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Maintenance assessment of fuel cell systems for regional aircraft

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ABSTRACT

With the EU's Green Deal Climate Act, airlines encounter the challenge of reducing their impact by operating in a climate-neutral manner. Fuel cell technologies, including Low Temperature Proton Exchange Membrane Fuel Cells and Solid Oxide Fuel Cells, are suitable candidates for this endeavour. However, there is uncertainty surrounding the maintenance scope and corresponding costs of novel systems such as fuel cells, that is leading to reluctance within the industry to implement these technologies. This study addresses this research gap by assessing the fuel cell systems using the Reliability Centered Maintenance approach and the MSG-3 framework. For this purpose, task intervals are determined based on statistical reliability values from literature and data from legacy aircraft. As a final step, the scheduled maintenance scope is derived, accounting for the required maintenance tasks, corresponding intervals, and parts of the labor and material scope. The aim of this comparative study is to identify the fuel cell system best suited for regional aircraft operations based on its maintenance characteristics. This enables us to provide designers and researchers with valuable insights to support the development of technically feasible fuel cell systems for the aviation industry.

1. Introduction

The aviation industry is currently being shaped by many efforts to reduce its climate impact. For example, the EU's Green Deal Climate Act aims to achieve emission-free aviation by 2050 [1]. Air traffic emissions make a substantial contribution to global anthropogenic climate change [2] and also impact local air quality, particularly in areas surrounding airports [3]. Since conventional propulsion systems powered by fossil fuels can only exploit their potential to a limited extent in this regard, new technologies must be considered in order to achieve ambitious climate goals. In this context, hydrogen as an energy source offers great potential for reducing carbon emissions [4]. Fuel cells are particularly promising, given that they do not produce any direct emissions during operation, with the exception of water vapor [5]. Due to their high efficiencies, the Low Temperature Polymer Electrolyte Membrane Fuel Cell (LT-PEMFC) and the Solid Oxide Fuel Cell (SOFC) offer great potential for applications in the aviation sector [6,7]. As a result, these systems are a central focus of efforts in electrified aircraft and for reaching climate targets [6].

In addition to carbon dioxide emissions, operating costs are also an important factor to consider when introducing new technologies, with maintenance playing a key role. According to Meissner et al. [8], maintenance can account for up to 20 % of an aircraft's direct operating costs, whereas novel systems such as fuel cells are subject to considerable uncertainty in this regard [7]. In general, maintenance of fuel cells intended for aviation applications is currently only considered at a rudimentary level, as limited expertise and data are available. Accordingly, there exist only a few estimates on this subject in the literature. Studies dealing with fuel cell maintenance in the context of aviation can be found in Hoff et al. [9] and Gerbec et al. [10]. In this regard, economic and environmental impact studies are conducted by Wehrspohn et al. [11] and Barke et al. [12]. Mylonopoulos et al. [13] and Aarskog et al. [14] consider maintenance of fuel cells in their research on the operation of cargo vessels and ferries. Bubna et al. [15] and Eudy at al. [16,17] have gained experience in the operation and maintenance of fuel cells in public transport, such as buses. Furthermore, Metzger et al. [18] compare the economic characteristics of a battery, a direct methanol fuel cell and a LT-PEMFC as a main power source for a forklift. However, the service life and reliability of fuel cell components were not explicitly taken into account in most of the studies mentioned, even though these can be considered important cost factors. Based on a literature review, Strazza et al. [19] conclude that the lifetime of fuel cell systems have often been omitted due to simplifications and a lack of data, resulting in an insufficient investigation of the overall system. In their own analysis, they consider degradation and recommend a stack replacement every 7,000 h of operation for stationary operations. However, the results of economic and environmental studies depend heavily on the underlying assumptions regarding the system's service life and corresponding maintenance intervals [20].

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Acronyms

ATA	Air Transport Association
ATR	Avions de Transport Régional
BIT	Built In Test
BoP	Balance of Plant
CBM	Condition Based Maintenance
DC	Direct Current
DET	Detailed inspection
DIS	Discard
DLR	German Aerospace Center
EIS	Electrochemical Impedance Spectroscopy
EoL	End of Life
FC	Flight Cycle
FFI	Failure-Finding Interval
FH	Flight Hour
FMEA	Failure Mode and Effect Analysis
FNC	Functional check
GVI	General visual inspection
GWP	Global Warming Potential
LLP	Life Limited Part
LRU	Line Replaceable Unit
LT-PEMFC	Low Temperature Polymer Electrolyte Membrane Fuel Cell
LUB	Lubrication
MH	Man Hours
MPD	Maintenance Planning Document
MRBR	Maintenance Review Board Report
MSG-3	Maintenance Steering Group 3
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
OPC	Operational check
RCM	Reliability Centered Maintenance
RST	Restoration
SDI	Special detailed inspection
SOFC	Solid Oxide Fuel Cell
SoH	State of Health
SRC	Servicing
SRU	Shop Replaceable Unit
TMS	Thermal Management System
TRL	Technology Readiness Level
VCK	Visual check

In most of these studies, maintenance is mainly considered superficially, or the focus is on other aspects such as prognostic health management or prescriptive lifetime management. Consequently, as Gerbec et al. have suggested, there remains a need for implications on scheduled maintenance for fuel cells [10]. According to Meissner et al. [21], current maintenance activities in aviation are firmly based on Reliability Centered Maintenance (RCM) approaches, with regular manual checks and inspections. In this regard, a Maintenance Review Board Report (MRBR) for fuel cell operation could be a valuable input, outlining maintenance requirements and activities to be performed.

Given the current lack of information regarding scheduled maintenance of fuel cells, our study will conduct a comparative analysis of potential fuel cell systems for aircraft applications from a preventive maintenance perspective. The novelty of this work lies in the maintenance estimation using an RCM approach for fuel cells in early design stages and in the provision of a comprehensive maintenance plan, including reliability data for the components. This analysis provides a structured, reproducible basis for evaluating maintenance characteristics while also supplying background information on the system architectures and operational functions on which the evaluation is based. We also point out shortcomings in the maintenance estimation of novel technologies. The main objectives of this study are to identify the most suitable fuel cell system for aircraft operation with respect to its maintenance characteristics and to explore preliminary considerations regarding Condition Based Maintenance (CBM) approaches for these systems. This enables us to provide information for designers and researchers in order to support the development of technically-feasible fuel cell systems for aviation from a maintenance perspective.

The remainder of this paper is structured as follows. An overview of the fundamentals of aircraft maintenance, including the specification of maintenance tasks and CBM approaches, is provided in Section 2. This is followed by the introduction of the fuel cell systems, which will be presented alongside the baseline aircraft configuration in Section 3. Here, the technologies, system layouts, and initial implications on safety and maintenance are presented. In Section 4, we will introduce the methodology of this maintenance assessment by providing a general overview of the approach, with a detailed explanation of how maintenance intervals can be determined based on statistical reliability data. In Section 5, the results of the assessment are presented by setting up MRBR-like tables for each subsystem and by conducting a comparative analysis of the two fuel cell systems. Here, we will derive implications on material demand, labor scope, operational aspects, and safety. We will also briefly discuss how prospective CBM approaches could be embedded within the maintenance schedule. Finally, in Section 6, the fuel cell system with the most favorable maintenance characteristics for aviation will be determined.

2. Fundamentals to aircraft maintenance

This section introduces the fundamentals of scheduled maintenance activities in the aviation sector. We will also introduce the most important statistical metrics for estimating the reliability of components in our study. Subsequently, we will present the approach for defining scheduled maintenance tasks. In addition, the concept of CBM in aviation and the potential benefits of implementing these systems are discussed.

2.1. Scheduled maintenance

Maintenance is a crucial aspect of aviation to ensure flight safety, reliability, and airworthiness, ultimately contributing to aircraft availability [22]. In general, it can be divided into scheduled and unscheduled activities. Scheduled maintenance, also known as preventive maintenance, aims to maintain the system's intended reliability, thereby preventing deterioration to a point where it can no longer be used. The maintenance actions are executed following a predetermined schedule defined by utilization parameters such as Flight Hours (FHs) or Flight Cycles (FCs) of the respective system, or condition-based, i.e., when the operating capability falls below a certain threshold [23,24]. Usually, scheduled maintenance activities are specified according to the RCM approach. The focus here is not on the failures themselves, but on their potential impact on safety and operations. This approach to maintenance planning ensures that the operating capability meets the users' requirements [25].

Activities can be further subdivided into line and base maintenance, as well as on-wing and off-wing maintenance. Line maintenance is performed at the gate to guarantee daily operational availability; base maintenance, on the other hand, is more extensive and is performed in the hangar. On-wing maintenance is performed directly on the aircraft, whereas off-wing maintenance involves the removal of components and further processing them in a maintenance shop. In this regard, systems defined as Line Replaceable Units (LRUs) can be replaced on-wing,

Table 1
Overview of defined maintenance tasks according to the MSG-3 analysis [28].

Tasks	Subtasks	Abbreviation	Description
Lubrication & servicing	Lubrication Servicing	LUB SRC	Exchange or check consumables such as oil and coolant to reduce functional deterioration
Operational & visual check	Operational check Visual check	OPC VCK	Check to identify whether a component has failed or passed by visual inspection or during operation - qualitative check
Inspection & functional check	Functional check General visual inspection Detailed inspection Special detailed inspection	FNC GVI DET SDI	Identification or detection of failure resistance or failure itself, either visually or using measuring tools - quantitative check
Restoration	–	RST	The scope of restoration can range from cleaning to the replacement of individual components, such as bearings, to a complete overhaul
Discard	–	DIS	Exchange of single-cell components, such as filters

whereas further maintenance activities on individual Shop Replaceable Units (SRUs) or piece parts are carried out off-wing.

To measure the reliability of components and as information for logistics planning of spare parts, commonly used statistical parameters are Mean Time Between Failure (MTBF) or Mean Time To Failure (MTTF) values [26]. They describe the mean lifetime of a component based on a probability function. In this regard, the MTBF refers to repairable components and the MTTF refers to non-repairable components. If only a single component is in operation, it can be assumed, purely statistically, that this component will function reliably over the specified period, as indicated by its mean service life [27]. However, it should be noted that in real-world operations involving a large number of components, such as in an aircraft fleet, some components will fail before or after this specified service life. Assuming that reliability is based on an exponential probability distribution, the MTBF and MTTF values can be determined as the reciprocal of the failure rate λ, which indicates the average number of failures to be expected over a certain time period (see Eq. (1) and Eq. (2)).

$$\lambda = MTBF^{-1} \tag{1}$$

or

$$\lambda = MTTF^{-1} \tag{2}$$

2.2. Defining maintenance tasks

Considering the framework of aviation guidelines and procedures, the maintenance assessment of this work includes an Maintenance Steering Group 3 (MSG-3) analysis. This approach is related to RCM, as it aims to maintain the safety and reliability of the aircraft [28]. The MSG-3 analysis is a common method for complying with the minimum requirements for scheduled maintenance [29]. The basis for this assessment is a safety analysis, which is conducted according to the Guidelines for Conducting the Safety Assessment Process on Civil Aircraft, Systems, and Equipment ARP 4761 A [30]. In our study, a functional Failure Mode and Effect Analysis (FMEA) is adapted to the needs of the MSG-3 process.

The MSG-3 framework and its decision logic are used to define scheduled (routine) maintenance tasks. The decision logic consists of two levels, each focusing on different aspects. In level 1, functional failures and their effects are evaluated. This determines whether functional failures are evident or non-evident (hidden) to the crew during operation. In general, the evident category considers individual isolated failures, while non-evident cases become important when a combination of failures occurs. In this regard, non-evident failures are primarily associated with backup or redundant systems. Distinctions are also made between functional failures that impact safety, operations or economics. Based on this assessment, failure effect categories are assigned, which then serve as the basis for level 2 for defining maintenance tasks. The minimum scope of maintenance work is determined to guarantee safety while aiming for cost-effectiveness. A redesign of the system may be necessary if no maintenance work can be identified to reduce the risk or impact of a failure. All tasks that can be defined in this step are described in Table 1.

Table 2
Overview of the maintenance intervals of a regional aircraft configurations such as the ATR-42 [31].

Maintenance	Check	Interval
Line	Daily	1 day
Base	A	750 FH
	C	5,000 FH
	D	2/4/8/ or 12 years

Our study outlines the results of the MSG-3 analysis in an MRBR-like list containing all scheduled maintenance tasks identified. In addition to the tasks, corresponding intervals need to be derived, which, however, lie outside the scope of the MSG-3 approach. We will present other suitable methodologies for this purpose in Section 4. Since performing isolated scheduled maintenance tasks on a single component is not financially viable, these intervals are generally clustered into different types of checks shown in Table 2, using the regional aircraft Avions de Transport Régional (ATR)-42 as an example.

2.3. Condition based maintenance

Maintenance procedures within CBM can be regarded as a form of preventive maintenance [21,32]. However, while conventional maintenance tasks are performed at fixed and predefined intervals, this approach enables the execution based on the measured condition of a component. Usually, condition monitoring via onboard sensors or non destructive testing is involved for monitoring components and their operating capability [33]. CBM approaches can be divided into online or offline monitoring, continuous or periodic monitoring, and with or without external testing.

In general, the increasing complexity of electronic components and systems requires timely fault and condition monitoring [34]. To identify and locate potential failures and enhance the maintainability of electronic items, a Built In Test (BIT) system could be integrated for continuous or offline monitoring. This could include passive fault management and diagnostic equipment to support conventional maintenance processes. The BIT can be used as the interface between the hardware components and supporting entities such as the maintenance control center or the maintenance team [35]. The overall objective of this approach is to verify whether the function of the system or component can be guaranteed [36].

Implementing maintenance concepts other than RCM for aircraft remains challenging, as there is currently no conclusive framework available for supporting the design and integration of certifiable CBM

Table 3
List of parameters for the defined fuel cell systems.

Design parameter	LT-PEMFC	SOFC
Stack design	Multi-stack	Multi-stack
Operational temperature[1]	60 °C to 100 °C [9,40,41]	650 °C to 800 °C [42]
Operational pressure	1 bar to 1.6 bar [41]	1.5 bar to 8 bar [43]

1– Operational temperature refers to the fuel cell stacks.



Fig. 1. Illustration of our use case configuration. Regional, fuel cell-powered aircraft with distributed electric propulsion, based on the D70 fuel cell configuration of the EXACT project [37,38], provided by the DLR Institute of System Architectures in Aeronautics.

systems [21]. Therefore, at the current state, the scope is limited to non-safety-related tasks [32]. However, for future systems, such as more- or all-electric aircraft, CBM could be beneficial for tracking degradation of electrochemical systems like fuel cells and batteries. These systems are inherently more digital and electronically controlled, making it easy to integrate sensors. Additionally, many parameters are already recorded for the management systems and control units. However, it must always be borne in mind that all systems introduced within the framework of CBM increase the complexity of the overall system and must also be part of the maintenance process.

3. Introduction to the fuel cell systems

To enable a thorough evaluation, the fuel cell systems to be examined are presented below. First, the baseline aircraft configuration is introduced. The system design is then presented following this configuration. Subsequently, general implications regarding the safety and maintenance characteristics of fuel cell systems are evaluated.

3.1. Design description

For a comprehensive understanding of the results derived in this study, a brief description of the aircraft configuration and fuel cell systems is provided. This illustrate the scope of the systems. It also improves the understanding of the defined maintenance tasks, as the configuration has impact on the analysis and thus on the determination of maintenance measures.

3.1.1. Aircraft configuration

The fuel cell systems are specified using a regional aircraft in the class of 50 to 80 seats as baseline, see Fig. 1. This aircraft configuration is based on designs from the German Aerospace Center (DLR) internal projects EXACT [37,38] and H2EAT [39].

For this configuration, the fuel cell system is intended as the primary energy source. A failure of the fuel cell system would correlate to a higher criticality compared to the use case of a secondary energy supply source, such as an auxiliary power unit [9]. However, we assume multiple fuel cell stacks for each module to introduce redundancy. For the maintenance assessment in our study, we therefore consider a single fault in a fuel cell system to be non-safety-critical, as it would only result in a power loss of 1/10 of the total output. The respective preliminary design parameters for the fuel cell systems are specified in Table 3.

The following presents the basic architecture of the two fuel cell systems considered in this study, i.e., the LT-PEMFC and the SOFC system. For the assessment, the fuel cell systems are further divided into subsystems visualized in Fig. 2 for the LT-PEMFC and in Fig. 3 for the SOFC. The essential functions of the systems are also listed there. Additionally, safety features such as damping elements for the mounting, ventilation in case of leakage, monitoring, and sensors (e.g., temperature, voltage, current, and pressure sensors) are considered. For the sake of simplicity, these units are not visualized in Figs. 2 and 3.

3.1.2. LT-PEMFC system

The main function of fuel cells can be summarized as converting stored hydrogen into electricity. The LT-PEMFC is a subcategory of fuel cells, primarily consisting of an anode, a cathode, and a membrane as an electrolyte (most commonly Nafion) between the bipolar plates. The fuel cell operates within a temperature range of 60 °C to 100 °C [9,40,41] and can be started and shut down in seconds to minutes. The system requires humidification to ensure its performance and function. The LT-PEMFC technology has already been adopted in various forms of commercial transportation, e.g., in the automotive sector (Toyota Mirai [44]) or in the train sector (Alstom Coradia iLint [45]). Exemplary LT-PEMFC designs and layouts for the aviation sector can be found in various publications [9,40,46–48]. While these designs are similar in their basic architecture, they differ mainly in how hydrogen is supplied to the system. A possible layout for the aviation sector, considered for this assessment, is shown in Fig. 2. The corresponding subsystems are briefly described below.

Hydrogen supply. Hydrogen is supplied from a cryogenic tank and filtered at the end of the distribution line to prevent impurities. A heat exchanger then converts the hydrogen into a gaseous state. A pressure-regulating valve provides the required operating pressure. While part of the hydrogen is provided to the fuel cell itself, excess hydrogen is circulated via the recirculation pump. The recirculation is required for this configuration in order to mitigate starvation [49]. In the event of a malfunction or required shutdown, the shutoff valve interrupts the hydrogen supply. For this analysis, we assume a lubricant-free recirculation pump. For more detailed information on hydrogen and air supply, readers are referred to the studies conducted by Han et al. [49] and Zhao et al. [50].

Air supply. The air is supplied to the LT-PEMFC after being filtered, compressed by the lubricant-free radial compressor [40], cooled by the intercooler, and humidified by the humidifier. At the end of the air supply line, the pressure regulator ensures the required operating pressure and flow rate. The humid air is exhausted, while some of it can be reused for humidification purposes. In this regard, the mixing valve regulates the required humidity.

Power generation. The reactants are supplied to the LT-PEMFC, where an electrochemical reaction occurs at 80 °C. This generates electrical power and heat, whereby moist gas is produced as a byproduct.

Thermal management system. The Thermal Management System (TMS) controls the heat extraction of the LT-PEMFC. This subsystem involves a coolant pump, a bypass valve, a heat exchanger, and an additional heating element. Coolant filter and ion exchange filter keep the coolant free of contamination and prevent ionization. The expansion vessel ensures the required pressure.

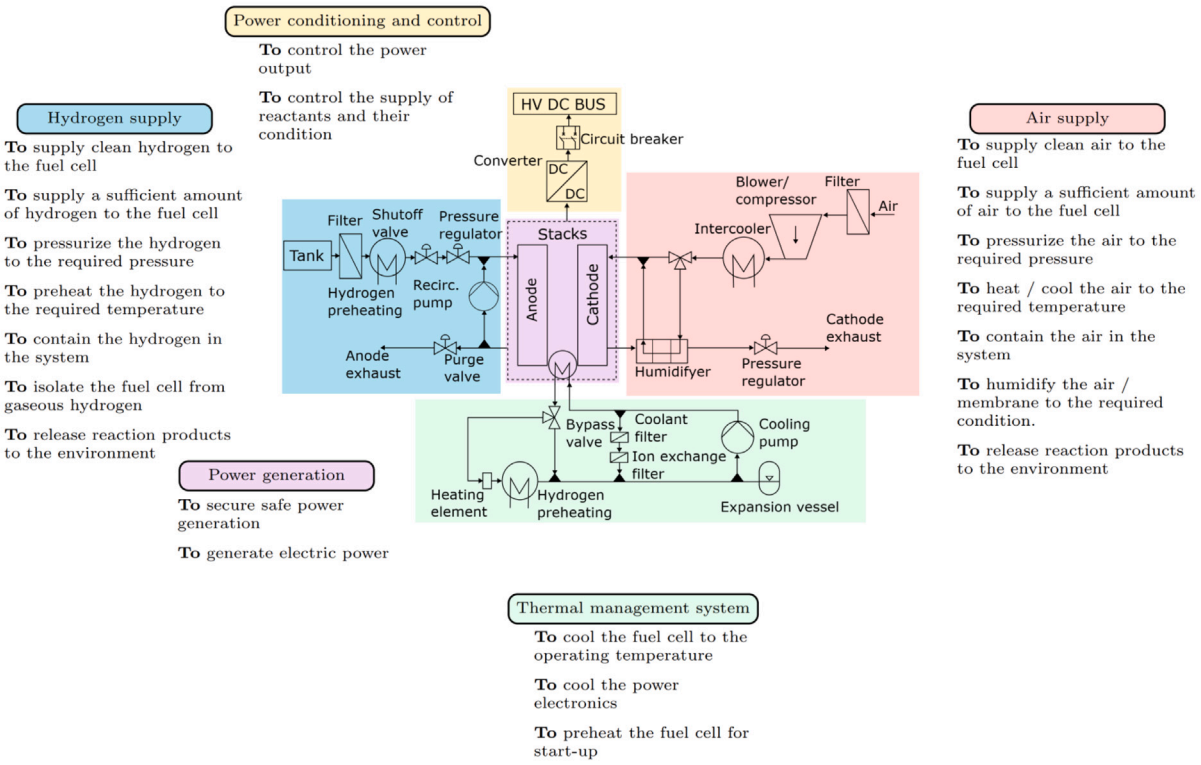


Fig. 2. Schematic representation of the LT-PEMFC and its subsystems, including the most important functions for this maintenance analysis.

Power conditioning and control. The converter adjusts the power output of the fuel cell to the required voltage and supplies it to the high-voltage Direct Current (DC) bus. The circuit breaker disconnects the power line in the event of a fault. For a potential converter layout, readers are referred to Barhoumi et al. [51].

3.1.3. SOFC system

The SOFC is the second subcategory of fuel cell systems that we consider in this study. Compared to the LT-PEMFC, it is characterized by a lower Technology Readiness Level (TRL) in the transportation sector, but also by lower system complexity [6]. It consists of an anode, a cathode, and an oxide ion-conducting ceramic material as the electrolyte. The SOFC operates at a temperature range between 650 °C and 800 °C [42]. Due to this high operating temperature, the waste heat can be used to achieve high specific power and performance, whereas the system does not require a catalytic layer. The high temperature also enables internal fuel reforming, thereby enabling a broader range of fuels. In contrast, an LT-PEMFC requires very high hydrogen purity to avoid accelerated degradation [52,53]. On the other hand, the SOFC involves a long start-up and shut-down period with a gradient of 2 K/min [54]. Currently, SOFCs are mainly used in stationary systems for high power generation [53]. Exemplary SOFC designs and layouts for the aviation sector are presented in various publications [55–58]. A possible layout for this assessment is shown in Fig. 3. The corresponding subsystems are briefly described below. Due to its high operating temperature, we are considering a hybrid system, which is described in more detail below.

Hydrogen supply. As with the LT-PEMFC, hydrogen is supplied from a cryogenic tank and filtered to remove impurities introduced during storage and distribution. The hydrogen is also supplied in a gaseous state. To reach an operating temperature of 800 °C, additional preheating components are required, i.e., a heat exchanger and electric heating elements. Here, we assume that the use of a single heat exchanger is insufficient and that a two-stage system is needed, as demonstrated by Xu et al. [59]. Excess hydrogen is burned in the afterburner. The waste heat from the system is used to drive the turbine in order to achieve higher efficiency. An additional bypass line parallel to the fuel cell stack provides hydrogen to the combustion chamber.

Air supply. The air is supplied to the SOFC after being filtered, compressed by the lubricant-free radial compressor, and preheated in the heat exchanger. Due to the high operating temperature, the TMS can be simplified and relies on convection air cooling as part of the air supply, which is why it is not shown separately in Fig. 3. Accordingly, the fuel cell is supplied with a considerable excess of air by the compressor. Additionally, an electric heating element is included. Similar to the LT-PEMFC, a pressure regulator ensures the required pressure and flow rate. However, humidification or water separation is not required for the SOFC.

Power generation. The reactants are supplied to the SOFC, where the electrochemical reaction occurs at 800 °C. Electrical power and high-temperature heat are generated. The waste heat is employed in a turbine, and the residual heat is used to elevate the temperature of the reactants in the supply lines. The generator supplies energy to the onboard power grid. A turbomachinery connection between the turbine and the compressor could further simplify the system.

Power conditioning and control. Power conditioning and control are handled by the inverter in the same way as with the LT-PEMFC. In addition, a hybrid configuration is introduced. The turbine converts mechanical energy into electrical energy, which is processed by the rectifier. A circuit breaker ensures the safety of the system in the event of a malfunction.

3.2. Safety implications for fuel cell systems

Safety is one of the most important concerns for fuel cell systems, particularly given the use of hydrogen. In this regard, the Hydrogen

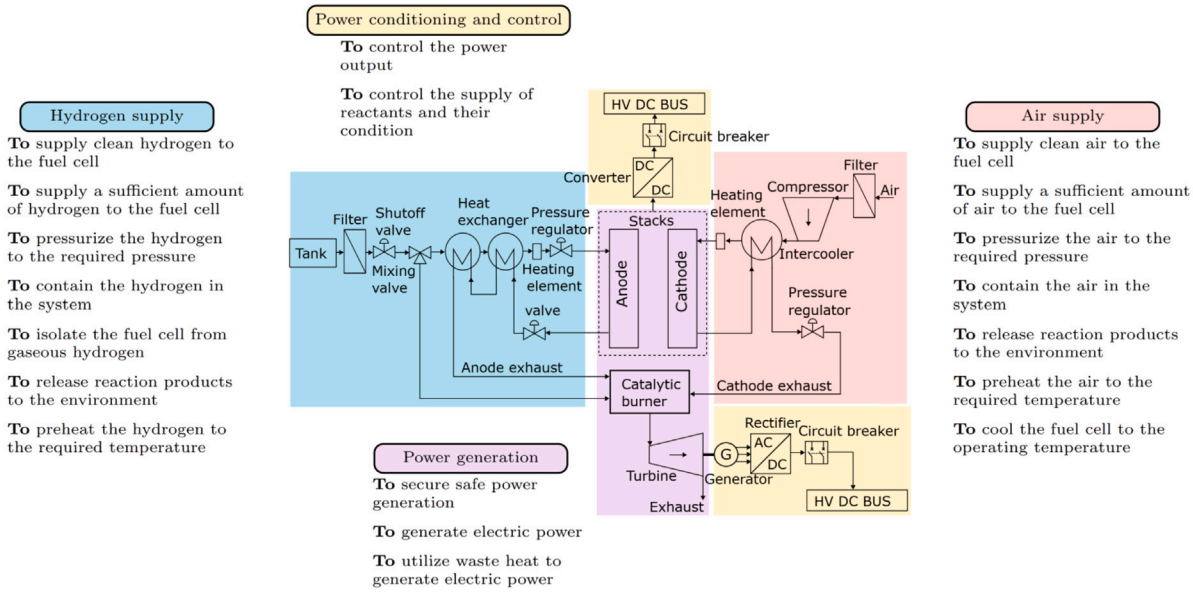


Fig. 3. Schematic representation of the SOFC and its subsystems, including the most important functions for this maintenance analysis.

Fuel Cells Aircraft Fuel Cell Safety Guidelines (AIR6464) [60] provide guidance in the integration of fuel cells, hydrogen storage, hydrogen distribution, and electrical systems. The LT-PEMFC forms the basis of the guideline since it is currently the most mature fuel cell technology in aviation. To identify potential hazards and possible countermeasures, individual risk assessments must be carried out, as defined by ARP4761 A [30].

Hydrogen in dry air at 101.3 kPa and ambient temperature has an ignition range of 4.1 % to 74.8 % by volume, while concentrations above 18.3 % pose an explosion risk [61]. Given these characteristics, hydrogen leakage can quickly become highly hazardous [62], which highlights the importance of having reliable leakage mitigation measures. To mitigate hazardous leakage, the accumulation of a deflagrating and detonating mixture must be prevented. This can be achieved through ventilation, hydrogen detection, and leakage localization. In the event of major leaks, the system must be capable of shutting down immediately to minimize the volume of combustible gas released [42,53]. Additionally, an inerting system and appropriate firefighting system should be considered [42,60]. Installing backup systems would require the establishment of appropriate maintenance measures for these systems. In accordance with ARP4761 A and the CS-25 [30,63], the accepted probability of failure for these backup systems would be between 10^{-9} and 10^{-7}.

As the operating temperature of the SOFC is above the autoignition temperature of hydrogen, immediate ignition can occur in the event of a leakage. Therefore, an oxygen-free hotbox design, as presented by Rahimipetroudi et al. [64], is recommended. Furthermore, the high operating temperatures of the SOFC necessitate effective insulation to safeguard surrounding systems and structures. With regard to fire, Gerbec et al. [10] propose a hydrogen flame barrier to prevent possible flame propagation.

3.3. Maintenance implications for fuel cell systems

In general, fuel cell systems have less moving parts and lower maintenance requirements can be expected compared to combustion engines [65]. However, these systems may experience significant degradation and some components are expected to fail comparatively early. The most common faults of the LT-PEMFC are related to water management (flooding and drying), durability, and leakage [62]. The SOFC inhibits several severe degradation mechanisms that arise from interactions between the cell's components related to the high operational temperatures, leading to microstructural changes, thermal stresses, and chemical stresses [66].

The service life of the fuel cell stack and the Balance of Plant (BoP) largely determines the overall system's reliability. The BoP refers to all auxiliary components that are necessary to support the operation of a fuel cell system. In general, internal damage mechanisms, external defects, or inadequately functioning BoP components impact the service life of the fuel cell. An inadequately operating BoP can lead to degradation or damage of the fuel cell or to a loss of performance. In addition, fuel cells are subject to vibration and shocks, fluctuating environmental conditions (e.g., temperature, humidity, and air pressure), and contamination during flight operation. The system must be able to adapt to or withstand these conditions and prevent contamination. Conditions such as thermal vibration, thermal cycling, and humidity cycling can lead to degradation, leakages, structural damage, and power losses for the LT-PEMFC and SOFC [66–69]. Therefore, the State of Health (SoH) of the fuel cells needs to be periodically checked or continuously monitored to determine when the operating capabilities are no longer met and the End of Life (EoL) is reached. According to Jouin et al. [70], the SoH of fuel cells can be divided into the following stages.

- Good health: 0%–5% power loss
- Acceptable health: 5%–10% power loss
- Degraded health: > 10 % power loss

The stack's SoH can be assessed by measuring the value of stack resistance. While direct measurement is not possible, it can be estimated from measurements obtained through characterization methods. Methods such as Electrochemical Impedance Spectroscopy (EIS) or polarization curves can be used for this purpose [71]. EIS is a non-destructive electrochemical testing method and is based on the perturbation of an electrochemical system in steady state [72]. A sinusoidal signal with a wide frequency range is applied and the response is monitored to characterize the fuel cell's health. It should be noted that characterization methods require several minutes, during which the power output must be steady. Subotić et al. [73] mentioned that the duration for one EIS cycle is 10 min, but can be further reduced for a specific characteristic frequency. Consequently, the EIS could be carried out periodically after a flight. A constant-power query for the selected

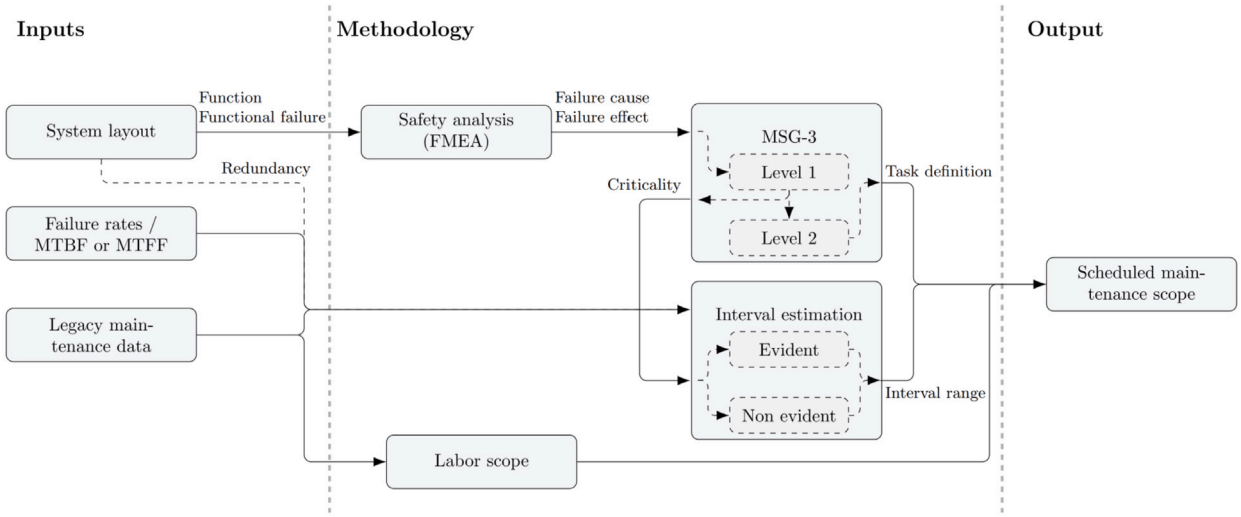


Fig. 4. Workflow of the maintenance assessment of fuel cell systems in aircraft.

frequency spectra is required and can be performed during taxiing or turnaround of the aircraft.

In addition to determining the SoH, a leakage test must be carried out. According to the College of the Desert maintenance document [74], a leak-down test, a transfer test, and an external test are required. The leak-down test detects leaks in any component within the hydrogen supply; the external leak test quantifies leaks from all supply paths into the atmosphere; and the transfer leakage test quantifies leaks to the internal system. In addition to leakage tests, hydrogen pressure and coolant flow checks, as well as cathode inlet-filter checks, are needed [10]. For specific inspections or functional tests of valves, pumps, and compressors, an inerting or purging process using helium must be established to mitigate deflagrating and detonating mixtures [42,60].

Information on the lifetime of fuel cell systems can be found in the literature, but with a wide range of values. In this regard, it should be noted that there is no clear definition of lifetime or durability. The EoL can be defined by gradual reductions in cell voltage, current density or rated power, or by failure of key components [75]. The lifetime or MTTF ranges between 8,900 h and 29,240 h for an LT-PEMFC [11,12,47,76–78] and between 39,857 h and 80,000 h for the SOFC [79–83]. For the SOFC, the data are mostly gathered for stationary applications. In comparison to the stated lifetimes, in their ecological study, Bicer et al. [84] assume an EoL of 5 years for the SOFC.

4. Methodology of the maintenance assessment

This section outlines the overall workflow we employ in our study to evaluate the maintenance requirements of the fuel cell systems. Fig. 4 shows an overview of this assessment workflow, including the required input and the resulting output, which is presented in the form of MRBR-like tables. This approach builds upon the research conducted by Meissner et al. [8]. In the following, we will first discuss the general approach for specifying scheduled maintenance activities and the safety analysis required for this. We will then introduce the corresponding methodologies for determining the associated maintenance intervals.

4.1. Safety analysis and specification of maintenance activities

Our maintenance analysis is based on the component or LRU level. At this stage, we define appropriate maintenance tasks by following the RCM approach and applying the MSG-3 analysis, which is described in more detail in Section 2.2.

As the MSG-3 analysis requires input corresponding to a safety analysis of the systems, we conduct an FMEA for each fuel cell system. The functions for this FMEA are listed in Fig. 2 for the LT-PEMFC and in Fig. 3 for the SOFC. This should be considered as a preliminary set of generic functions, which could be further specified or subdivided during a more detailed system design. We distinguish between no operation, partial operation, and faulty operation regarding functional failures. To determine whether individual functional failures are evident to the operating crew, assumptions are made about certain parameters being displayed on the electronic centralized aircraft monitoring panel or warning lights that indicate certain faults. For a more detailed description of this approach, readers are referred to the work of Meissner et al. [8]. For this safety analysis, we assume a ventilation system and a hydrogen detection system, which are intended for use in the event of hydrogen leakages. For the SOFC, we assume that a hotbox will be installed for safety reasons. The hydrogen storage and distribution, potential batteries for power buffering, and the propulsion system are outside the scope of this study.

To further specify the labor scope of the defined tasks, we take into account existing Maintenance Planning Documents (MPDs) from legacy aircraft. For the sake of simplicity, we assume that the labor scope of the legacy system can be applied to this analysis if the legacy component and the component in the fuel cell system are similar. We are aware that this involves a significant degree of uncertainty, but given the limited data available, we resort to this approach.

4.2. Determination of maintenance intervals

The MSG-3 analysis does not provide any specific method for determining maintenance intervals for the defined tasks as it suggests taking into account experience and engineering judgment. However, for novel systems such as fuel cells in the aviation sector, such practical experience is very rare. Therefore, in addition to data from legacy aircraft, we use the following two approaches for interval estimation in our study. On the one hand, intervals for similar components in legacy aircraft maintenance serve as an initial reference. We take into account the data from the legacy MPDs and the Air Transport Association (ATA) chapter of the corresponding component. For converting legacy intervals from FC to FH, we use a factor of 0.83 FH/FC as a reference for our mission scenario, which is based on the operating scenario of an ATR-42 [85]. On the other hand, statistical lifetime or failure data for the components (e.g., MTBF or MTTF values) is used for deriving intervals using analytical approaches. This approach

Table 4
Exemplary demonstration of the workflow for interval determination for non-evident and evident failures.

Component	MSG-3 Level 1	MSG-3 Level 2		Derived interval[1,2]			
	Failure effect category	Task code	Description	MTBF & MTTF	Input	Approach	Interval
Circuit breaker	Safety (non-evident)	OPC	Operational check: Checking if the circuit breaker gets triggered by high current	Circuit breaker Converter Wires Fuel cell Hazardous event	M_{TIVE} = 26,960 h to 402,443 h M_{TED} = 10,115 h to 23,243 h M_{MF}= 10,000,000 h	Non-evident (Eq. (3))	100 h to 1,900 h
Heat exchanger	Operational (evident)	RST	Restoration: Cleaning of the heat exchanger	Heat exchanger	$MTBF$ = 57,803 h to 123,762 h	Evident (Eq. (7))	3,000 h to 6,300 h

1– A complete list of all MTBF and MTTF values used in this study is provided in Table B.18.
2–The mean values and standard deviations are used to establish the interval's range.

differs depending on whether the failure is evident or not, as presented below. For this statistical failure data, parameters such as actual flight operations and environmental parameters (e.g., vibration, humidity, or temperature) are not considered, as there is currently insufficient information available.

4.2.1. Interval determination for non-evident failures

For non-evident failures, a failure finding task is to be conducted. This is typically applicable for a protection or backup system, such as a circuit breaker, where a failure would only be detected during operation when the protection system must be used. In this regard, SAE JA1012 defines the Failure-Finding Interval (FFI) [86]. The corresponding time T_{FFI} is specified by Eq. (3). Here, M_{TED} represents the MTBF or MTTF for the protected function and M_{TIVE} represents the corresponding value for the protective function. The probability of multiple failures is expressed as $1/M_{MF}$, which can be considered the maximum allowable MTBF or MTTF of the entire system before an operator assumes the system to have failed with its protective functions.

$$T_{FFI} = \frac{2 \cdot M_{TED} \cdot M_{TIVE}}{M_{MF}} \tag{3}$$

To determine the protected function M_{TED} of a system consisting of multiple units, it may be necessary to combine the MTBF or MTTF values of each component c of the allocated system. Assuming (a) that all sub-components are necessary to perform the required system function and (b) an exponential failure distribution, the combined value of the system can be determined with Eq. (7) [87].

$$M_{TED}(c_1; ...; c_n) = \left(\sum_{k=1}^{n} \frac{1}{MTBF(c_k)} \right)^{-1} \tag{4}$$

For specifying the probability of multiple failures $1/M_{MF}$ within this study, we use the conservative assumption that the failure combination of protective and protected functions can lead to a fire or other hazardous event [88]. According to CS-25 [63], a probability of $1/M_{MF} = 10^{-7}$ is therefore assumed.

In this analysis, the FFI is derived for operational check tasks of the circuit breaker, the ventilation, and the shutoff valve. The overall approach for the circuit breaker will be described in more detail as an example, with the individual steps summarized in Table 4. An detailed overview of level 1 and level 2 of the MSG-3 analysis is provided in Tables A.16 and A.17 in the appendix. The basic system function of ensuring safe power generation serves as the starting point. A defective circuit breaker can lead to a functional failure, as a protected faulty component may not be isolated from the bus system. Potential hazards, such as a fire due to short circuits, must be taken into account as a failure effect. In level 1 of the MSG-3 analysis, this functional failure due to a non-functional circuit breaker is therefore assessed as safety-critical but non-evident. To check the functionality of the circuit breaker during maintenance, an operational check is then defined for this purpose in level 2. For determining the interval of this operational check, the FFI is applied, whereas the protective circuit breaker is allocated to the protected function comprising the fuel cell, wires, and the converter. For deriving the respective MTBF or MTTF values in Eq. (3), statistical failure rates from literature are used. Since there exists a high degree of uncertainty here, we do not use individual values, but establish a range in each case. Taking into account the mean value and standard deviation, the interval for operational checks of the circuit breaker then results in a range of 100 h to 1,900 h.

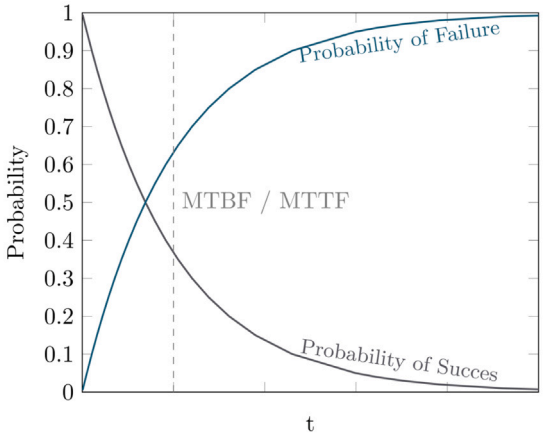


Fig. 5. Correlation between the probability of failure and the probability of success, with the corresponding MTBF or MTTF value [27].

4.2.2. Interval determination for evident failures

In general, no specific method is specified for deriving intervals for tasks that have been defined for evident failures. Therefore, in our analysis, we estimate these intervals taking into account statistical failure data commonly used in aviation, i.e., MTBF and MTTF values. When using MTBF and MTTF values, a constant failure rate λ and an exponential failure distribution are assumed. This results in a probability of failure of 63.2 % for a period of time (t) when the MTBF or MTTF of a component is reached [26].

Following the exponential distribution, the failure probability is described by Eq. (5). According to ARP 4761 A [30], the complementary probability of success P_s is then defined by Eq. (6).

$$P_f = 1 - e^{-\lambda t} \tag{5}$$

$$P_s = e^{-\lambda t} \tag{6}$$

This correlation is shown in Fig. 5. Consequently, the time at which the MTBF or MTTF of a component is reached corresponds to a probability of success of 36.8 %. Given the safety requirements in the aviation sector, this appears to be an insufficient interval for carrying out maintenance work to maintain the aircraft's operation and airworthiness. For the analysis in this study, we therefore derive

Table 5
Determination of probability of success, using a generator control unit of the legacy aircraft as an example [31].

MTBF/ MTTF [h]	Reference	Maintenance interval [FH]	Maintenance task	Probability of success
244,653	[89]	4,000	Operational test of AC generator control unit	98 %
30,000	[90]			88 %
189,200	[91]			98 %
204,082	[92]			98 %

a more suitable probability of success for maintenance intervals. For this purpose, we compare intervals from actual aircraft maintenance with the statistical failure probability of these components. As a first reference, we use a generator control unit of an ATR-42. For this component, the legacy MPDs specifies an operational test at an interval of 4,000 FH [31]. Various control units from the literature serve as references for the statistical MTBF and MTTF values, although it should be noted that most of these are intended for ground applications. The resulting probabilities of success, taking into account the statistical failure data and the legacy interval, are listed in Table 5 and range between 88 % and 98 %.

We determine the mean value of these probabilities at $P_s = 95\%$, which seems sufficient for an initial approach and the preliminary investigation in this study. As shown in Fig. 5, this value significantly reduces the resulting maintenance interval compared to an interval corresponding to the MTBF value. The corresponding interval $T_{evident}$ of a component can then be determined with Eq. (7), taking into account the MTBF value of the component.

$$T_{evident} = -\ln(P_s) \cdot MTBF \tag{7}$$

with

$$P_s = 95\% \tag{8}$$

This approach for evident failures is shown exemplary for the heat exchanger in Table 4, whereas a detailed overview of level 1 and level 2 of the MSG-3 analysis is provided in Tables A.16 and A.17 in the appendix. In this case, the basic system function refers to preheating the hydrogen to the required temperature. A functional failure, e.g., caused by fouling of the heat exchanger, could result in insufficient preheating and thus resulting in reduced power generation and efficiency. In level 1 of the MSG-3 analysis, this functional failure is assessed as operational but evident. To reduce the heat exchanger's susceptibility to fouling, a restoration task including cleaning is then defined in level 2. Taking into account statistical failure data from literature and applying Eq. (7), the interval for restoration tasks of the heat exchanger results in a range of 3,000 h to 6,300 h.

For our purposes, and as a first application of this approach, we assume that this constant probability threshold can be applied to all components under investigation, as well as to different task categories and failure severity levels. In the current maintenance schedule for aircraft components, however, all of these criteria are taken into account when determining the frequency of maintenance activities. In terms of a component's remaining reliability, an operational check, for example, may tend to be performed earlier than a functional check. In addition, we expect the frequency of these checks to vary depending on whether the criticality of the component's failure is assessed as safety-related or non-safety-related. Therefore, after first examining the fundamental applicability of this idea in the present work, the approach will be further expanded and refined in subsequent studies. To this end, a comprehensive data set of LRU failure data from actual operation of a widely used passenger aircraft is currently compared with the task intervals specified in the aircraft's MPD. This will enable us to derive a specific probability of success threshold for different types of components (e.g., electronic or mechanical), specific types of tasks, and failure severity levels. The refinement of our method currently under development is explicitly intended as a supplementary step to interval estimation following the application of MSG-3. Applicants of this approach will then be able to identify specific probability of success thresholds for each task and component using the task category and failure effect category derived from the MSG-3. To subsequently derive the corresponding task interval, they will require only information on a component's failure probability, (e.g., MTBF values) from aviation operations or experimental results that take the actual operational conditions into account. By incorporating extensive reliability data from global aircraft operations over the past five years and linking it to the corresponding maintenance schedule, we expect this method to provide a solid foundation for further preliminary estimates of maintenance scope. However, this approach will likely not be suitable for all types of components. For components that are subject to significant performance degradation, such as the fuel cell stack, we therefore recommend determining the task frequency based on condition-based factors. In this context, degradation models can provide useful insights into service life and aging characteristics.

5. Results of the maintenance assessment

As previously described, the decision logic of the MSG-3 enables the definition of suitable maintenance tasks. The following provides an overview of the tasks, the intervals, and the respective labor scope presented for the subsystems of both fuel cell systems. This will lead to a comparative analysis of the systems, considering material demand, labor scope, and implications on safety and operations. To this end, we will also take into account a possible implementation of CBM approaches.

5.1. Specification of scheduled maintenance

To identify the fuel cell system with the highest potential for aircraft operations and to determine which tasks could be replaced by BIT, a MRBR-like list of maintenance tasks is provided for each subsystem. Furthermore, certain assumptions, the derived intervals, and the corresponding labor scope are introduced. Tasks and intervals that are specific to one system and differ from those of the others are highlighted in gray.

5.1.1. Power generation subsystem

The most important subsystem of the fuel cell system is power generation itself, for which the scheduled maintenance tasks are shown in the MRBR-like list in Table 6. For this study, we apply a rather conservative limit for the exchange frequency of the fuel cell stacks due to the limited data and the associated uncertainty (see Section 3.3), as well as the safety requirements in the aviation sector. In light of technological developments over the years, we anticipate that a significant maintenance task will be necessary at least every 5,000 FH.

To this end, we have compiled perspectives and experimental test results from literature and used them as the basis for our assessment. In their white paper for the ZA600 System, ZeroAvia estimates that a fuel cell-powered propulsion system will require significant maintenance after 10,000 h of operation [93]. In this instance, the degradation-induced EoL limit was not directly considered in relation to the SoH, as this is dependent on various design decisions. In another publication about their 150 kW SuperStack Flex fuel cell system [94], they state a service life of > 2,000 h. For aviation applications, we assume that the replacement frequency of fuel stacks will primarily be determined by

Table 6
Overview of the determined maintenance tasks and intervals for the power generation subsystem.

Subsystem	Task		Interval			Labor scope	
	Task code	Task description	Based on statistical values [FH]	Based on legacy MPD[1]	Applied [FH]	Based on legacy MPD[1,2] [MH]	Comment
Power generation LT-PEMFC (see 3.1.2)	FNC	Functional check of the LT-PEMFC including EIS as well as an inspection	600 to 1,300	800 FH	750	0.2	Emergency battery (ATA 24)
	DIS	Discard of the stacks after defined EoL	600 to 1,300	–	5,000	0.4	Assuming higher potential lifetime
	FNC	Functional check with a calibration to be carried out if necessary for the voltage sensor	–	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	FNC	Functional check with a calibration to be carried out if necessary for the current sensor	–	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	DIS	Discard of the damping elements (potential combination with discard of FC stack)	–	9,200 FC/7.700 FH	7,700	1	Engine vibration isolation (ATA 54)
Power generation SOFC (see 3.1.3)	FNC	Functional check of the SOFC including EIS as well as an inspection	1,700 to 3,300	800 FH	750	0.2	Emergency battery (ATA 24)
	DIS	Discard of the stacks after defined EoL	1,700 to 3,300	–	5,000	0.4	Assuming higher potential lifetime
	FNC	Functional check with a calibration to be carried out if necessary for the voltage sensor	–	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	FNC	Functional check with a calibration to be carried out if necessary for the current sensor	–	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	DIS	Discard of the damping elements (potential combination with discard of FC stack)	–	9,200 FC/7.700 FH	7,700	1	Engine vibration isolation (ATA 54)
	SDI	A special detailed inspection of the turbine and generator in combination with a functional check is needed to detect degradation	1,400 to 3,400	4,000 FH	4,000	0.4	Generator (ATA 24)
	RST	Cleaning and inspection of the after burner	4,300 to 8,200	5,000 FH	5,000	3	Heat exchanger (ATA 21)
	DET	Detailed inspection of the thermal insulation and pressure tank seen as hotbox for damages	1,100 to 12,500	–	750	0.6	Cowlings (ATA 71)

1– ATR-42 500 MPD [31] used as reference, when referred to legacy.
2– Assuming that a single individual is required for the specified labor scope.

a strict SoH limit, since the residual performance of the system can be considered a particularly critical requirement. Due to the significant performance degradation, the actual failure of the system is generally not the decisive factor for determining the replacement interval. In this regard, the study by Kurtz et al. [95] includes data of more than 10 years and indicates that the LT-PEMFC degrades by 10 % for an average fleet operation of 2,000 h and by approximately 30 % for 5,000 h of operation. In a study by Vichard et al. [96], the power loss at stack level was examined for an open-cathode LT-PEMFC under various operating conditions. After 5,000 h of operation, a power loss of 9 % was observed. These degradation levels can be considered a limiting state at which the EoL is reached after the respective operating time. For our study, we define the useful lifetime of the fuel cell stack as 5,000 h, referring to the latest data on lifetime testing and applying the SoH definition by Jouin et al. [70] (see Section 3.3).

To obtain a specific usage limit for our intended application, a further analysis of the degradation rate is to be conducted in upcoming studies, taking into account operating conditions. To accurately track the SoH and the remaining useful lifetime of the system during operation, the introduction of a BIT system is recommended.

It is assumed that an EIS for measuring the SoH is performed every 750 FH, in accordance with the legacy A-Check [31]. The SOFC requires a hotbox, whereas with LT-PEMFCs, this can be compensated for by other safety aspects, which speaks in favor of the LT-PEMFC. The maintenance scope of the hotbox is derived taking into account data for conventional engine cowlings (ATA 71), resulting in frequent checks at an interval of 750 FH.

As part of the hybridization, the SOFC is equipped with an afterburner, a turbine, and a generator. For the afterburner, regular cleaning and inspection tasks are defined at an interval of 5,000 FH. This is based on the maintenance scope of the conventional heat exchanger (ATA 21) specified in the legacy MPD. The turbine and generator are assumed as one combined LRU. In accordance with a generator (ATA 24) in the legacy MPD, an interval of 4,000 FH is defined for these components.

5.1.2. Air and hydrogen supply subsystems

Since both subsystems, the air supply and the hydrogen supply, have a high degree of similarity, they are described together in the following. In contrast to the SOFC, the LT-PEMFC requires a water management system for conditioning. It is primarily these components and the recirculation system that distinguish the fuel cell supply systems from one another, which is why they are highlighted in Table 7.

In general, a defect or failure of a subcomponent has a direct impact on the service life of the fuel cell system. For example, for the LT-PEMFC, insufficient humidification can lead to flooding and drying of the membrane, which are critical defects during fuel cell operation [62]. Accordingly, humidification systems are critical subsystems that must be maintained in order to guarantee a reliable operation of the overall LT-PEMFC system. As shown in the MRBR-like table, the humidifier, intercooler, and hydrogen preheating heat exchanger are the key components in this regard and require regular cleaning. The labor scope of the humidifier is initially derived based on a heat exchanger (ATA 21) from a conventional ATR-42 aircraft. Since these components involve regular removals and extensive off-wing cleanings, this results in a comparatively high labor scope of 3 MH per task. Assuming that each fuel cell stack has its own humidification, the required maintenance activities are considered to be within the scope of these off-wing restoration tasks. However, this assumption would need to be verified as part of a more detailed system definition.

Based on statistical data listed in Table B.18, the LT-PEMFC recirculation pump for hydrogen supply seems to have a short service life. Applying Eq. (7) for evident failures, this results in an inspection task at an interval of 2,000 FH. Due to this low reliability, potential removals and inspections need to be examined closely and good accessibility is required. The SOFC, on the other hand, does not necessarily require an active hydrogen recirculation, since the remaining fuel can be oxidized downstream in a burner and the released thermal energy can be further utilized, for example in a turbine. This eliminates the need for the recirculation pump and its corresponding maintenance task. However, using a conventional heat exchanger (ATA 21) as reference, the task for

Table 7
Overview of the determined maintenance tasks and intervals for the reactant delivery and conditioning subsystems.

Subsystem	Task		Interval			Labor scope	
	Task code	Task description	Based on statistical values [FH]	Based on legacy MPD[1]	Applied [FH]	Based on legacy MPD[1,2] [MH]	Comment
Reactant delivery and conditioning LT-PEMFC (see 3.1.2)	FNC	Leak down test (external) and transfer leak test (internal) for leakage in the system	3,700 to 8,800	–	4,000	0.5	Mapping the lower range
	FNC	A local external leak test for the system side on a different interval	3,700 to 8,800	–	8,000	1	Mapping the higher range
	DIS	Discard of the hydrogen filter	–	3,000 FH	3,000	0.6	Filter (ATA 73)
	DIS	Discard of the air filter	2,500	3,000 FH	3,000	0.6	Filter (ATA 73)
	SDI	A special detailed inspection of the compressor in combination with a functional check is needed to detect degradation	600 to 4,800	–	4,500	0.4	Generator (ATA 24)
	FNC	Functional check of the pressure regulator anode and cathode side in combination with a functional test	17,100 to 37,700	8,000 FH	8,000	0.5	Pressurization control/valve (ATA 30)
	FNC	Functional check with a calibration to be carried out if necessary for the pressure sensor on anode and cathode side	70,300	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	FNC	Functional check of the shutoff valve	250,200	8,000 FH	8,000	0.5	Pressurization control/valve (ATA 30)
	OPC	Operational check of the shutoff valve	7,700 to 17,400[3]	750 FH	750	0.2	Shutoff valve (ATA 30)
	FNC	Functional check of the purge valve in combination with a functional test	250,200	8,000 FH	8,000	0.5	Pressurization control/valve (ATA 30)
	FNC	Functional check of the mixing valve in combination with a functional test	19,000	8,000 FH	8,000	0.5	Pressurization control/valve (ATA 30)
	SDI	A special detailed inspection of the recirculation pump in combination with a functional check is needed to detect degradation	600 to 2,100	–	2,000	0.4	Generator (ATA 24)
	RST	A restoration task for the humidifier, like cleaning, is necessary	384,600	5,000 FH	5,000	3	Equivalent heat exchanger
	FNC	Functional check with a calibration or cleaning to be carried out if necessary for the humidity sensor	14,600	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	RST	Cleaning task for the heat exchanger of the air supply (intercooler)	3,000 to 6,300	5,000 FH	5,000	3	Heat exchanger (ATA 21)
	RST	Cleaning task for the heat exchanger of the hydrogen preheating	3,000 to 6,300	5,000 FH	5,000	3	Heat exchanger (ATA 21)
	OPC	Operational check of the ventilation system as well an inspection	100 to 3,000[3]	–	750	0.02	Legacy battery ventilation
	FNC	Functional check with a calibration to be carried out if necessary for the hydrogen sensor	37,200	–	750	0.4	Interval due safety reasons, labor scope temperature control (ATA 21)
Reactant delivery and conditioning SOFC (see 3.1.3)	FNC	Leak down test (external) and transfer leak test (internal) for leakage in the system	3,700 to 8,800	–	4,000	0.5	Duration based on assumption
	FNC	A local external leak test for the system side on a different interval	3,700 to 8,800	–	8,000	1	Potentially higher interval/duration based on assumption
	DIS	Discard of the hydrogen filter	–	3,000 FH	3,000	0.6	Filter (ATA 73)
	DIS	Discard of the air filter	2,500	3,000 FH	3,000	0.6	Filter (ATA 73)
	SDI	A special detailed inspection of the compressor in combination with a functional check is needed to detect degradation	600 to 4,800	–	4,500	0.4	Generator (ATA 24)
	FNC	Functional check of the pressure regulator anode and cathode side in combination with a functional test	17,100 to 37,700	8,000 FH	8,000	0.5	Pressurization control/valve (ATA 30)
	FNC	Functional check with a calibration to be carried out if necessary for the pressure sensor on anode and cathode side	70,300	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	FNC	Functional check of the shutoff valve	250,200	8,000 FH	8,000	0.4	
	OPC	Operational check of the shutoff valve	7,700 to 17,400[3]	750 FH	750	0.2	Shutoff valve (ATA 30)
	FNC	Functional check of the mixing valve in combination with a functional test	19,000	8,000 FH	8,000	0.5	Pressurization control/valve (ATA 30)
	RST	A Cleaning task for the air heat exchanger	3,000 to 6,300	5,000 FH	5,000	3	Heat exchanger (ATA 21)
	FNC	Functional check of the heating elements	2,700 to 12,300	5,000 FH	5,000	0.2	–
	FNC	Functional check with a calibration to be carried out if necessary for the temperature sensor anode and cathode side	107,300 to 145,500	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	RST	Cleaning task for the heat exchanger of the hydrogen preheating	3,000 to 6,300	5,000 FH	5,000	6	Heat exchanger (ATA 21), consideration of two
	OPC	Operational check of the ventilation system as well an inspection	100 to 3,000[3]	–	750	0.02	Legacy battery ventilation
	FNC	Functional check with a calibration to be carried out if necessary for the hydrogen sensor	37,200	–	750	0.4	Interval due safety reasons, labor scope temperature control (ATA 21)

1– ATR-42 500 MPD [31] used as reference, when referred to legacy.
2– Assuming that a single individual is required for the specified labor scope.
3– Based on non evident failures.

the afterburner involves maintenance labor of 3 MH. Compared to the scope of 0.4 MH for the recirculation pump, this reduces the benefit.

For the air supply of the SOFC, we consider a compressor, a heating element, and a heat exchanger. The compressor is considered as a key component for the fuel cell operation as it provides cooling and supplies air. By applying Eq. (7), we specify a special detailed inspection at an interval of 4,500 FH for this component. Regarding the labor scope, a conventional generator (ATA 24) is used as reference. For the heating element, a functional check at an interval of 5,000 FH is specified in accordance with the interval of the heat exchanger. Based on the legacy MPD, the labor scope for this task is estimated as 0.2 MH. Due to the significant difference in operating temperature, we assume that the heat exchanger of the SOFC is less critical regarding fouling compared to the LT-PEMFC. In general, this difference could lead to lower maintenance requirements for the SOFC. However, due to the complexity of such an assessment, this difference is not taken into account in this study.

Table 8
Overview of the determined maintenance tasks and intervals for the TMS subsystem.

Subsystem	Task		Interval			Labor scope	
	Task code	Task description	Based on statistical values [FH]	Based on legacy MPD[1]	Applied [FH]	Based on legacy MPD[1,2] [MH]	Comment
Thermal management system LT-PEMFC (see 3.1.2)	FNC	Functional check of the heating element	2,700 to 12,300	5,000 FH	5,000	0.2	–
	FNC	Functional check with a calibration to be carried out if necessary for the temperature sensor	107,300 to 145,500	5,000 FH	5,000	0.4	Temperature control (ATA 21)
	DIS	Discard of the ion exchange filter of the cooling system	–	3,000 FH	3,000	0.6	Filter (ATA 73)
	SRC	Inspection of the cooling system for leakages - regular fill up of coolant	3,700 to 8,800	–	8,000	0.1	Duration legacy evidence of leakage inspection (zonal task with no corresponding ATA chapter)
	SDI	A special detailed inspection of the coolant pump in combination with a functional check is needed to detect degradation	900 to 3,300	–	3,000	0.4	Generator (ATA 24)
	DIS	Discard of the coolant filter	–	3,000 FH	3,000	0.6	Filter (ATA 73)

1– ATR-42 500 MPD [31] used as reference, when referred to legacy.
3– Based on non evident failures.

To incorporate the difference in operating temperature to some extent, we assume a two-stage heat exchanger system for the SOFC (see Section 3.1.3) resulting in a labor scope of 6 MH compared to the regular 3 MH. Based on the assumptions within our study, this would result in an increased labor scope for the hydrogen preheating of the SOFC.

To detect leakage, we define respective check tasks for both fuel cell systems. This involves a check for the overall system at an interval of 4,000 FH and a local check combined with valve testing at an interval of 8,000 FH. For specifying these intervals, we apply Eq. (7) for evident failures. The labor scope of the local leakage detection check is derived based on the zonal task of compartment inspection assuming a similar labor scope of 1 MH.

5.1.3. Thermal management subsystem

The scheduled maintenance tasks of the TMS are listed in Table 8, whereas this MRBR only takes into account tasks for the LT-PEMFC. This is due to the fact that we consider the TMS of the SOFC to be part of the respective air supply system, as described in Section 3.1.3. The LT-PEMFC requires a more complex cooling than the SOFC, and therefore likely involves a higher maintenance scope. Defects or failures of these components can rapidly lead to LT-PEMFC failure, underscoring the need for leak and fill-level checks of the liquid cooling system. An inspection of the compartment or the line is to be performed to identify any leakage. If necessary, the fill level of the TMS could be checked regularly. The respective labor scope is specified based on a zonal task for checking the evidence of a leakage in the legacy MPD.

Furthermore, additional filters are required for the TMS of the LT-PEMFC. Ion exchange filters in particular are crucial for the operation of the system, as they prevent short circuits. As shown in the MRBR, these components involve additional discard tasks for the LT-PEMFC, which are specified at an interval of 3,000 FH, based on the fuel filter (ATA 73) of the legacy aircraft. Even though filters are not expected to have a significant impact on the overall material and labor costs, they should be easily accessible to enable these regular replacements. Taking statistical data into account, such as MTBF values listed in Table B.18, a special detailed inspection of the coolant pump is specified at an interval of 3,000 FH. Regarding heating and cooling, fouling of the heat exchanger can pose a higher risk for the LT-PEMFC, as the system involves low temperature differences to the environment and therefore a low temperature gradient. Fouling reduces heat transfer, which ultimately leads to inadequate heat dissipation.

5.1.4. Power conditioning subsystem

The scheduled maintenance tasks for power conditioning and control for both fuel cell systems are shown in Table 9. For this subsystem, the scheduled maintenance tasks derived in this analysis are largely identical. However, the SOFC includes an additional rectifier for the turbine. Using a converter from the legacy MPD of the ATR-42 as a reference, we specify a functional check at an interval of 4,000 FH for this rectifier unit. It should also be mentioned that the scheduled maintenance tasks for this subsystem will be the same for both fuel cell configurations if a mechanical connection between turbine and compressor is assumed.

5.2. Comparison of SOFC and LT-PEMFC

Once the scope of the scheduled maintenance for the fuel cells has been determined, there will be a discussion and comparison regarding the labor scope, material demands and operational aspects, and safety aspects. This serves as a basis for identifying, in line with the assumptions made in our study, the system with the characteristics most likely to be most suitable for aviation.

5.2.1. Implications on labor scope and material demand

The number of tasks for each fuel cell system and subsystem is shown in Table 10, whereas the distribution with regard to the task category is shown in Fig. 6. A total of 32 tasks for the LT-PEMFC and 29 tasks for the SOFC are specified for the chosen systems layouts, whereby a large part of these tasks are identical for both systems. Consequently, the LT-PEMFC tends to involve approximately 10 % more tasks than the SOFC. This can mainly be attributed to the additional complexity of the TMS and the additional water management of the air and hydrogen supply.

For a comparison with regard to direct maintenance cost of an aircraft, labor and material costs are particularly relevant [97]. The following presents an initial comparison of the two fuel cell systems with regard to the labor scope. Additionally, we briefly discuss implications for material demand driven by discard tasks. To this end, we determine the number of scheduled tasks throughout the entire lifetime of the aircraft based on the maintenance activities specified in this analysis.

In accordance with actual aircraft maintenance scheduling (see Table 2), we group the tasks into bundles, each with the same interval range (see Table 11 and Fig. 7). Tasks performed at an interval of ≤1,000 FH can be allocated to safety aspects, which account for a larger share in the SOFC system. Tasks with an interval of 2,000 FH to 3,000 FH are mainly related to filters and pumps, which are present in greater quantities in the LT-PEMFC. For both fuel cell systems, approximately half of all tasks are performed within an interval of 4,000 FH to 5,000 FH, representing the largest maintenance bundle. Tasks to be conducted within a range of 7,000 FH to 8,000 FH are mainly related to valves and mounting. Considering the entire service life of the aircraft, we derive the overall amount of tasks. For this purpose, we consider the design

Table 9
Overview of the determined maintenance tasks and intervals for the power conditioning and control subsystem.

Subsystem	Task		Interval			Labor scope	
	Task code	Task description	Based on statistical values [FH]	Based on legacy MPD[1]	Applied [FH]	Based on legacy MPD[1,2] [MH]	Comment
Power conditioning LT-PEMFC (see 3.1.2)	FNC	Functional check of the controller	4,400 to 12,800	5,000 FH	5,000	0.1	Generator control unit (ATA 24)
	FNC	Functional check of the converter	0 to 9,100	5,000 FH	5,000	0.25	Generator control unit (ATA 24)
	OPC	Operational check of the fuel cell circuit breaker	100 to 1,900[3]	–	750	0.1	–
Power conditioning SOFC (see 3.1.3)	FNC	Functional check of the controller	4,400 to 12,800	5000 FH	5,000	0.1	Generator control unit (ATA 24)
	FNC	Functional check of the converter	0 to 9,100	5,000 FH	5,000	0.25	Generator control unit (ATA 24)
	OPC	Operational check of the fuel cell circuit breaker	100 to 4,500[3]	–	750	0.1	–
	OPC	Operational check of the turbine circuit breaker	100 to 5,200[3]	–	750	0.1	–
	FNC	Functional check of the rectifier	100,500 to 163,100	5,000 FH	5,000	0.25	Generator control unit (ATA 24)

1– ATR-42 500 MPD [31] used as reference, when referred to legacy.
2– Assuming that a single individual is required for the specified labor scope.
3– Based on non evident failures.

Table 10
Task distribution over the subsystems for the fuel cell systems.

Subsystem	Lubrication & servicing		Operational & visual check		Inspection & functional check		Restoration		Discard		Sum	
	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC
Power generation	–	–	–	–	3	5	–	1	2	2	5	8
Hydrogen and air supply	–	–	2	2	11	10	1	2	2	2	18	16
TMS	1	–	–	–	3	–	2	–	2	–	6	–
Power conditioning	–	–	1	2	2	3	–	–	–	–	3	5
Sum	1	–	3	4	19	18	3	3	6	4	32	29

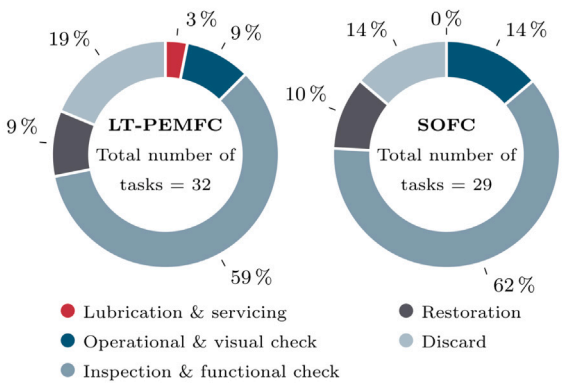


Fig. 6. Distribution of the task codes determined in the MSG-3 analysis.

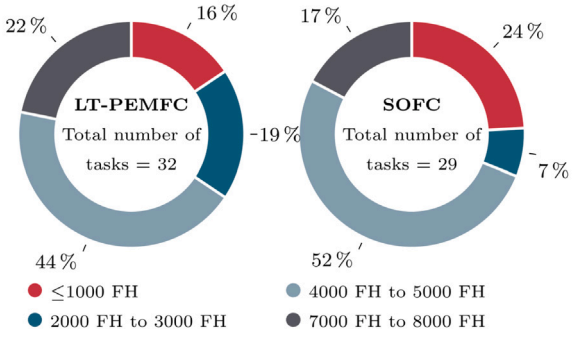


Fig. 7. Qualitative distribution of the clustering of the intervals based on the defined MRBR-like list.

service aim of an ATR-42 of 70,000 FH [98]. The total number of tasks throughout the aircraft's service life is listed in Table 12, taking into account the various task categories.

With regard to the assumptions made in our assessment, the scheduled maintenance scope throughout the aircraft life is primarily driven by the task categories operational & visual check, as well as inspection & functional check. A high number of operational and visual checks are likely to be performed in particular for the SOFC, which is attributable to the safety aspects that are more present for this system. This can also be considered as the main reason why the SOFC is expected to involve approximately 10 % more total tasks throughout the lifetime than the LT-PEMFC. Since the task categories listed above are generally associated with a high labor scope, high labor costs are expected for both systems. By taking into account the labor hours derived in this analysis for the individual tasks, we can estimate the total labor scope for both systems for the entire aircraft life (see Table 13), with 379.6 MH for the LT-PEMFC and 435.0 MH for the SOFC.

Our evaluation therefore suggests that the SOFC requires a 15 % higher labor scope, even though the LT-PEMFC involves a higher total number of maintenance tasks. This can partly be attributed to the fact

Table 11
Interval distribution of the fuel cell systems, grouped in bundles.

Subsystem	≤1,000 FH		2,000 FH to 3,000 FH		4,000 FH to 5,000 FH		7,000 FH to 8,000 FH	
	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC
Power generation	1	2	–	–	3	5	1	1
Hydrogen and air supply	3	3	3	2	7	9	5	2
TMS	–	–	3	–	2	–	1	–
Power conditioning	1	2	–	–	2	3	–	–
Sum	5	7	6	2	14	15	7	5

Table 12
Amount of scheduled maintenance activities carried out throughout the entire lifetime of the aircraft.

Subsystem	Lubrication & servicing		Operational & visual check		Inspection & functional check		Restoration		Discard		Sum	
	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC	LT-PEMFC	SOFC
Power generation	–	–	0	–	121	231	–	14	23	23	144	268
Hydrogen and air supply	–	–	186	186	228	199	42	28	46	46	502	459
TMS	8	–	–	–	51	–	–	–	46	–	105	–
Power conditioning	–	–	93	186	28	42	–	–	–	–	121	228
Sum	8	–	279	372	428	481	42	42	115	69	872	955

Table 13
Labor scope of the fuel cell systems throughout the entire lifetime of the aircraft.

Subsystem	Lubrication & servicing		Operational & visual check		Inspection & functional check		Restoration		Discard		Sum	
	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]
Power generation	–	–	–	–	29.8	92.4	–	42.0	14.6	14.6	44.4	149.0
Hydrogen and air supply	–	–	20.5	20.5	100.9	84.9	126.0	126.0	27.6	27.6	275.0	259.0
TMS	0.8	–	–	–	17.6	–	–	–	27.6	–	46.0	–
Power conditioning	–	–	9.3	18.6	4.9	8.4	–	0	–	–	14.2	27.0
Sum	0.8	–	29.8	39.1	153.2	185.7	126.0	168.0	69.8	42.2	379.6	435.0

that the SOFC requires a higher amount of frequent safety checks, especially of the hotbox. On the other hand, the SOFC has several heat exchangers on the hydrogen side. Both involve labor-intensive maintenance activities. However, it should be noted here that the specific fuel cell design and certain assumptions have a significant impact on the derived labor scope. If, for example, only a single heat exchanger for hydrogen preheating is taken into account for the SOFC, the corresponding labor scope would be reduced to 399.9 MH, reducing the percentage difference between the fuel cells to around 5 %. Therefore, a final estimation of the labor scope can only be made once extensive design studies, including detailed maintenance assessments, have been carried out.

The consideration of discard tasks with regard to the aircraft life enables us to estimate the preliminary material scope within an operating time of 1,000 FH. Based on our scheduled maintenance specification, the fuel cell stacks, filters, and damping elements are replaced as part of these activities. In this regard, a material demand of 14 fuel cell modules (including multiple stacks) and 9 damping elements is expected for both of the SOFC and LT-PEMFC systems. The LT-PEMFC is expected to require 92 filters, whereas 46 filters are estimated for the SOFC. As the restoration tasks are mainly specified as cleaning tasks in this analysis, any potential effects on the inventory are not considered here.

5.2.2. Implications on operation and safety

The difference in operating temperature of the two fuel cell systems has a significant impact on operational implications. The SOFC operates at temperatures of approximately 800 °C, at which conventional maintenance activities cannot be performed. Therefore, the system has to be cooled before maintenance can be conducted. As Eichhorn Colombo et al. [54] state, the cooling process should be executed at a rate of 2 K/min, with a target maintenance temperature of 200 °C, necessitating a cooling time of 5 h. After the maintenance activity has been carried out, the same amount of time will be required to warm up the system again. Therefore, a minimum downtime of 10 h is expected for any major maintenance activity. Additionally, maintaining a constant temperature gradient across diverse environments can be challenging. Different thermal expansion coefficients may even result in damage of the fuel cell. These limitations are expected to have a major impact on the feasibility and duration of maintenance activities for the SOFC, especially for unscheduled events. Therefore, from an operational perspective, maintenance of the LT-PEMFC seems to be beneficial within the scope of our preliminary analysis.

In accordance with the findings presented in Section 5.2.1, we expect a higher level of material efficiency for the LT-PEMFC. This must be considered during operation as well as in the provision of materials and logistics. Furthermore, it still needs to be specified whether the entire system or only subsystems should be hydrogen-free for maintenance activities to be carried out, particularly when exchanging components. In that case, it could be beneficial to consider the fuel cell as an LRU, i.e., a system that can be removed and installed as a single unit during on-wing maintenance. Additionally, further connections may be required to allow a particular section of the system to be flooded with inert gas.

From a safety perspective, other criteria must be taken into account. Due to the autoignition temperature range of 500 °C to 577 °C [61], usually no explosive atmosphere can develop in the event of leakage for the SOFC, as the escaped hydrogen reacts immediately with the

ambient air. Hydrogen accumulation is only possible here if the leakage is located upstream of the heat exchanger and if the hydrogen temperature is below the ignition threshold. For the LT-PEMFC, leakage is considered to be the main safety concern, as hydrogen can accumulate easily and lead to deflagration. In this regard, the SOFC appears to be less safety-critical, provided that a reliable leakage detection system and sufficient ventilation are in place. However, in the case of the SOFC, a leakage in the air supply can be considered critical, as the air can reach a temperature of 800 °C and therefore could damage surrounding components.

To fully assess the operation of both systems from an economic and an environmental perspective, further analyses are recommended. A sound comparison can only be made by carefully examining the entire life cycle, therefore, the insights presented here should be regarded as preliminary findings. A simulation-based economic analysis and environmental life cycle assessment, such as conducted by Wehrspohn et al. [11], Ramm et al. [99] and Rahn et al. [100], could provide a good foundation in this regard. For an economic assessment, it would be essential to include a detailed breakdown of the maintenance-driven material and labor scopes, as well as the associated operating costs, throughout the entire service life of the aircraft. Here, the accessibility of components will be a decisive factor in estimating the man-hours required to perform certain maintenance tasks, whereas repairability and spare part costs will serve as the basis for estimating material costs. In addition, the life cycles of the systems should be compared in terms of their environmental impact, where the respective Global Warming Potential (GWP) could be used as an evaluation criterion. To conduct a comprehensive analysis, factors other than maintenance should also be taken into account, such as flight scheduling, logistics, energy consumption, and the criticality of required materials. For the fuel cell systems discussed in the present work, these more comprehensive evaluations could give special attention to the influence of the SOFC hotbox on the labor scope or on specific operational effects of the fuel cell's temperature gradient.

5.2.3. Consideration of condition based maintenance

Given the novelty of these systems, the following section considers other approaches to preventive maintenance, such as CBM. Especially when degradation has a significant impact on the system's lifetime, CBM offers the potential to improve reliability and durability, as shown in the study by Kurtz et al. [95]. As we assume a high redundancy due to the multiple fuel cell units included in the design, a single fault in a fuel cell system would be non-safety-critical. In accordance with Verhagen et al. [32], we therefore assume that a BIT and CBM system can be established. Nevertheless, as Meissner et al. [21] describes, there is currently no holistic framework available for implementing such a system in the aviation sector. For this reason, the following should be regarded as a preliminary consideration of CBM and BIT systems. Additionally, each system introduced requires maintenance procedures to ensure reliable data generation and processing.

Tasks of the maintenance categories operational & visual check as well as inspection & functional check can be substituted by BIT, including electrical components such as converters and rectifiers. In addition, leakage tests performed on a regular basis could be replaced by a CBM system. To this end, sensor technology must be installed for monitoring purposes and for preventing severe degradation by avoiding harmful operating conditions [101]. However, restoration or discard tasks will likely still need to be addressed through conventional scheduled maintenance activities.

We are aware that, due to the unresolved certification procedure, CBM will most likely only be used as a supplement to the existing maintenance at the beginning and will not immediately lead to a reduction in scheduled maintenance tasks. Alternatively, it could initially be used primarily for fault identification and localization to reduce troubleshooting [16,17], and to make fuel cell maintenance more efficient. In this study, we aim to roughly examine the potential influence of a CBM or BIT implementation on the labor scope in maintenance. For this purpose, we consider these strategies for supporting the RCM approach in preventive maintenance to be as comprehensive as possible. Therefore, we assume that the scheduled operational and functional checks of the fuel cell, the sensors, the control unit, the converter, the rectifiers, and the circuit breakers, as listed in Table 14, can be omitted, since they are replaced by CBM or BIT systems.

However, we do not take into account any maintenance implications of the actual CBM units or cost increases due to the development and implementation of these systems. Based on these assumptions, we compare the two fuel cell systems once again in terms of the resulting scheduled labor scope, as shown in Table 15. Looking at the total values for this scenario throughout the entire aircraft life, this results in 281.6 MH for the LT-PEMFC and 336.7 MH for the SOFC. We therefore expect that a very extensive CBM implementation could reduce the labor scope of the LT-PEMFC by approximately 26 % and of the SOFC by approximately 24 %. Even though the most extensive maintenance activities cannot be completely avoided, the implementation of CBM is expected to significantly reduce the number of scheduled maintenance tasks.

5.3. Limitations of the analysis

Due to the novelty of the investigated fuel cell systems and the approach based on statistical values, the estimation of the scheduled maintenance scope is subject to some uncertainty. Since this analysis is based on generic system designs, the results may differ for a different architecture or design.

For statistical values such as MTBF and MTTF, the underlying failure mode is usually not specified. In addition, most of the operating conditions are unknown in this study, even though they can have a major influence on the degradation and failure characteristics of a component. Statistical failure data also vary depending on the intended application and the conditions under which they were obtained. Therefore, our long-term goal is to focus on specific values from the aviation sector, which are not yet available in sufficient quantities. Some of the differences in the results between the two systems could also be attributed to the uncertainty of these statistical data, as values for LT-PEMFC are mostly derived from aviation and heavy-duty applications, while values for SOFC originate primarily from marine and energy applications. In general, the TRL of the system has a major influence on when a fuel cell stack is likely to be replaced. The TRL for fuel cells in aviation is lower than for ground applications, with SOFCs in aviation having a lower TRL than LT-PEMFC systems. However, the influence of technological maturity on the replacement frequency of the fuel cell stacks was not examined in detail in our study, so this estimate is subject to corresponding uncertainties. To address these uncertainties regarding statistical failure data, we take mean values and standard deviation into account for the interval estimation. In future analyses, the replacement frequency should also be considered taking into account degradation intensities depending on specific influencing parameters.

Most intervals for the maintenance categories inspection & functional check, restoration, and discard are determined using Eq. (6), with an estimated probability of success threshold of $P_s = 95\%$. Considering the strict safety requirements in aviation, we assume that this estimate is sufficient for the current level of detail of this study. However, the applied method for deriving maintenance intervals relies on a simplified, conservative approach. As described in detail in Section 4.2.2, a much more comprehensive method is currently being developed, in which different probability of success values are determined for different tasks, failure severities, and component classes. To systematically establish this relationship, extensive empirical data from operational aviation are used. This would enable the transition from a conservative approach to a data-driven, multi-factorial approach. The dependencies mentioned have not yet been taken into account in our present study, therefore,

Table 14
Overview of omitted maintenance tasks for taking into account potential CBM or BIT approaches.

Subsystem	Fuel cell	Task code	Task description
Power generation (see Table 6)	LT-PEMFC	FNC	Functional check of the LT-PEMFC including EIS as well as an inspection
		FNC	Functional check with a calibration to be carried out if necessary for the voltage sensor
		FNC	Functional check with a calibration to be carried out if necessary for the current sensor
	SOFC	FNC	Functional check of the SOFC including EIS as well as an inspection
		FNC	Functional check with a calibration to be carried out if necessary for the voltage sensor
		FNC	Functional check with a calibration to be carried out if necessary for the current sensor
Reactant delivery and conditioning (see Table 7)	LT-PEMFC	FNC	Functional check with a calibration to be carried out if necessary for the pressure sensor on anode and cathode side
		FNC	Functional check with a calibration or cleaning to be carried out if necessary for the humidity sensor
		FNC	Functional check with a calibration to be carried out if necessary for the hydrogen sensor
	SOFC	FNC	Functional check with a calibration to be carried out if necessary for the pressure sensor on anode and cathode side
		FNC	Functional check with a calibration to be carried out if necessary for the temperature sensor anode and cathode side
		FNC	Functional check with a calibration to be carried out if necessary for the hydrogen sensor
Thermal management system (see Table 8)	LT-PEMFC	FNC	Functional check with a calibration to be carried out if necessary for the temperature sensor
Power conditioning (see Table 9)	LT-PEMFC	FNC	Functional check of the controller
		FNC	Functional check of the converter
		OPC	Operational check of the fuel cell circuit breaker
	SOFC	FNC	Functional check of the controller
		FNC	Functional check of the converter
		OPC	Operational check of the fuel cell circuit breaker
		OPC	Operational check of the turbine circuit breaker
		FNC	Functional check of the rectifier

Table 15
Labor scope of the fuel cell by considering BIT and CBM systems throughout the entire lifetime of the aircraft.

Subsystem	Lubrication & servicing		Operational & visual check		Inspection & functional check		Restoration		Discard		Sum	
	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]	LT-PEMFC [MH]	SOFC [MH]
Power generation	–	–	–	–	–	62.6	–	42.0	14.6	14.6	14.6	119.2
Hydrogen and air supply	–	–	20.5	20.5	52.5	36.5	126.0	126.0	27.6	27.6	226.6	210.6
TMS	0.8	–	–	–	12.0	–	–	–	27.6	–	40.4	–
Power conditioning	–	–	–	–	–	–	–	–	–	–	–	–
Sum	0.8	–	20.5	20.5	64.5	99.1	126.0	168.0	69.8	42.2	281.6	329.8

the application of a constant probability of success threshold should be regarded as preliminary indication.

Furthermore, there is a lack of long-term studies on the operation and maintenance of fuel cell systems. Given the development of these systems, the results of the few studies that do exist may be questionable. In addition, no reference data on SOFCs for utilization in transportation could be found. Ideally, the values determined here would be validated using data from practical applications. However, this is only partially the case, leading to conservative assumptions. For all estimates in this work, such as certain intervals or the scope of maintenance tasks, the validity of MPDs from legacy aircraft as a reference should be critically evaluated. Although these values take aviation-specific criteria into account and are therefore a reliable reference, it is often difficult to determine whether the corresponding components and tasks are comparable to our use case.

In general, the results presented here should be regarded as a preliminary trend based on the assumptions and simplifications made within the assessment. The absolute values should not be taken as being definitive or universally applicable; rather, they must be viewed within the context of this study, and reassessed as conditions change. For instance, they strongly depend on the final system design. Due to these uncertainties, the results of our study primarily serve to derive relative trends between the two fuel cell systems.

6. Conclusion

In order to identify the fuel cell system with the highest potential for aircraft operations from a maintenance perspective, we have conducted a comparative maintenance analysis for SOFC and LT-PEMFC systems in this work. To this end, we have defined the two system architectures

and identified methodologies for estimating the scheduled maintenance scope at a preliminary design stage. We followed the RCM approach and applied the MSG-3 analysis to specify the scheduled maintenance tasks for both systems. We then applied various metrics to estimate the intervals of the corresponding tasks and the associated labor requirements. Extensive statistical failure data and references from real aircraft operations were taken into account. Based on these results, we conducted a preliminary assessment of the material demands and labor scope for both systems. In addition to the pure scheduled maintenance scope, we also evaluated the two fuel cell systems in terms of operational and safety-specific implications. Finally, we considered the broad impact of CBM and BIT systems on the maintenance characteristics of these systems.

Our comparison of the two fuel cell systems suggests that the LT-PEMFC has a higher complexity and a greater number of components, primarily due to the more comprehensive temperature management system. In this context, the LT-PEMFC is also expected to have a higher material demand due to discard tasks. On the other hand, the SOFC involves more demanding maintenance requirements, resulting in the specification of high-frequency and labor-intensive tasks. In terms of operational aspects, the systems also show a clear difference, as the SOFC entails significant restrictions in this regard due to its high operating temperature and the requirements for the temperature gradient. Above all, unscheduled maintenance activities could lead to significant disruptions in operation, which is why the LT-PEMFC is likely to have better planning capabilities for the time-critical aviation sector. However, taking into account safety-related aspects, the SOFC appears to be less safety-critical, since leakage may lead to hydrogen accumulation and deflagration to a smaller extent. For both systems, we suggest a major maintenance activity as part of the legacy aircraft C-check, which is to be conducted off-wing at an interval of 5,000 FH.

Based on this comparative analysis, we can identify the following three key findings.

- The SOFC system is likely to have higher maintenance requirements, and we therefore expect 10 % more maintenance tasks and a 15 % higher labor scope throughout the lifetime of the aircraft than the LT-PEMFC.
- From an operational perspective, the LT-PEMFC appears to be more feasible, as the maintenance of SOFCs involves long downtime due to the high operating temperatures.
- Replacing some scheduled maintenance activities with the implementation of CBM and BIT approaches could lead to noticeable reductions in the labor scope, with reductions of up to 26 % expected for the LT-PEMFC and up to 24 % for the SOFC.

However, these results should initially be regarded as trends and must be interpreted within the framework of the assumptions made in our study. They strongly depend on the specific fuel cell design and the underlying statistical reliability data.

All these conclusions can contribute to the selection of a suitable fuel cell system for aircraft applications. By providing MRBR-like tables for each fuel cell system, that include all scheduled maintenance tasks to be conducted, the respective interval, and the labor scope, we provide trends and valuable information for future maintenance estimates and planning for these systems. Our study can also provide useful input for assessing the economic and environmental impact of these systems in a more comprehensive analysis. Finally, these estimates and can be taken into account by designers and researchers in order to support the development of technically feasible fuel cell systems in aviation from a maintenance perspective.

Based on this work, we recommend that future developments for fuel cells in aviation focus on prolonging their service life. Future studies should consider specific operational conditions, such as temperature, pressure, vibration, shock, and fouling, as well as their impact on durability and reliability. Furthermore, due to the regulatory restrictions of the RCM approach, condition monitoring and predictive maintenance are important research topics with high potential for improving aircraft maintenance, especially for novel technologies such as fuel cells. In this regard, possible requirements must be defined through appropriate regulations and certification processes.

CRediT authorship contribution statement

Moritz Pick: Writing – original draft. **Jan-Alexander Wolf:** Conceptualization, Data curation, Writing – review & editing. **Rebecca Rodeck:** Writing – review & editing. **Gerko Wende:** Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Exemplary MSG-3 analysis

See Tables A.16 and A.17.

Appendix B. Reliability data

See Table B.18.

Table A.16
Exemplary demonstration of the MSG-3 process for determining the failure effect category.

Component	Failure effect description	Is the occurrence of a functional failure evident to the operating crew during the performance of their normal duties?	Does the functional failure or secondary damage resulting from the functional failure have a direct effect on operating safety?[1]	Does the functional failure have a direct adverse effect on operating capability?[1]	Does the combination of a hidden functional failure and one additional failure of a system related or back-up function have an adverse effect on the operating safety?[2]	Failure effect category
Circuit breaker	Possible spurious component function; possible defect of components; possible fire	No	–	–	Yes	Safety (non-evident)
Heat exchanger	Insufficient preheating of the fuel cell; reduction of efficiency	Yes	No	No	–	Operational (evident)

1– It follows the evident path.
2– It follows the non-evident path.

Table A.17
Exemplary demonstration of the MSG-3 process for determining the maintenance task.

Component	Failure cause description	Failure effect category	Lubrication & servicing	Operational & visual check[1]	Inspection & functional check	Restoration	Discard	Combination of any of the tasks[2]
Circuit breaker	Circuit breaker fails to break the current	Safety (non-evident)	Not applicable	Operational check if the circuit breaker gets triggered by high current	Not effective	Not applicable	Not effective	Not effective
Heat exchanger	Fouling of the heat exchanger	Operational (evident)	Not applicable	–	Not effective	Cleaning task for the heat exchanger	Not effective	–

1– Only applicable to non-evident failures.
2– Only applicable to safety related failures.

Table B.18
List of MTBF and MTTF used fo the maintenance interval determination.

Component	MTBF and MTTF [h]	Reference
LT-PEMFC	29,240	[78]
	8,900	[12]
	10,000	[90]
	20,000	[11]
	20,000	[77]
	18,182	[47]
	20,000	[14]
SOFC	80,000	[83]
	45,000	[80]
	40,000	[81]
	40,000	[82]
	39,857	[79]
Fuel cell control unit	244,653	[89]
	30,000	[90]
	189,200	[91]
	204,082	[92]
Turbine	6,173	[79]
	62,905	[102]
Turbocharger	1,138,794	[103]
	427,048	[103]
Generator	65,574	[79]
	28,100	[104]
After burner	142,857	[79]
	100,000	[105]
Heat exchanger/intercooler	123,762	[106]
	57,803	[79]
Coolant pump	22,910	[106]
	16,722	[107]
	82,932	[108]
	41,667	[109]
	40,000	[110]
Hose/pipes	171,527	[107]
	71,448	[111]
Pressure regulator	278,552	[109]
	555,556	[92]
	769,231	[92]
Shutoff valve	4,878,049	[109]
Purge valve	4,878,049	[109]
Recirculation pump (gas pump)	18,000	[112]
	41,667	[109]
Electric evaporator	175,193	[78]
	21,089	[102]
	244,653	[89]
Pressure transmitter	1,369,863	[109]
Temperature transmitter	3,773,585	[109]
	3,030,303	[91]
	588,235	[107]
Hydrogen transmitter	724,638	[109]
Current transmitter	1,550,388	[91]
	500,000	[107]
Voltage transmitter	27,624,309	[91]
	555,556	[107]
Humidity transmitter	284,698	[103]
Flow switch (bypass valve)	370,370	[109]
Air Filter	100,000	[108]
Compressor (air pump)	21,978	[109]
	110,011	[76]
	26,508	[108]
Humidifier	384,615	[47]
Converter	282,965	[113]
	333,333	[114]
	58,411	[78]
	434,783	[47]
	489,306	[89]
	210,526	[106]
Rectifier	3,180,490	[89]
	1,960,032	[115]
Circuit breaker	244,653	[89]
	508,466	[116]
	79,264	[117]
	26,421	[117]
Wires	1,468,429	[89]
	10,000,000	[107]
	23,624,073	[115]
	4,728,738	[115]
Hotbox/insulation	244,653	[89]
	21,089	[102]
Ventilation	841,188	[115]
	50,000	[118]

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(continued).

Data availability

No data was used for the research described in the article.

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