may arise more costs, than a simple replacement, so that a scheduled VCK is not cost effective.

Question three determines, if a (deeper) inspection could lead to prevention or reduction of the corresponding failure cause. This includes the GVI, the SDI or the DET. In advance, a FNC may be used to identify any risks or failures. Towards the filter, a FNC is not applicable, but depending on the accessibility, a SDI or DET can be possible. The disadvantage of these kind of tasks is, that they are usually time consuming, require specialized tools and staff and are accordingly expensive and in consequence are not to be preferred.

The fourth question, examines the applicability of a restoration task for the filter. Assuming, that the filter is a rather simple unit, not specialized for a certain fluid or special requirements of the cooling circuit, the filter can expected to be an average part. Accordingly, the costs for a removal with consecutive restoration and installation, would create more costs than a simple replacement.

This leads to question five, in which a replacement task is evaluated. As stated within question four, the filter is expected to be a simple and low-cost part, so that the DIS-task is applicable and (cost) effective.

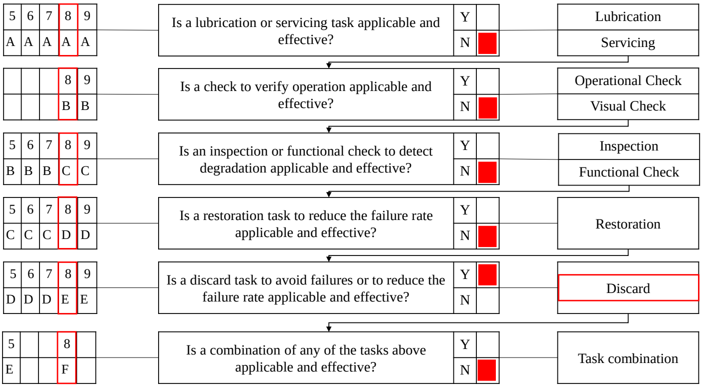


Figure 4.2 MSG-3 Level 2 Failure Case 15

Question six, the last one, determines the effectiveness of a combination of tasks, if a single task within question one to five has not proven to be effective. For example, a combination can be used to monitor the filters condition by a GVI and replacing it at a certain state (DIS), which would be applicable in case of a specialized and expensive unit. Regarding failure case 22A, this question does not need further consideration as the DIS-task has been determined to be be applicable and effective.

In conclusion, depending on the assumptions made, in general all tasks are applicable and more or less effective in regard to the result of conduction. However, not all of them require an equal effort regarding labor and downtime, so that the arising costs, as one of the the limiting factors, lead to the DIS-task as only cost effective variant. The decision logic of failure case 22A is depicted in Fig. 4.2.

A second example shall explain the design related assumptions made and their influence on conduction of level two. Therefore, one of the dominant failure causes of the electric motor has been chosen. Failure cause 13A12 describes the failure of electric motor's stator winding insulation. Starting with question one towards servicing or lubrication, regarding the stator windings neither a LUB-task nor any variant of servicing is applicable, so that both can be neglected. Resulting from the categorization of failure case 13A as FEC 6, the second question is not applicable and thus can be neglected as well. This leads to question three, which shall examine the applicability of a FNC or any type of inspection. In regard to the Electrical Motor (M), it is assumed, that to fulfill the needs of an aircraft the design is not yet completely defined. Accordingly, future full electric engines, based on this type of motor, may have incorporated an access point for a detailed inspection of the stator windings. An appropriate method, already common practice on conventional engines, is the borescope inspection, which can be performed even with small access. Consequently, the DET is applicable. Compared to a restoration or discard task, which would cause a massive amount of costs, the costs of this inspection (including specialized tooling and trained staff) are rather low, and thus (cost) effective. Accordingly, questions four to six do not need further consideration, after question three delivers an appropriate task to identify possible degradation.

As of this work, several components are assumed to have integrated maintenance supporting accesses or interfaces (i.e. BITE) in order to conduct certain maintenance tasks. This enables to include tasks, that require less maintenance effort, such as in this example. These design related assumptions can be included in the design requirements of the corresponding components for application in aviation. At this point of investigation, they support the development of the corresponding maintenance implications, such as here, to apply a SDI to the motor stator.

During the System Safety Assessment, Dauer [14] identified the necessity for specific maintenance tasks for a certifiable system design. They are called Certification Maintenance Requirements (CMRs) and have mandatory character. As of this work, it was decided that these requirements shall be addressed by the maintenance tasks derived within level 2 of the MSG-logic. This involves a condition monitoring for the HEX and INVs capacitor, whereas it is assumed that the monitoring of the INV includes this sub component.

The second example is intended to demonstrate the influence of the CMRs on the decision process. Accordingly, herein function *20 - To adapt coolant temperature* shall be discussed, in which the HEX has to dissipate the heat generated within the EPS. The corresponding CMR required by the SSA is a condition monitoring of the HEX. Unlike the first example, this failure is categorized as FEC 6 and does not necessarily require a maintenance task. By addressing the requirements of the SSA, the conduction of a monitoring task is necessary.

Within the first question the applicability of any servicing or lubrication shall be identified. With regard to failure case 20A, especially addressing failure cause 20A11 (HEX leakage and cracks), a lubrication task is not applicable, as well as any servicing task.

Question two is not applicable to failure causes categorized as FEC 6.

Subsequently, question three aims on identifying the applicability of a GVI, a FNC or inspections with different level of complexity. A FNC of the HEX is not applicable to identify the considered failure. A more appropriate approach to identify cracks and leaks is the GVI, but is only a rough inspection not necessarily detecting all failures. SDI or DET are more detailed inspections with a high probability of detection. The HEX is considered a complex component and accordingly assumed to be expensive, so that the inspection shall be less expensive compared to a RST or DIS. As it currently is not possible to estimate the arising costs for complex inspection, it is assumed that the DET is less expensive than the SDI. Consequently, the DET is assumed to be cost effective, and has been chosen for the maintenance schedule. The remaining questions are not necessary to answer.

In the next step a selection is made from those tasks, that have been identified as applicable and effective, and defined in more detail afterwards. This process will be described in the following section.

The results of level 2 are listed in Tab. A3.

4.4 Task Selection

A selection of those tasks identified in level two is made, because performing each task would evoke a huge amount of downtime and consequently maintenance costs. Accordingly, at this point a variety of tasks is chosen, based on engineering judgment and available literature. This selection is intended to maintain the aircraft's airworthy condition by prevention or detection of degradation and wear before a loss or impairment of a specific function becomes critical. In advance, by selecting tasks and thus reducing the interaction of maintenance personnel with systems, a reduction of risk due to damage or failures can be achieved.

To address this, tasks with the lowest impact regarding required downtime and complexity of conduction have been chosen, whereby for at least functional failures categorized as FEC 5 and 8 must be selected. As a conservative approach, for nearly each failure cause, examined within the FMEA, a task has been chosen in the first instance. That a specific failure cause can lead to different failure cases results in a certain task that addresses various failure cases so that they are grouped together, to avoid multiple execution. Hereby, if two different FECs are

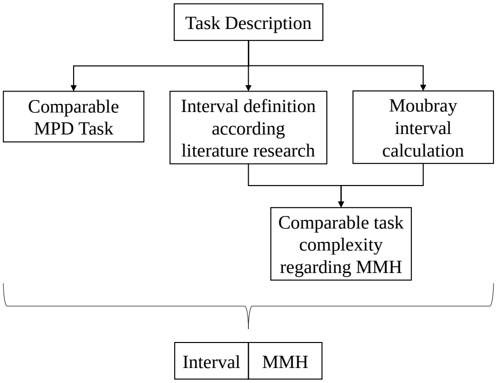


Figure 4.3 Decision logic for task definition

combined, the corresponding tasks list both FECs in the maintenance schedule. Regarding the maintenance implications of sensors it was decided, that instead of maintaining a sensor, which would cause complex deinstallation or even more complex redesign for integration of self-test equipment, the item shall be operated until total loss and subsequently replaced. Further, the Detailed Inspection (DET) of the BAT cooling has been integrated in the Restoration (RST) task of the battery. The corresponding explanation is given in Sec. 4.5.1.

As mentioned above, not for each failure cause a maintenance action has been chosen. Some tasks are excluded from the maintenance plan as their failure has no significant influence, neither to operation of the aircraft nor to safety. This concerns the tasks regarding ensuring the functionality of sensors. Further, the system design this work is based on, is transferred from the author's previous work, where maintenance implications are used to satisfy the requirements of the System safety Analysis (SSA). These CMRs must be included in the maintenance program, so that both, condition monitoring of the inverter's capacitor and of the HEX must be addressed by a corresponding task.

Regarding the capacitor, a detailed condition monitoring of a subitem is assumed to complex, so that the complete INV is regularly monitored by an OPC. This task satisfies the need resulting from the CMR and as well is applicable by the MSG logic categorized with an FEC 6 - operational. Further, the requirement of monitoring the HEX is addressed by a regularly Detailed Inspection (DET). Equally to the INV, according the MSG logic the HEX is categorized as FEC 6 and consequently a maintenance task is applicable. For both CMR-tasks, task 9 for the INV and task 22 for the HEX, this reference is given in the maintenance schedule.

By summary and selection of certain tasks, the results of level 2 is that the amount of 72 failure causes has been reduced to 30 different tasks, that shall provide safe and reliable operation of the EPS and are displayed in Tab. A5 in the appendix. These tasks need to be defined afterwards in regard to their interval and required labor (working hours), which will be discussed in the following.

4.5 Task Definition

The schema displayed in Fig. 4.3 shows the three options, according to which the chosen tasks have been defined. Using the selected task's content, the MPD of the conventional A320 has been investigated for a comparable task regarding task code, comparable extent of the task to be performed and the corresponding component. If the MPD does not provide a comparable task, the interval was chosen according degradation patterns and corresponding failure intervals given by literature, which is the second option within the logic. In case the literature as well, does not deliver usable intervals, a Failure Finding Interval (FFI) as been calculated, based on the failure rates used in the author's previous work and Eq. 4.1 provided by Moubray [45]. Regarding the last two options of the decision logic, the MMH of the corresponding task have been chosen according tasks of the MPD with a comparable extent.

Some tasks, only contain the removal of the considered component for an In-Shop treatment. To evaluated the necessary amount of spare parts to replace them, and in advance to compare it to the legacy system, within the interval and MMH investigation, these tasks have been marked accordingly.

4.5.1 Task Interval

The determined maintenance plan has to be performed on a regular basis, which means, that each task must be conducted within a predefined interval. As described in Sec. 3.3, therefore the usage parameters are used.

The within level 2 examined tasks are intended to prevent or reduce degradation or identify any impairing of the considered component. Regarding a failure finding tasks, its interval majorly depends on the probability of detection and consequently on the considered component's degradation behavior. Maintenance tasks that, on the other hand, shall restore or ensure a certain condition require defined limits at which a recovery must be performed. These limits depend on the components design and its rest of useful life, which is majorly influenced by individual degradation behavior. As there is no similar system in aviation with comparable requirements, the definition of the intervals is based on degradation behavior to be expected and analysis on reliability conducted in the past. Mainly, most intervals are based on the maintenance schedule of the conventional A320 depending on potential task equality. An example for this case is task 9, *Perform Functional Check (FNC) of static inverter via BITE*, which was completely taken over from the legacy MPD. The corresponding task contains an OPC of the inverter and is integrated, based on a CMR and FEC 8. Further, the MPD provides the same task with different intervals. To address the task's requirements of this work, that task has been chosen, which matches best. Accordingly, the task required by a CMR with the longest interval has been chosen, as the task of the EPS is only categorized as FEC 6, and thus less critical.

Those components not addressed in the legacy MPD, resilient data are taken over from literature. This has been the approach for defining the interval of the BAT restoration. Mathew et al. [42] used for their simulations an amount of 4000 cycles to describe the cell life. The presentation of Pesaran [47] states, that a LIBs calendar based end of life is 15 years. These two intervals will be used for the restoration of the BAT. However, this includes a high uncertainty regarding the BATs actual degradation and failure behavior. To address this issue, within chapter 5 a comparative investigation regarding differentiation of these intervals is made.

For those tasks without an equal counterpart from the A320 MPD or resilient values from literature, the interval has to be calculated in accordance with possibility of occurrence of the considered failure. A first approach is the calculation presented by Moubray [45], who uses Eq. 4.1 to calculate a Failure Finding Interval (FFI). This calculation is based on Mean Time Between Failure (MTBF) and results from Eq. 4.2 using the corresponding failure rate. The failure rates used for calculation of FFIs are taken over from Dauer [14] and are listed in Tab. A4.

$$FFI = 2 * Unavailability * MTBF \tag{4.1}$$

$$MTBF = 1/\lambda \tag{4.2}$$

This method has been used to calculate the interval of task 14, for example. The conventional A320 propulsion system does not include a clutch to transmit shaft power, so that there is no task in the MPD. Using the data from [14], the failure rate of the clutch equals 1.22E-06 h^{-1}. This leads to a MTBF of 8.2E05 h^{-1}. The *unavailability* describes the acceptable ratio of out-of-service-time to service-life-time [45] and is chosen in this work to equal 0.1%. Entering these values to Eq. 4.1 provides the corresponding FFI according Eq. 4.3:

$$FFI = 2 * 0.001 * 8.2E05h^{-1} = 1639\,\text{FH} \tag{4.3}$$

As the interval is rather inconvenient, in the MPD for the EPS the interval was chosen to 1600 FH.

To optimize the maintenance plan of the EPS, the calculated or taken over intervals are grouped together, so that tasks with focus on the same component or requiring the same access, are conducted at the same time. This is common practice in aviation's maintenance and shall address the demand for minimum on downtime and maintenance costs. An example is the above mentioned Restoration (RST) of the BAT. To restore a battery, the whole battery pack needs to be removed from the aircraft, which includes the integrated cooling. Accordingly, the removal for a cell replacement after 4000 FC and a second removal after another 1500FC (interval of the BAT cooling RST-task equals 5500 FC) would create a high amount of unnecessary downtime. Consequently, it was decided that the restoration of the battery cooling is included into battery's in-shop restoration task. Hereby, the battery pack is removed only once to conduct both tasks and send to a shop, where all defective cells are replaced and at the same time, the cooling circuits are restored. Afterwards, the completely restore battery is reinstalled.

Further optimization, to group the different maintenance tasks into check packages has not been made.

Some tasks have more than one interval-value triggering this task, even though it only has to be performed once at the interval which comes first.

The intervals of the selected tasks are as well listed in Tab. A5

4.5.2 Determination of MMH

For economical reasons and to compare the maintenance program to similar systems the investigation of necessary Maintenance Man Hour (MMH) shall be made. As described in Sec. 4.5, there are three different types, of which this work focuses on the MMH necessary for conduction of the actual task.

The above selected tasks, for a major part, are adapted from the legacy system's MPD. Accordingly, the MMH can be copied as well. Those tasks which do not have a comparable counterpart from the legacy system regarding the specific component, can be at least comparable in regard to severity and task content. Thus, the MPD provides several tasks with the same focus or content, what allows to transfer the corresponding MMH.

The identified MMH are allocated to the corresponding task and included in the maintenance plan in Tab. A5 of the appendix. These values describe the time demand for performing the task on one component. Therefore, to address several components, the MMH must be multiplied by the amount of components, integrated in the system to obtain the total maintenance effort.

MMH determination according MPD

Using the example from above, in task three (battery restoration), due to conceptual state of the system design and its not yet defined integration, only a rough estimation of the required MMH can be made. The legacy MPD provides two tasks with comparable maintenance effort, the replacement of the nose landing gear requiring 16 MMH and the replacement of an engine, which takes 32 MMH. To remove a battery from the aircraft, based on author's engineering judgment, it was chosen to use the average of both tasks, which leads to 24 MMH.

MMH determination according literature

Regarding the example from above, task 14 DET of the clutch, the MPD does not provide a comparable task. However, the literature provides an usable approach. Sieb et al. [54] calculate in their work the maintenance effort of an electric propulsion system, including a clutch. The corresponding effort towards maintenance time and consequently the MMH uses the average total working time for a Detailed Inspection (DET) from ATA chapters 20 to 50. Moreover, this calculation is adjusted by a *long-term correction factor* of 3.3, so that the used maintenance task time equals 350 minutes. As this method include next to the actual execution time as well the preparatory time and the access time, within this work the execution time is recalculated. Consequently, dividing 350 minutes by the factor of 3.3 and subsequently assuming that the actual conduction of the task accounts for 60% leads to about 60 minutes, which seems reasonable.

5 Evaluation and comparative analysis of the maintenance implications of the EPS

Within chapter 4 the development of the maintenance schedule for a battery-driven propulsion system has been shown, of which the results are listed in Tab. A5. Next to the tasks, their intervals and corresponding MMH had been determined. These values are used in this chapter to evaluate the corresponding maintenance implications and consecutively, compare them to the schedule of the legacy system. Therefore, a suitable basis, on which these schedules are comparable must be defined.

5.1 Comparability and Utilization

To compare the maintenance implications of both, the legacy system and the EPS, it is necessary to put them in relation to a common basis. As not all maintenance tasks are given in FH, but also in FC or MO, those intervals have to be transformed. Accordingly, there will be presented different utilization scenarios first, so that based on a certain amount of FHs or FCs a reference amount of maintenance (in MMH) per 1000 FH can be calculated.

In their comparative analysis of a hydrogen based system, Meissner et al. [43] used the annual average utilization of a representative A320 passenger aircraft, whereby they excluded extended ground times during the corona virus lock down. Based on that, Tab. 5.1 provides an overview of typical utilization rates for different operating scenarios. The first column lists the values for an Average Utilization Rate (AVG), which is given by 1500 FC and 2750 FH annually. This results in an average flight duration, displayed as FH-to-FC-ratio, of 1.8.

Furthermore, this work investigates the scheduled maintenance implications for an aircraft with a High Utilization Rate (HUR), which includes the upper most 5% (annual utilization within the 95% percentile) of the worldwide A320 fleet. Additionally, the counterpart, an aircraft with a Low Utilization Rate (LUR), that focuses on the bottom 5% (annual utilization within the 5% percentile) of the worldwide A320 fleet, is investigated as well. There are two exceptions regarding the utilization rates of the APU, which are constant for all utilization scenarios. They are given in the two lower lines of Tab. 5.1 and equal 0.47 APU Hours (APUH) per FH and one APU cycle (APUC) per FC. These values are presented in the work of Kensbock [34], regarding the investigation of a fuel cell replacing the APU. In addition, this work examines the effects of different flight lengths within the average utilization. Hereby, two different cases are investigated, the Short Flight Segment (SFS) and the Long Flight Segment (LFS). While the SFS considers a FH-to-FC-ratio equal to one, the LFSs ratio equals three. Accordingly, the maintenance effort can be evaluated by the aircraft's annual usage and in dependence of the flight length.

Table 5.1 Utilization Scenarios for comparative analysis [43]

Dimension	AVG	LUR	HUR	SFS	LFS
FH per year	2750	1650	3900	2750	2750
FC per year	1500	900	2100	2750	917
FH per FC	1.8	1.8	1.9	1	3
FH per Month (MO)	229	138	325	229	229
APUH per FH			0.47		
APUC per FC			1		

In order to calculate the MMH per 1000 FH for each scenario, the corresponding values of Tab. 5.1 are used. For those tasks, having various intervals (e.g. 24 MO or 2500 FH) the value whichever comes first was taken for the calculation, which addresses the conservative approach.

For simplification, it will be assumed that all connections and interfaces regarding monitoring and controlability of the legacy system and its associated components, will be necessary for operation of the EPS as well, and consequently, requires the same maintenance.

5.2 Battery-Electric Propulsion System (EPS) maintenance evaluation

The conduction of the MSG-logic was intended to derive a first draft of the upcoming maintenance implications for a battery-Electric Propulsion System (EPS), that completely replaces the conventional, fuel-based propulsion system. Therefore, many assumptions towards the system but as well on the process have been made. However, this work provides an amount of 29 tasks, necessary to maintain the system's airworthy condition. These tasks can be allocated to the three subsystems, according the following table.

Table 5.2 Allocation of EPS maintenance tasks to subsystems

Subsystems	ESD	EDS	TMS
Amount of tasks	9	9	12
Share of total amount (%)	30.00	30.00	40.00
Corresponding total MMH	78.48	73.44	10.64
Share of total MMH (%)	48.28	45.18	6.55

From Tab. 5.2 it can be seen, that the tasks are nearly equally distributed, only the share of the TMS is slightly higher. Despite that the TMS requires the most tasks, it has the lowest share of MMH with less than 7 %. Regarding the ESD and the EDS, their required amount is nearly equal with around 70 MMH and about 45 %.

Furthermore, the MMH per 1000 FH for the different utilization scenarios have been calculated. Tab. 5.3 displays the results.

Table 5.3 Utilization Scenarios of EPS

	AVG	LUR	HUR	SFS	LFS
MMH /1000 FH	23.04	23.39	22.75	34.84	17.53

According to these calculated values, there is no significant difference between the different utilization scenarios as they are nearly equal. The conclusion drawn from this, is that the maintenance schedule very little depends on the actual flight hours per year. Moreover, by comparing the differentiation of the flight segments, it can be seen, that the required MMH decreases with longer flight duration, which means less cycles per flight hour. Accordingly, it can be assumed that the maintenance schedule highly depends on the flight cycles. Consequently, the best use case for a battery based EPS, only focusing on resulting MMH, would be a long range utilization. On the other hand, by reducing the flight range, the maintenance effort significantly increases, which can be derived from Short Flight Segment (SFS) use case. Hereby it is necessary, to keep in mind, that these different flight segments refer to the AVG utilization case.

Another point of investigation was the component consumption and demand. Within the MSG process, 8 tasks have been identified, whereby the considered component shall be removed from the aircraft, whereby 7 parts are intended for an in-shop treatment.

An important measure to evaluated the corresponding maintenance effort is the task code distribution. Therefore, in the next step the several task codes depending on their share of MMH per 1000 FH for overall maintenance haven been evaluated. Thus, maintaining an EPS, mainly focuses on FNCs with 30% of all scheduled tasks. Furthermore, the task distribution shows with 17% a high amount of RST-tasks. In addition, with around 10 to 15% GVI, OPC, DET and DIS are represented in the developed maintenance schedule. This distribution is displayed in Fig. 5.4 and explained later, in Sec. 5.4.

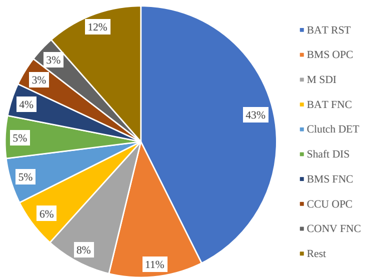
To reduce the operating costs of the EPS, the maintenance effort of those tasks most elaborate need to be reduced. Therefore, it is necessary to identify these tasks. Accordingly, Fig. 5.1a displays the 9 tasks with the highest maintenance effort per calculation in MMH/1000 FH. The remaining 21 tasks are, due to minor effort, summarized as *Rest*. These values are taken over from the AVG usage scenario. With slightly above 40%, the restoration of the battery dominates the maintenance effort of the EPS. This results from the high amount of required MMH and a moderate interval. The second highest position, with 11%, is the OPC of the BMS. This is caused by the short interval, and consequently the more frequent execution. Despite the small amount of required MMH to perform the task, due to frequent execution there results a high effort. With about 8%, the Special Detailed Inspection (SDI) of the electric motor's stator windings, requires the third highest effort of maintenance.

Beyond that, the amount of times each task has to be performed per 1000FH, depending on the utilization scenario, can be calculated as well. Fig. 5.1b displays the ten most affording maintenance tasks in terms of this amount, whereby nearly the same tasks can be found, compared to the effort depending on the MMH. As displayed in the figure, the OPC of the BMS is the most elaborate task with 22%, followed by FNC of the INV (8%) and OPC of BMS sensors and FNC of the battery (7% each). Equal to description above, due to relatively short intervals, their conduction is more often required, so that the corresponding amount increases.

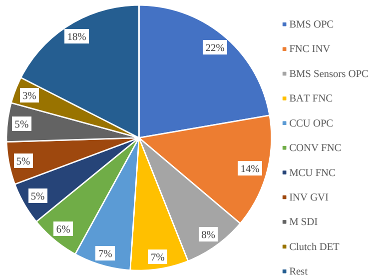
Accordingly, two tasks (RST of BAT and OPC of BMS) cause over 50% of the overall maintenance effort per MMH, so that optimizing them towards improved accessibility or automation has a tremendous potential on the extent of the required downtime and to perform the corresponding maintenance task. Further, only 4 tasks are responsible for over 50% of the maintenance effort, depending on the frequency of their conduction. They need to be optimized towards higher intervals and thus a higher reliability of the corresponding component. Especially for these tasks, another approach is to automate them, as they focus on determination of electrical component's condition.

As mentioned in Sec 4.5.1, regarding the BAT, the differentiation of the RST-interval shall be determined, so that its influence can be estimated. In his work, Wolf [63] investigated different usage scenarios of a battery in regard to its degradation behavior in an aircraft. Herein, due to capacity fading, at a long flight segment, the interval of battery cell replacement significantly reduces to about 280 FC. Entering this value into the scheduled maintenance calculation delivers a tremendous increase of maintenance as depicted in Fig. 5.2. The values displayed in the figure are the absolute changes of required MMH per 1000 FH. In regard to the percentage increase, for the utilization scenarios it would mean about 550%, for the Short Flight Segment (SFS) even about 700%. The share of RST-tasks increases from 10.42 to 140.86 MMH per 1000 FH, which equals an increase from 45 to 92%.

Due to the importance of this task in terms of maintenance effort, and the uncertainty regarding the necessary interval, the RST-task is decisive for economical operation of a battery based propulsion system.



(a) Task effort distribution in regard to required MMH per 1000FH of EPS



(b) Task effort distribution in regard to required amount of tasks per 1000FH of EPS

Figure 5.1 Task effort comparison of EPS

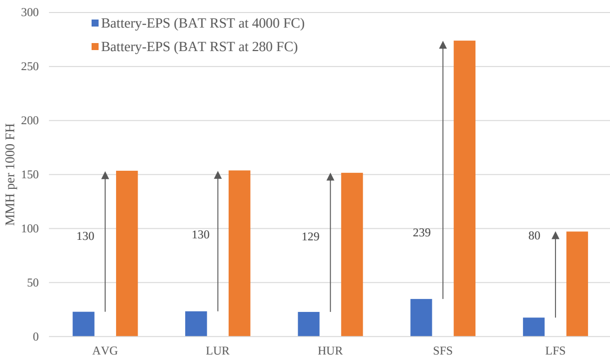


Figure 5.2 Change in maintenance effort due to interval reduction of BAT RST-task

5.3 Kerosene based propulsion system maintenance evaluation

As described in Sec. 3.4, the legacy system is subjected to several assumptions. Accordingly, regarding the task selection, only those tasks concerned by these assumptions shall be used. The last column within Fig. 2.6 allocates the corresponding task within the MPD to the component it is applicable to. This concerns especially the APU and the engines.

As already stated in Sec. 2.3.1, the ATA-Chapters affected by the changes, necessary for the battery driven propulsion system are ATA 26 (Fire Extinguishing), 28 (Fuel), 49 (APU) and all chapters regarding the engines (ATA-Chapter 70-80). Within ATA-Chapter 26, 15 tasks have been selected, which will be replaced or obsolete with the new system design. Regarding the ATA-Chapter 28, which contains all tasks dealing with the fuel system, 53 tasks have been selected. Also 9 tasks of the ATA-Chapter 49, addressing the APU have been chosen. Within the chapters from 70 to 80, not all of them contain tasks, as they concern especially the engine-intern components and systems. Accordingly, these tasks are listed in the engine maintenance manual. Those tasks, still referring to the aircraft, are listed in ATA-Chapter 72 (Engine), which contains 9 tasks, Chapter 73 (engine fuel and control) containing 2 tasks, chapter 78 (Exhaust) with 5 tasks, chapter 79 (Oil) with 4 tasks and chapter 80 (Starting) containing 3 tasks. Summarizing, this leads to 100 tasks, relevant for the selected and most common [43] aircraft-engine-APU-combination of the legacy system.

For a better comparability, these chapters are allocated in accordance with the three subsystems of the EPS. Tab. 5.4 displays this allocation.

Table 5.4 Allocation of ATA-Chapters to EPS-Subsystems

Subsystems	ESD	EDS	TMS
Allocated ATA-Chapters	28, 73	49, 72, 78, 80	26, 79
Amount of tasks	55	26	19
Corresponding total MMH	91.17	150.9	12.66
Share of total MMH	35.8	59.2	5.0

During task selection, those tasks to be expected on both, the EPS and the legacy system, are neglected. An example would be the inspection of the engine mounting, because both engines somehow need to be installed on the aircraft's structure.

Furthermore, Tab. 5.4 provides an overview of the total MMH per subsystem and its percentage share. The total amount results from the summation of required MMH per task and component, given in the corresponding ATA-Chapter. From this table, it can be seen, that the drive train has, with more than 50%, the major share of necessary maintenance, while energy storage and distribution requires only but about a third. Unless more than half of all tasks are allocated to the ESD-subsystem, the corresponding amount of MMH is only but a third. On the other hand, there are only 26 tasks allocated to the EDS-subsystem, which require nearly two thirds of the total amount of the MMH. Accordingly, it can be derived, that tasks regarding the EDS are more complex, than for the ESD.

Table 5.5 Utilization Scenarios of legacy system

	AVG	LUR	HUR	SFS	LFS
MMH /1000 FH	36.31	41.36	34.10	49.89	35.71

Conduction of the summary of maintenance tasks and calculation according the mentioned utilization scenarios delivers Tab. 5.5. Herein, the total amount of required MMH per 1000 FH is displayed for each scenario. Consequently, it can be seen that there is no big difference between the average and high utilization, but for low utilization. Another aspect noticeable, is the difference between short and long flight segments, after which a significant increase of required maintenance results from a low FH-to-FC-ratio. According to these values, the most favorable scenario is a high utilization combined with long flight length, whereas a low utilization on a short flight segment is the worst case in terms of maintenance.

Another essential aspect in maintenance is the demand for necessary spare parts, of which the task selection of the legacy system addresses 17. Spare parts in this context means items, that shall be replaced on wing and than either discarded or send for in-shop maintenance. 10 of these 17 items are determined for an in-shop restoration.

In regard to task code distribution, the OPC has the highest amount with about 40% followed by DET, GVI, DIS and FNC with about 10 to 15% each.

5.4 Comparison of maintenance implications

After designing the battery based EPS and deriving its associated maintenance implications, this section aims on a quantitative examination of these implications towards execution and compare them to the legacy system. Thereby, it shall identify the differences of both maintenance schedules, their task distribution as well as tendencies depending on usage scenarios. Further, the implications resulting from in-shop maintenance task shall be discussed.

As of this work, to maintain the airworthy condition of the kerosene based system, 100 maintenance tasks are necessary. The amount for the EPS significantly reduces to 30 tasks. Hereby, tasks to be performed on several components are counted once.

Scheduled maintenance effort

Within the first step, the EPS and the kerosene-based propulsion system are compared in regard to the maintenance effort they are subjected to. Herein, focus is laid on the change of task quantity and MMH per sub system and additionally, change of MMH per 1000 FH depending on utilization scenarios, previously discussed in Sec. 5.1.

Generally, the EPS is intended to replace the conventional system, including all fuel based systems as well as the APU. Three subsystems, as explained in Sec. 2.4, will provide all necessary functions.

As described in Sec. 5.3 and displayed in Tab. 5.4, the selected maintenance tasks of the legacy system can be allocated to these three subsystems, the EPS is divided into. Comparing these values to the associated tasks of the EPS, displayed in Tab. 5.2, this leads to the changes listed in Tab. 5.6.

Table 5.6 Maintenance effort change per subsystem

Subsystems	ESD	EDS	TMS
Change of task amount	- 46	-17	-7
Change in Share of task amount (%)	-25,00	+4,00	+21,00
Change of total MMH	- 12,69	-77,46	-2,02
Change in Share of MMH (%)	+12,49	-14,06	+1,58

According the first column, the amount of tasks regarding the ESD significantly reduces by nearly 50 tasks, so that the resulting share on overall maintenance reduces by 25%. Despite the significant reduction of tasks, the maintenance effort only reduces by about 13 MMH. Compared to the legacy system's share of ESD related maintenance effort, within the EPS its share increases by about 12,5%. Consequently, the ESD is becoming more important in terms of maintenance, which can be attributed to the relevance of the battery. The second column represents the changes of the EDS, after which the task amount also reduces, but only by 17 tasks. In the context of the complete EPS, the share of EDS related tasks slightly increases. Despite that, there is a significant reduction of corresponding maintenance effort by about 77 MMH, so that its share compared to the legacy system decreases by 14%. Nevertheless, the quantity of tasks regarding the TMS decreases, its percentage share on the overall maintenance schedule increases by about 21%. From this it can be derived, that the TMS has an increasing relevance in terms of maintaining the EPS. The reduction of tasks, consequently leads to a reduced maintenance effort of about 2 MMH, but in terms of comparison to the legacy systems, the effort necessary to maintain TMS related components increases, so that the share of this effort on the overall maintenance increases by about 2%. Thus, it can be concluded, that by replacing the legacy system with an EPS, the amount of necessary tasks to keep the system in an airworthy condition reduces significantly, which in consequence means a reduction of MMH.

Another approach to evaluate the changes of the upcoming maintenance effort, due to a different propulsion system is the comparison regarding the utilization scenarios, discussed in Sec. 5.1. Therefore, the calculated MMH per 1000FH according to each scenario are displayed in Fig. 5.3 for both propulsion systems. Out of this, it can be observed that, for each scenario the sum of required MMH is decreasing to about 20 MMH per 1000FH. As outlined in Sec. 5.2, the upcoming maintenance effort is nearly equal for all utilization cases, so that the extent of reduction depends only on the effort of the legacy system. Within the figure theses changes are displayed as arrows and the corresponding absolute change of MMH between the blue bars of the legacy system and the orange bars of the EPS. Thus, for the LUR the highest reduction can be expected with about 43%, while for the HUR a decrease of only 33% can be assumed. The AVG utilization scenario provides a reduction of about 37%. Furthermore, the figure shows a reduction in both cases of different flight duration, whereby the maintenance effort reduction of the LFS (about 51%) is higher than regarding the SFS (about 30%). From the percentage change it can be concluded, that the EPS should preferably be operated with a Low Utilization Rate (LUR). Beyond that, the examination shows, that increasing the flight length additionally benefits the required maintenance effort.

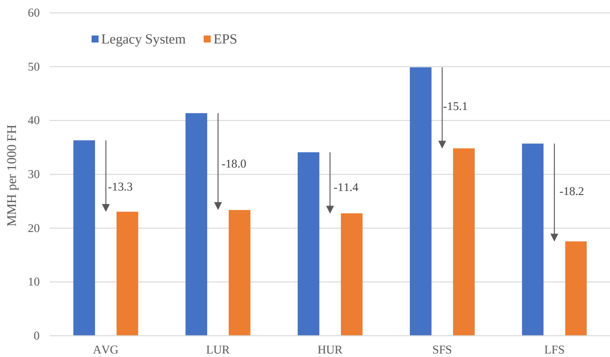


Figure 5.3 Change of maintenance efforts per utilization scenario

Task distribution

The second step, investigates the changes in share of task code distribution within the maintenance schedules. Furthermore, the connection between utilization scenario and task code distribution shall be examined, so that an estimation regarding possible maintenance implications can be discussed.

Firstly, the amount of each task code is derived from the maintenance schedule of the EPS and the legacy system, so that they can be compared. The percentage share of each task regarding the overall maintenance effort of the legacy system (blue bars) is displayed next to its counterpart of the EPS (orange bars). The relative percentage change is depicted in between by directed arrows and the associated values. These results are displayed in Fig. 5.4.

As already mentioned in Sec. 5.3, the dominant task code of the legacy system is the OPC, which share within the EPS decreases by nearly 70%. As well DET- and DIS-task, which belong to the major task codes of the legacy system, decrease by about 60 and 20%. Moreover, the VCK-task, which has only a share of less than 5% in the legacy's maintenance effort, is completely excluded in the EPSs maintenance requirements. This seems reasonable, as within electronic and electric components faults are barely detectable by a simple visual check. In contrast to this, the amount of FNCs increases by 200% for the EPS, which can be attributed to the need of quantitative values to determine the appropriate working. Furthermore, there is a significant increase of RST-tasks to over 20% of system's overall maintenance. A major driver of this is the already discussed battery restoration. Beyond that, various components of the cooling circuit require a restoration on a regular basis. This also appears to be reasonable, due

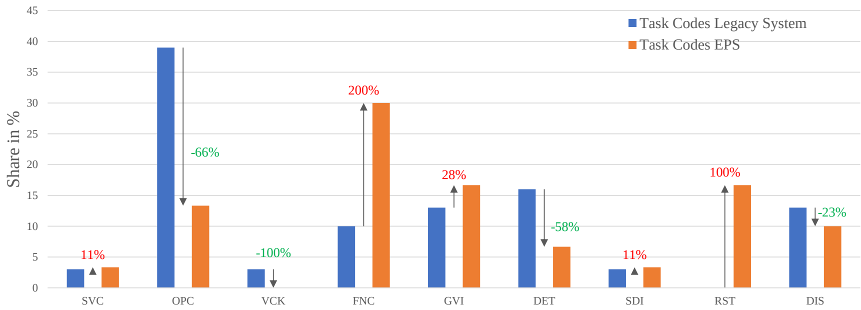
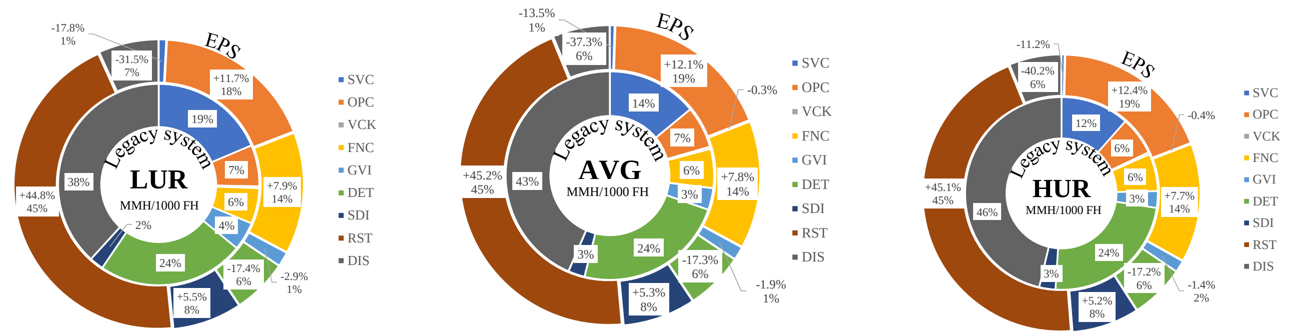


Figure 5.4 Change in share of task codes

to their importance in terms of safety but in advance their likelihood to degrade (as described exemplary in Sec. 2.4.2). Despite, stated that visual inspections do not serve to maintain the EPS, the share of GVIs increases by about 28%. This can be attributed to the increased share of the TMS and its components, at which degradation is detectable due to their visual condition. A very slight increase is depicted for SVC and SDI tasks, which are both represented by only one task in the developed maintenance plan. Accordingly, their increase can be justified by the reduction of the overall task amount. In conclusion, this task distribution shows a reduction in complex tasks, such as DET and DIS-tasks, but as well an increasing complexity for components intended for in-shop maintenance (RST). Further, a quick replacement by a spare part during a short downtime interval, to ensure continuing operation entails logistical effort. Additionally, an increase of time consuming tasks like FNC and GVI, can be derived from the distribution, which depends on the integration and consequently the accessibility of the components to determine the actual time effort.

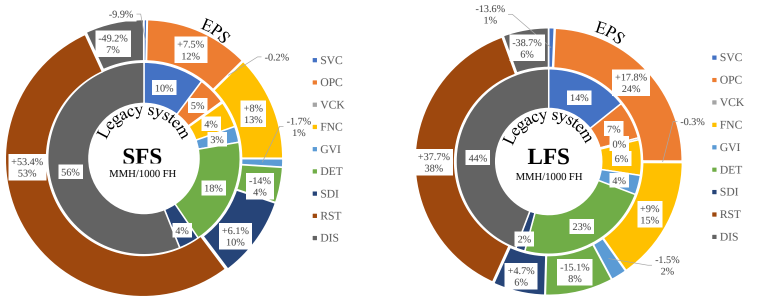


(a) Maintenance task distribution - LUR scenario

(b) Maintenance task distribution - AVG scenario

(c) Maintenance task distribution - HUR scenario

Figure 5.5 Maintenance task distribution according utilization scenarios



(a) Maintenance task distribution - SFS scenario

(b) Maintenance task distribution - LFS scenario

Figure 5.6 Maintenance task distribution according flight segments

Fig. 5.5 displays the results of the comparison of the different utilization scenarios and their task distribution according their demand of MMH per 1000FH. Each scenario is addressed by its three-letter code in the middle of the circle. The inner circle represents the task distribution of the legacy system, while the outer circle shows the distribution of the EPS. For a better comparability the different task codes are allocated to a certain color code and each task code is linked to a certain value that addresses the associated share of the overall MMH. Additionally, the outer circle is supplemented by the percentage change of each task code, compared to the legacy system's proportion. Furthermore, the corresponding task code distribution, depending on the flight duration is displayed in Fig. 5.6. The structure of the figure corresponds to that of the utilization scenarios.

As already described in Sec. 5.2 and above, there is only a slight difference between the different utilization scenarios of the EPS in regard to the corresponding MMH demand (see Fig. 5.3). Equally, within this part of the analysis, it can be seen, that the share of MMH per 1000FH for each task code only differs by a few percent with variation of the utilization scenario. Accordingly, the change in regard to the conversion from the legacy system to the EPS shall be explained exemplary on the AVG scenario.

As displayed in Fig. 5.5b, the share of the Servicing (SVC) task for the legacy system is 14%, which reduced to 1% (-13,5%) with conversion to the EPS. At a reduced utilization (LUR), the corresponding share of SVC is slightly higher (19%), so that the reduction to 1% increases. By increasing the utilization (HUR), the share of the SVC-task for the legacy system decreases to 12% and consequently reduces to nearly zero with conversion to an EPS. This pattern continues for the remaining task codes and the different utilization scenarios.

Following the explanation, from the figures 5.5a to 5.5c it can be derived that, the demand for MMH, to perform servicing significantly decreases, equally regarding DET and DIS. In contrast, the demand for MMH to conduct a restoration, a Functional Check (FNC) or a Special Detailed Inspection (SDI) increases. The corresponding percentage changes are nearly equal for all three utilization scenarios.

In conclusion, it can be drawn from this, that there is an increasing demand for specialized tools and qualified staff to address the complexity arising by i.e. SDI. Furthermore, the significant increase of RST-tasks has to be taken into account for the design and integration into the aircraft. Improving the accessibility of the corresponding components, can lead to a reduction of necessary MMH.

Focusing on the figures 5.6a and 5.6b, the same tendencies can be observed, only a little more distinct. What is particularly noticeable, is the significant increase of RST-tasks within the Short

Flight Segment (SFS) with over 50%. Therefore, it can be determined that with an increase of flight cycles, the demand for downtime and spare parts significantly arises. In contrast, the share of DIS-tasks significantly decreases, so that finally there is a difference of only 4% of corresponding MMH that are additionally required for part replacement. The change of the remaining tasks is comparable to the changes within the utilization scenarios.

Regarding an increase of the flight duration, the corresponding results lead to a higher demand of OPC and FNC-tasks. Consequently, this leads to an improved accessibility or automation of the tasks to optimize the upcoming maintenance effort. The change of the remaining task codes is comparable to those of the different utilization scenarios.

An essential observation of this analysis is that the highest reduction of corresponding maintenance effort can be expected with low utilization at a long flight segment.

In-shop maintenance

In addition, within this work's comparative analysis, the amount of spare parts included in the maintenance schedule shall be discussed. Further, the share of parts requiring in-shop maintenance shall be determined. All kerosene based systems considered in this work, deliver a need for 17 spare parts of which 10 additionally require a subsequent in-shop maintenance treatment. The EPS on the other hand, only includes 8 maintenance tasks, that require a spare part, which is an decrease of more than 50%. Even though the amount of associated in-shop maintenance requiring parts decreases as well to 7, its share of the spare parts is higher by about 30%. As mentioned above, the replacement of components, whether for discard or for restoration entails an additional logistical effort for spare parts, so that a reduction of more than 50% highly benefits the overall maintenance effort.

6 Conclusions and Outlook

After various aspects of changes towards scheduled maintenance for an Electric Propulsion System (EPS) have been discussed and then compared with the legacy, kerosene-based aircraft, this chapter is intended to summarize the central observations of this study and assess them in context of accuracy regarding the results and the process of their development. Furthermore, an outlook shall be given, what these results can be used for and how their accuracy may be improved.

Summary and Conclusion

To address the scheduled maintenance of a battery-based propulsion system, first of all, the system design has been evaluated towards the associated structure, its corresponding components with their associated functions and tasks these components are intended to provide. Additionally, failure mechanisms and their possible avoidance or reduction had been discussed. Subsequently, by conducting the MSG-3 analysis, failures their criticality and appropriate maintenance approaches had been identified. They have been supplemented by intervals, based on their degradation behavior and comparable tasks, as well as potentially required MMH. Based on this maintenance plan an upcoming maintenance effort estimation and a comparative analysis between the conventional, kerosene-based system and the EPS has been conducted for different utilization scenarios.

Summarizing the results of this work, the questions posed at the beginning shall be answered below. Regarding the *first question*, what maintenance implications can be expected for a battery-based propulsion system, the MSG-3 logic determined 30 maintenance tasks to maintain the airworthy condition of the initial system design. Thereof, 9 tasks each address the ESD and the EDS and another 12 tasks are necessary for the TMS. Thus, it can be seen, that the maintenance effort according amount of tasks is nearly equal distributed to the three subsystems. The most affording tasks in regard to demand of MMH, concern the battery RST and the OPC of BMS. In terms of required frequency of task execution, most affording are the OPC of BMS and the FNC of the inverter.

The *second research question* deals with the changes in maintenance effort resulting from the conversion to an EPS and shall identify a best case utilization scenario. Due to extensive replacement of the kerosene-based system by the electric system there is a high reduction of necessary maintenance tasks. Accordingly, the corresponding maintenance effort decreases as well. Within this work, it has been determined that, depending on this conversion the amount of tasks reduces by 70%. Most significantly reduction can be allocated to the ESD in regard of task amount, whereas the ESD referred MMH decreases by about 77 MMH. Depending on the circumstance, that the maintenance effort of the EPS is not likely to differ with different utilization, the highest decrease compared to the legacy system, is to be expected at LUR. Furthermore, a significant decrease in necessary maintenance effort can be recognized with an increased flight duration (LFS). Consequently, a maintenance optimized use case of a Battery-EPS would be designed for long range flights, which will collide with technical feasibility. By increasing the flight range, the BAT dimension has to be increased as well, so that the mass of it, to provide enough energy capacity for the flight, would exceed the aircraft's permitted total weight by several magnitudes due to current battery storage technology.

Finally, the *third research question* focuses on the structure and distribution of the maintenance effort and if there are dominant parameters driving the effort. As described in detail within Sec. 5.4, there is a significant increase in FNC and RST tasks, while the amount of OPCs and DETs significantly decreases. Furthermore, there is an increase in GVIs noticeable, which can be allocated to the TMS. The corresponding task code distribution is widely constant for the different utilization scenarios. Equally, the associated amount of MMH changes only in very small ranges. As the battery can be expected as one of the major drivers of maintenance demand, a comparative analysis regarding different intervals of the battery restoration has been conducted. Thereby, it has been shown that decreasing the interval to a worst case scenario, the maintenance effort would increase up to 550% and an associated demand of 141 MMH per 1000 FH.

Additional outcome of this work's investigation are possible approaches for the system design and integration. Those design requirements that can be derived from the analyses are:

- improved accessibility for those components requiring an RST, i.e. battery restoration
- automation approach for those tasks that have to be performed more often, i.e. OPC of BMS
- implement monitoring methods for tasks with higher complexity; DET of clutch

In advance, this work identified the need for spare parts to replace those components removed for restoration but as well for those discarded. The maintenance tasks for parts, requiring in-shop maintenance, address only the removal of the components. The actual maintenance effort, due to subsequent logistics and restoring within the facility is not considered. Accordingly, a significant share of the total costs and corresponding effort results from this off-wing maintenance. Thus, it can be expected that the total maintenance effort for this type of task may increase.

This investigation is based on many assumptions, as described in Sec. 3.4, and an initial system design approach discussed in Sec. 2.4.1. Accordingly, the result is just a rough tendency towards an actual system behavior. Many components, used in this system design are not scaled up or designed for the requirements in aviation, so that in an aviation environment additional failure mechanisms can occur. Further, unknown failure mechanisms remain undetected within the predictive maintenance approach which, also reduces the accuracy and demonstrates the initial character of this work. Consequently, similar to changes in maintenance intervals, the individual tasks may be subjected to change with additional operating experience and are not necessarily constant.

Besides these insights on the expected changes in scheduled maintenance, it shall be mentioned, that this analysis focuses solely on the labor aspect for the task execution. Thus, neither any necessary preparatory work, e.g. to gain access, nor necessary repair material has been taken into account. Consequently, for a complete investigation of the overall maintenance implications, these proportions may be addressed in future work. In advance, with further investigations towards system architecture, capability of several parts and advanced monitoring techniques, the herein developed maintenance schedule delivers a first approach on understanding the necessities of the system design as well as the maintenance requirements for the selected components and corresponding units.

Outlook

As this work only delivers a first approach on system design and its evaluation regarding maintenance, within the next iteration of the SSA a maintenance optimized design may be considered. There are several methods to improve the system design for an deeper insight regarding the upcoming maintenance effort.

Firstly, based on improved component design for reduced degradation, a replacement of components, that have been identified with high amount of time consuming or costly maintenance tasks, for example a mechanically geared clutch could be replaced by a magnetic geared one

[13]. Furthermore, enabling automation of maintenance tasks, improving accessibility to simplify execution or incorporation of monitoring are additional methods to reduce the necessary maintenance effort, in regard to component design.

The second method focuses on optimization of the system layout in regard to economical efficiency. This may include the redesign of the Electric Drive System (EDS), by separating the two electrical motors per shaft and integrate four engines instead of two, so that the safety requirements still are satisfied.

To generate a robust and resilient system, the third method considers extraordinary operating scenarios, such as charging the battery within a harsh environment, for example at low temperatures, which can lead to severe battery damage. Therefore, cooling circuit has to be design for active heating [15].

Furthermore, a major topic of maintenance in future is an increase of monitoring to predict the necessity of maintenance. As mentioned above, by integration of appropriate observation of the component's condition and usage of algorithm tools for maintenance demand calculation [50] or parametric failure mechanism models to estimate the lifetime distribution [2], a reduction of the effort can be achieved.

However, by replacing maintenance tasks with measurement and investigation units a redesign of the regarding component is necessary. Accordingly, the costs for a redesign and the costs connected with integration in the existing system need to be lower than the costs arising with periodically conduction of the concerned maintenance task, which can also be part of future investigations.

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Appendix A

Table A1 Determination of system failures (FMEA)

Ref	Function	Ref	Failure Description	Ref	Failure Effect	Ref	Failure Cause
1	To measure BAT status	1A	fails to measure BAT status	1A1	loss of indications of electrical system condition	1A11	defect BMS sensors
						1A12	defect of BMS
		1B	erroneous measured BAT status	1B11	ECAM indications not in accordance with electrical system condition	1B11	defect BMS sensors
						1B12	defect of BMS
2	To provide BAT status	2A	fails to provide BAT status	2A1	electrical parameters not available on ECAM System	2A11	defect of BMS
		2B	incorrect BAT status provided	2B1	ECAM indications not in accordance with electrical systems condition	2B11	Defect of BMS
3	To control amount of provided electrical energy	3A	Loss of control of electrical energy flow	3A1	possible loss of energy supply or over voltage, ECAM warning	3A11	defect of BMS
		3B	incorrect electrical energy flow control	3B1	possible loss of energy supply or over voltage, ECAM warning	3B11	defect of BMS
4	To provide electrical energy	4A	fails to provide electrical energy	4A1	loss of energy supply/ thrust, ECAM warning	4A11	defect of BMS
						4A12	over discharge

continuing on next page

Table A1 FMEA (cont.)

Ref	Function	Ref	Failure Description	Ref	Failure Effect	Ref	Failure Cause
						4A13	short circuit
						4A14	circuits disconnected
		4B	incorrect electrical energy provided	4B1	possible loss of energy supply or over voltage, ECAM warning	4B11	defect of BMS
						4B12	high internal cell temperature
						4B13	chemical side reactions
5	To convert electrical energy	5A	fails to convert electrical energy flow	5A1	energy niveau not sufficient causing lack of thrust	5A11	defect of CONV
						5A12	CB defect (fail open)
6	To disconnect energy source	6A	erroneous ESD disconnection of energy source	6A1	loss of energy supply/ possible damage	6A11	CB defect (fail open)
		6B	fails to disconnect energy source (ESD)	6B1	no emergency turn off possible during dangerous event, ECAM warning	6B11	CB defect (fail close)
7	To expel surplus heat (ESD)	7A	fails to expel surplus heat	7A1	overheating, decrease of performance and capacity, ECAM indication	7A11	BAT cooling clogged
						7A12	CONV cooling defect
						7A13	coolant leak

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Table A1 FMEA (cont.)

Ref	Function	Ref	Failure Description	Ref	Failure Effect	Ref	Failure Cause
						7A14	defect temperature sensor
		7B	incorrect rejection of surplus heat	7B1	over cooling, decrease of performance and capacity, ECAM indication	7B11	BAT cooling damaged
						7B12	CONV cooling damaged
						7B13	defect temperature sensor
8	To measure performance of conversion and distribution of electrical energy	8A	fails to measure conversion performance	8A1	loss of indication of electrical system condition	8A11	defect sensors
9	To measure BAT temperature	9A	fails to measure BAT temperature	9A1	loss of indication of BAT temperature	9A11	defect temperature sensor
10	To store electrical energy	10A	fails to store electrical energy	10A1	loss of energy supply, ECAM waning	10A11	damaged BAT pack
						10A12	over discharge
						10A13	circuit disconnected

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Table A1 FMEA (cont.)

Ref	Function	Ref	Failure Description	Ref	Failure Effect	Ref	Failure Cause
11	To invert electrical energy	11A	fails to invert electrical energy	11A1	no provision of 3 phase current to M, ECAM warning	11A11	defect of INV
						11A12	CB defect (fail open)
12	To supply electrical energy to EDS	12A	fails to supply electrical energy	12A1	loss of energy supply/ thrust, ECAM warning	12A11	power BUS damaged
13	To transform electrical energy to shaft power	13A	fails to transform electrical energy	13A1	loss of thrust, ECAM warning	13A11	M bearing failure
						13A12	M stator winding insulation failure
						13A13	defect M control
						13A14	clutch failure
						13A15	damaged shaft
14	To disconnect energy source from EDS	14A	erroneous disconnection of energy source	14A1	loss of energy supply, possible damage	14A11	CBdefect (fail open)
		14B	fails to disconnect energy source	14B1	no emergency turn off possible during dangerous event, ECAM warning	14B11	CB defect(fail close)

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Table A1 FMEA (cont.)

Ref	Function	Ref	Failure Description	Ref	Failure Effect	Ref	Failure Cause
15	To expel surplus heat (EDS)	15A	fails to expel surplus heat	15A1	overheating, damage on components, ECAM indication	15A11	INV cooling failure
						15A12	MCF defect
						15A13	coolant leak
						15A14	defect temperature sensor
		15B	incorrect rejection of surplus heat	15B1	over cooling, decrease of performance, ECAM indication	15B11	INV cooling damaged
						15B12	MCF stuck
						15B13	defect temperature sensor
16	To provide shaft power	16A	fails to provide shaft power	16A1	loss of thrust, ECAM warning	16A11	damaged shaft
17	To measure EDS temperature	17A	fails to measure EDS temperature	17A1	loss of temperature indication	17A11	defect temperature indication
		17B	incorrect EDS temperature measurement	17B1	ECAM indications not in accordance with electrical system condition	17B11	damaged temperature sensor

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Table A1 FMEA (cont.)

Ref	Function	Ref	Failure Description	Ref	Failure Effect	Ref	Failure Cause
18	To measure inverted (alternate) current	18A	fails to measure alternate current	18A1	loss of indication of electrical system performance	18A11	defect current sensor
19	To provide/ adapt coolant mass flow	19A	fails to provide coolant flow	19A1	overheating/ damage, ECAM warning	19A11	defect CP
						19A12	defect PTU
						19A13	leakage
		19B	incorrect coolant flow provided	19B1	over cooling/-heating, damage/ performance decrease	19B11	clogged circuit
						19B12	defect PTU
						19B13	CP failure
20	To adapt coolant temperature	20A	fails to adapt coolant temperature	20A1	overheating/ damage	20A11	cracks/leakage in HEX
						20A12	HEX blockage
						20A13	HEX fouling
						20A14	defect temperature sensor
21	To provide coolant	21A	fails to provide coolant	21A1	possible failure of TMS, overheating/ damage	21A11	RES damaged/ leaking

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Table A1 FMEA (cont.)

Ref	Function	Ref	Failure Description	Ref	Failure Effect	Ref	Failure Cause
						21A12	defect SOV (fail closed)
						21A13	defect SOV (fail open)
						12A14	coolant fill level low
22	To keep coolant free of contamination	22A	fails to keep coolant free of contamination	22A1	decreased coolant flow and heat rejection, increased degradation	22A11	clogged/ damaged F
23	To measure coolant mass flow	23A	fails to measure coolant mass flow	23A1	no effect but a single failure	23A11	defect mass flow sensor
24	To measure coolant temperature	24A	fails to measure coolant temperature	24A1	loss of indication of TMS temperature	24A11	defect temperature sensor
25	To control cooling circuit	25A	fails to control cooling circuit	25A1	possible loss of coolant provision (overheating/ damage) ECAM warning	25A11	defect CCU
26	To seal coolant tubing connections	26A	fails to seal coolant tubing	26A1	coolant leakage	26A11	degraded/ damaged sealing
27	To measure coolant fill level	27A	fails to measure coolant fill level	27A1	ECAM indication not in accordance with RES condition	27A11	defect fill level sensor

Table A2 Results of classification of failure criticality

Ref	Failure case	Question 1		Question 2		Question 3		Question 4		FEC
		Ans	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	
1A	fails to measure BAT status	YES	error message to ECAM	NO	redundancy available	X		NO	supplied by redundancy	7
1B	erroneous measured BAT status	NO	measured values displayed in ECAM without notice of correctness	X		YES	multiple erroneous BAT status causing reduced range	X		8
2A	fails to provide BAT status	YES	signal loss to ECAM	NO	redundancy available	X		NO	supplied by redundancy	7
2B	incorrect BAT status provided	NO	no comparability between correct and error value	X		YES	multiple erroneous BAT status causing reduced range	X		8
3A	loss of control of electrical energy flow	YES	error message to ECAM display	NO	redundancy available	X		YES	immediate crew action necessary	6
3B	incorrect elec. energy flow control	YES	error message to ECAM display	NO	redundancy available	X		YES	operation restriction, correction prior to next flight	6

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Table A2 Classification (cont.)

Ref	Failure case	Question 1		Question 2		Question 3		Question 4		FEC
		Ans	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	
4A	fails to provide elec. energy	YES	error message to ECAM display	NO	redundancy available	X		YES	immediate crew action necessary	6
4B	incorrect electrical energy provided	YES	error message to ECAM display	NO	redundancy available	X		YES	operation restriction, correction prior to next flight	6
5A	fails to convert electrical energy flow	YES	error message to ECAM display	NO	redundancy available	X		YES	automatically switched, correction within appropriate time	6
6A	erroneous ESD disconnection of energy source	YES	failure indication obvious	NO	redundancy available	X		YES	immediate crew action, correction prior to next flight	6
6B	fails to disconnect energy source	YES	failure indication obvious	NO	redundancy available	X		YES	immediate crew action, correction prior to next flight	6

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Table A2 Classification (cont.)

Ref	**Failure case**	**Question 1**		**Question 2**		**Question 3**		**Question 4**		**FEC**
		Ans	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	
7A	fails to expel surplus heat (ESD)	YES	temperature increase displayed on ECAM	NO	redundancy available	X		Yes	immediate crew action, operation restrictions, correction, correction	6
7B	incorrect rejection of surplus heat	YES	temperature increase displayed on ECAM	NO	redundancy available	X		YES	immediate crew action, operation restrictions, correction	6
8A	fails to measure conversion performance	YES	error message to ECAM display	NO	single event failure	X		NO	loss of information, safe flight continues	7
9A	fails to measure BAT temperature	YES	indication via BMS sensor	NO	redundancy available	X		NO	loss of information, safe flight continues	7
10A	fails to store electrical energy	YES	displayed on ECAM	YES	reduced usable range	X		X		5

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Table A2 Classification (cont.)

Ref	Failure case	Question 1		Question 2		Question 3		Question 4		FEC
		Ans	Justification	Ans	Justification	Ans	Justification	Ans	Justification	
11A	fails to invert electrical energy	YES	failure indication on ECAM	NO	redundancy available	X		YES	automatically switched, correction within appropriate time	6
12A	fails to supply electrical energy to EDS	YES	error message to ECAM display	YES	no redundancy, total loss	X		X		5
13A	fails to transform electrical energy to shaft power	YES	ECAM indicates motor failure	NO	redundancy available	X		YES	automatically switched, correction within appropriate time	6
14A	erroneous ESD disconnection of energy source	YES	failure indication obvious	NO	redundancy available	X		YES	immediate crew action, correction prior to next flight	6
14B	fails to disconnect energy source from EDS	YES	failure indication obvious	NO	redundancy available	X		YES	immediate crew action, correction prior to next flight	6

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Table A2 Classification (cont.)

Ref	Failure case	Question 1		Question 2		Question 3		Question 4		FEC
		Ans	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	
15A	fails to expel surplus heat (EDS)	YES	temperature increase displayed on ECAM	NO	redundancy available	X		YES	immediate crew action, operation restrictions, correction necessary	6
15B	incorrect rejection of surplus (EDS)	YES	temperature increase displayed on ECAM	NO	redundancy is available	X		YES	immediate crew action, operation restriction, correction necessary	6
16A	fails to provide shaft power	YES	ECAM indicates loss of rotational speed	YES	loss of engine circuit	X		X		5
17A	fails to measure EDS temperature	YES	temperature increase displayed on ECAM	NO	redundancy available	X		NO	redundant measurement via TMS temperature	7
17B	incorrect EDS temperature measurement	YES	ECAM indication of temperature	NO	redundancy available	X		NO	redundant measurement vie TMS temperature	7

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Table A2 Classification (cont.)

Ref	Failure case	Question 1		Question 2		Question 3		Question 4		FEC
		Ans	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	
18A	fails to measure alternate current	YES	indication via ECAM display	NO	single event failure	X		NO	loss of information, safe flight continues	7
19A	fails to provide coolant flow	YES	ECAM indicates coolant flow deviation	NO	redundancy available	X		YES	automatically switched, correction within appropriate time	6
19B	incorrect coolant flow provided	YES	ECAM indicates temperature increase	NO	redundancy available	X		YES	automatically switched, correction within appropriate time	6
20A	fails to adapt coolant temperature	YES	ECAM indicates temperature increase	NO	redundancy available	X		YES	automatically switched, correction within appropriate time	6

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Table A2 Classification (cont.)

Ref	Failure case	Question 1		Question 2		Question 3		Question 4		FEC
		Ans	Justification	Ans	Justification	Ans	Justification	Ans	Justification	
21A	fails to provide coolant	YES	valve failure indication via ECAM	NO	redundancy available	X		YES	automatically switched, correction within appropriate time	6
22A	fails to keep coolant free of contamination	NO	no Filter monitoring	X		YES	clogged coolant flow and defect temperature sensor	X		8
23A	fails to measure coolant mass-flow	YES	error message via ECAM	NO	single event failure	X		NO	coolant demand determined based on temperature	7
24A	fails to measure TMS temperature	YES	loss of data, ECAM indication	NO	redundancy available	X		NO	multiple redundancies	7
25A	fails to control cooling circuit	YES	ECAM error message indicated	NO	redundancy available	X		YES	automatically switched, correction within appropriate time	6

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Table A2 Classification (cont.)

Ref	Failure case	Question 1		Question 2		Question 3		Question 4		FEC
		Ans	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	**Ans**	**Justification**	
26A	fails to seal coolant tubing	NO	no monitoring/ indication	X		NO	coolant leakage rather low, long term damage by corrosion	X		9
27A	fails to measure coolant level	YES	RES equipped with fill level sensor	NO	single event failure	X		YES	reduced safety, ensure sufficient coolant quantity	6

Table A3 Results of maintenance options investigation

Ref	Comp	Question 1		Question 2		Question 3		Question 4		Question 5	
		Ans	Description	Ans	Description	Ans	Description	Ans	Description	Ans	Description
1A11	BMS sensor	NO	N/A*		X	YES	FNC of BMS sensors via BITE				
1A12	BMS	NO	N/A		X	YES	FNC of BMS via BITE				
1B11	BMS sensor	NO	N/A	NO	N/A	YES	FNC of BMS sensors via BITE				
1B12	BMS	NO	N/A	NO	N/A	YES	FNC of BMS via BITE				
2A11	BMS	NO	N/A		X	YES	FNC of BMS via BITE				
2B11	BMS	NO	N/A	NO	N/A	YES	FNC of BMS via BITE				
3A11	BMS	NO	N/A		X	YES	FNC of BMS via BITE				
3B11	BMS	NO	N/A		X	YES	FNC of BMS via BITE				
4A11	BMS	NO	N/A		X	YES	FNC of BMS via BITE				

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Table A3 Investigation (cont.)

Ref	Comp	Question 1		Question 2		Question 3		Question 4		Question 5	
		Ans	Description	Ans	Description	Ans	Description	Ans	Description	Ans	Description
4A12	BAT	NO	N/A		X	NO	N/A	YES	RST of BAT cells		
4A13		NO	N/A		X	NO	N/A	YES	RST of BAT cells		
4A14	CB	NO	N/A		X	YES	FNC of CB				
4B11	BMS	NO	N/A		X	YES	FNC of BMS via BITE				
4B12	BAT	NO	N/A		X	YES	FNC of BMS sensors via BITE				
4B13	BAT	NO	N/A		X	YES	FNC of BAT current transfer				
5A11	CONV	NO	N/A		X	YES	FNC via BITE				
5A12	CB	NO	N/A		X	YES	FNC of CB via offline monitoring				
6A11	CB	NO	N/A		X	YES	FNC of CB via offline monitoring				

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Table A3 Investigation (cont.)

Ref	Comp	Question 1		Question 2		Question 3		Question 4		Question 5	
		Ans	Description	Ans	Description	Ans	Description	Ans	Description	Ans	Description
6B11	CB	NO	N/A		X	YES	FNC of CB via offline monitoring				
7A11	BAT	NO	N/A		X	YES	DET of BAT cooling				
7A12	CONV	NO	N/A		X	YES	DET of CONV cooling				
7A13	Tubing	NO	N/A		X	YES	Leak Check (LCK) of tubing				
7A14	Temp. sensor	NO	N/A		X	YES	FNC of temp. sensor(s)				
7B11	BAT	NO	N/A		X	YES	DET of BAT cooling				
7B12	CONV	NO	N/A		X	NO	N/A	YES	RST of CONV cooling		
7B13	Temp. sensor	NO	N/A		X	YES	FNC of Temp. sensor				
8A11	Curr. sensor	NO	N/A		X	YES	FNC of Curr. sensor				

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Table A3 Investigation (cont.)

Ref	Comp	Question 1		Question 2		Question 3		Question 4		Question 5	
		Ans	Description	Ans	Description	Ans	Description	Ans	Description	Ans	Description
9A11	BMS sensor	NO	N/A		X	YES	FNC of BMS sensor	—	—	—	—
10A11	BAT	NO	N/A		X	YES	FNC of BAT via BMS BITE	—	—	—	—
10A12	BAT	NO	N/A		X	YES	FNC of BAT via BMS BITE	—	—	—	—
10A13	BAT	NO	N/A		X	YES	FNC of BAT via BMS BITE	—	—	—	—
11A11	INV	NO	N/A		X	YES	FNC via BITE	—	—	—	—
11A12	CB	NO	N/A		X	YES	FNC of CB	—	—	—	—
12A11	Power BUS	NO	N/A		X	YES	FNC of power BUS	—	—	—	—
13A11	M	YES	LUB of M bearing	—	—	—	—	—	—	—	—
13A12	M	NO	N/A		X	YES	SDI of M stator windings	—	—	—	—
13A13	M	NO	N/A		X	YES	FNC of Motor Control Unit (MCU)	—	—	—	—
13A14	Clutch	NO	N/A		X	YES	DET of clutch	—	—	—	—

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Table A3 Investigation (cont.)

Ref	Comp	Question 1		Question 2		Question 3		Question 4		Question 5	
		Ans	**Description**	**Ans**	**Description**	**Ans**	**Description**	**Ans**	**Description**	**Ans**	**Description**
13A15	Shaft	NO	N/A		X	NO	N/A	NO		YES	DIS of shaft
14A11	CB	NO	N/A		X	YES	FNC of CB				
14B11	CB	NO	N/A		X	YES	FNC of CB				
15A11	INV	NO	N/A		X	YES	DET of INV cooling				
15A12	MCF	NO	N/A		X	YES	GVI of MCF				
15A13	Tubing	NO	N/A		X	YES	LCK of tubing				
15A14	Temp. sensor	NO	N/A		X	YES	FNC of Temp. sensor				
15B11	INV	NO	N/A		X	YES	DET of INV cooling				
15B12	MCF	YES	LUB of M bearing								
15B13	Temp. sensor	NO	N/A		X	YES	FNC of Temp. sensor				
16A11	Shaft	NO	N/A		X	YES	DET of shaft				
17A11	Temp. sensor	NO	N/A		X	YES	FNC of Temp. sensor				
17B11	Temp. sensor	NO	N/A		X	YES	FNC of Temp. sensor				

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Table A3 Investigation (cont.)

Ref	Comp	Question 1		Question 2		Question 3		Question 4		Question 5	
		Ans	Description	Ans	Description	Ans	Description	Ans	Description	Ans	Description
18A11	Curr. sensor	NO	N/A		X	YES	FNC of Curr. sensor				
19A11	CP	NO	N/A		X	YES	GVI of CP				
19A12	PTU	NO	N/A		X	YES	FNC of PTU				
19A13	Tubing	NO	N/A		X	YES	LCK of tubing				
19B11	F	NO	N/A		X	NO	N/A	NO	N/A	YES	DIS of F
19B12	Tubing	NO	N/A		X	YES	LCK of tubing				
19B13	CP	NO	N/A		X	YES	GVI of CP				
20A11	HEX	NO	N/A		X	YES	DET of HEX				
20A12	HEX	NO	N/A		X	NO	N/A	YES	RST of HEX		
20A13	HEX	NO	N/A		X	NO	N/A	YES	RST of HEX		
20A14	Temp. sensor	NO	N/A		X	YES	FNC of Temp. sensor				
21A11	RES	NO	N/A		X	YES	LCK of RES				
21A12	SOV	NO	N/A		X	YES	GVI of SOV				
21A13	SOV	NO	N/A		X	YES	GVI of SOV				
21A14	Fill lvl sensor	NO	N/A		X	YES	FNC of fill lvl sensor				

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Table A3 Investigation (cont.)

Ref	Comp	Question 1		Question 2		Question 3		Question 4		Question 5	
		Ans	**Description**	**Ans**	**Description**	**Ans**	**Description**	**Ans**	**Description**	**Ans**	**Description**
22A11	F	NO	N/A		X	NO	N/A	NO		YES	DIS of F
23A11	Flow sensor	NO	N/A		X	YES	FNC of flow sensor				
24A11	Temp. sensor	NO	N/A		X	YES	FNC of Temp. sensor				
25A11	CCU	NO	N/A		X	YES	FNC of CCU via BITE				
26A11	Sealant	NO	N/A	YES	VCK of sealing						
27A11	Fill lvl sensor	NO	N/A		X	YES	FNC of fill lvl sensor				

* Not Applicable (N/A)

Table A4 Failure Rates used to determine task intervals

Component/ Event	Failure Rate λ	Data Source
Cooling Fan	$2{,}00{\cdot}10^{-5}$	[64]
Clutch	$1{,}22{\cdot}10^{-6}$	[62]
DC/DC Converter	$2{,}30{\cdot}10^{-6}$	[1]

Table A5 Maintenance Schedule - EPS

Task No.	Task Description	Task Code	FEC	Interval	MMH (per unit)	Source(s)
1	Perform Fault Diagnosis for Sensors via BITE	OPC	7	1000 FH	0.3	[41]
2	Perform Operational Check via BITE	OPC	7	350 FH	0.3	[41]
3	Remove Battery (BAT) pack for In-Shop Restoration (RST) of Cells and Cooling	RST	6	4000 FC 180 MO	24.0	[42],[47]
4	Perform Functional Check of Battery (BAT) and connectors	FNC	6	200 FC	0.5	[26]
5	Perform Functional Check of converter via BITE	FNC	6	850 FH	0.3	[45],[7]
6	Perform Functional Check of Circuit Breaker (CB) via BITE	FNC	6	18000 FH 140 MO	0.17	[31],[7]
7	Perform General Visual Inspection of Converter Cooling	GVI	6	2000 FH 24MO	0.06	[7]
8	Perform Restoration of Converter cooling	RST	6	12000 FH 109 MO	1.0	[7]
9	Perform Operational Check of inverter	OPC	CMR,6	750 FH 6 MO	0.1	[7]
10	Perform Operational Check of electric load distribution	OPC	5	24000 FH 180 MO	0.1	[7]

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Table A5 Maintenance Schedule (cont.)

Task No.	Task Description	Task Code	FEC	Interval	MMH (per unit)	Source(s)
11	Perform Lubrication of motor bearing	LUB	6	5500FH 15MO	0.1	[7]
12	Perform Functional Check of Motor Control Unit (MCU)	FNC	6	1000FH 12 MO	0.1	[7]
13	Perform SDI on Mstator windings	SDI	6	7800FH 1200FC 36MO	1.0	[45],[7]
14	Detailed inspection of clutch	DET	6	1600 FH	1.0	[45], [54]
15	Discard Engine Shaft	DIS	5	30000 FC	32.0	[8]
16	Perform General Visual Inspection of Inverter Cooling	GVI	6	2000 FH 24MO	0.06	[7]
17	Perform Restoration of inverter cooling	RST	6	12000 FH 108 MO	1.0	[7]
18	Perform General Visual Inspection of MCF	GVI	6	3000 FH 36 MO	0.1	[45],[7]
19	Remove Coolant Pump (CP) for In-Shop Restoration (RST)	RST	6	36 MO	0.42	[34]

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Table A5 Maintenance Schedule (cont.)

Task No.	Task Description	Task Code	FEC	Interval	MMH (per unit)	Source(s)
20	Perform Functional Check (FNC) of PTU	FNC	6	24000 FH 72 MO	0.1	[7]
21	Discard (DIS) Coolant Filter	DIS	6	8500 FH 72 MO	0.15	[43]
22	Perform Detailed Visual Inspection of HEX	DET	CMR,6	3000 FH 36 MO	0.3	[34]
23	Remove HEX for In-Shop high pressure water cleaning	RST	6	12000 FH 108 MO	1.0	[7]
24	Perform General Visual Inspection for leaks	GVI	6	6 MO	0.1	[7]
25	Perform Functional Check (FNC) of Shut-off Valve (SOV)	FNC	5	24000 FH 180MO	0.4	[7]
26	Perform Operational Check (OPC) of CCU via BITE	OPC	6	750 FH 6 MO	0.3	[7]
27	Perform General Visual Inspection of Coolant Seals	GVI	6	6000 FH 72 MO	0.1	[7]
28	Perform Functional Check (FNC) of piping to detect leakage	FNC	6	8000 FH 72 MO	2.0	[7]
29	Discard (DIS) Coolant Seals	DIS	9	12000 FH 48 MO	2.5	[7]

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Table A5 Maintenance Schedule (cont.)

Task No.	Task Description	Task Code	FEC	Interval	MMH (per unit)	Source(s)
30	Perform Functional Check (FNC) of RES Low Level Warning	FNC	6	36000 FH 252 MO	0.3	[7]