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Beyond flight operations: Assessing the environmental impact of aircraft maintenance through life cycle assessment

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ABSTRACT

As the aviation industry strives to minimise its environmental footprint, understanding the full life cycle impacts, including maintenance, becomes essential for sustainable development. This paper addresses the critical research gap in the environmental assessment of aircraft maintenance by conducting a comprehensive life cycle assessment based on an Airbus A320 aircraft. By combining a top-down check-level analysis and a detailed examination of the aircraft manufacturer's maintenance planning document, this study provides significant insights into the environmental implications of maintenance activities. The check-level analysis provides a general overview, while the analysis of the maintenance planning document delves into individual tasks, enabling the identification of components with the highest ecological impacts. This research emphasises the importance of including aircraft maintenance activities in life cycle assessment studies and provides valuable guidance for researchers, industry practitioners, and policy makers in prioritising sustainability measures and enhancing the environmental performance of aircraft throughout their life cycle.

1. Introduction

The aviation industry is under significant pressure to address and reduce the human-induced greenhouse gas emissions (EASA et al., 2019). This requires a thorough analysis of environmental impacts to identify where, for example, the potential for climate change mitigation is particularly high. A LCA is thereby a commonly used method that comprehensively evaluates the environmental impact of an asset or process throughout its entire life cycle, including manufacturing, use phase, and end-of-life. Compared to other environmental assessment methods, LCA has the advantage of not focusing on just one environmental impact, such as the carbon or water footprint. Instead, it looks at different aspects, avoiding potential burden shifting in environmental impact and providing a more comprehensive picture of the overall environmental impact (Hauschild et al., 2018).

While many LCA studies in aviation focus on the environmental impacts of flight operations, the ecological aspects of aircraft maintenance have not been sufficiently examined. This may be attributed to the perceived low environmental impact of maintenance in the aircraft life cycle, which does not seem to justify the considerable effort required for data collection and modelling (Krieg et al., 2012). However, aircraft maintenance is a highly complex discipline, with a variety of different types and categories of maintenance tasks performed at specific intervals. For instance, a conventional aircraft undergoes more than 2,000 different maintenance events per year,[1] most of which are differentiated by their activities. Without these essential maintenance events, the highly coordinated air travel would not be possible today, as ensuring the airworthiness of aircraft is paramount for their safe operation, contributing to their prolonged service life and sustained efficiency. According to a report by Airbus (2015), Maintenance, Repair, and Overhaul (MRO) activities were considered to be of significant importance for both short and long life cycles. This relevance also stems from the direct impact on the product during its in-service life, despite its associated environmental impact. These contrasting positions complicate the understanding of the true ecological impact of aircraft maintenance and the identification of critical factors.

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[1] The annual average number of maintenance events was calculated based on Aircraft Commerce (2006) with an average utilisation of 2,500 flight hours per year and a flight hour/flight cycle ratio of 1.5 of an Airbus A320.

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Nomenclature

Acronyms

APU	Auxiliary Power Unit
ASK	Available Seat Kilometre
ATA	Air Transport Association
EIO-LCA	Economic Input-Output Life Cycle Assessment
FC	Flight Cycle
FETP	Freshwater Ecotoxicity
FH	Flight Hour
FSNC	Full-Service Network Carrier
GPU	Ground Power Unit
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
LCA	Life Cycle Assessment
LCC	Low Cost Carrier
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LLP	Life Limited Part
LYFE	Life Cycle Cash Flow Environment
MM	Minerals and Metals
MPD	Maintenance Planning Document
MRO	Maintenance, Repair, and Overhaul
ODP	Ozone Depletion Potential

This research paper aims to address the research gap in the environmental assessment of scheduled maintenance activities using the case study of an Airbus A320 aircraft. To address the complexity of aircraft maintenance and achieve a comprehensive assessment of MRO in general, a combination of two approaches is used. A so-called check-level approach provides a top-down overview of the entire maintenance process that can be contextualised within the overall life cycle of the aircraft. The checks represent aggregated maintenance packages that do not list detailed tasks but provide general insights into an entire set of MRO activities. In addition, an in-depth analysis is employed in order to gain a more thorough understanding of individual tasks using the aircraft manufacturer's MPD. This approach provides very detailed information on specific tasks and therefore gives a more thorough perspective on the environmental impact. The study aims to gain a comprehensive understanding of the associated impacts of aircraft maintenance as a basis for evaluating and developing both sustainable maintenance technologies and strategies. Moreover, the developed approach enables the environmental maintenance assessment of novel aircraft technologies at a detailed level — even if they are still in the conceptual phase.

The paper is structured as follows: First, an overview of maintenance activities and current approaches for environmental assessment is given as a foundation for the combined LCA methodology that is described subsequently. After that, we describe the generation of the Life Cycle Inventory (LCI) and analyse the Life Cycle Impact Assessment (LCIA) results regarding the main drivers of the ecological implications to identify the possible reduction potentials. A sensitivity analysis then shows the influence of operational factors, such as the aircraft usage profile, on the environmental impact. Therefore, two different flight schedules, with short- and long-haul flights, and contrasting airline business models with different maintenance management practices are compared. The final conclusion and outlook summarise the results and provide information on how this approach can contribute other LCA practitioners when evaluating, for example, new aircraft technologies in the future.

2. Fundamentals

2.1. Aircraft maintenance

MRO is an essential process that includes technical, administrative, and management measures throughout the lifespan of an aircraft, with the aim of restoring or maintaining it in a functional state to achieve its required function (Deutsches Institut für Normung e.V., 2018). The aviation industry places great emphasis on maintenance as it ensures the continued airworthiness of the aircraft and restores the level of safety and reliability established during design and manufacture.

A distinction is drawn between routine and unscheduled maintenance. Unscheduled maintenance is a procedure that is not part of the regular planning process and is primarily performed in response to detected system abnormalities due to the unpredictability of certain technical wear processes. An unplanned maintenance activity can be triggered either by condition-based monitoring or by damage-related events that require immediate attention and repair (Meissner et al., 2021). Scheduled maintenance, on the other hand, involves pre-planned inspections and servicing of aircraft components at specific intervals to ensure continued airworthiness. In aviation, the maintenance strategy plays a crucial role in determining the timing and scope of required maintenance activities. The following parameters, either individually or in combination, can determine the maintenance interval according to the "whatever occurs first" principle (Hinsch, 2019):

- The time a component has already been in operation (in days, months, or years);
- The number of FHs;
- The performed Flight Cycles (FCs), whereby a cycle begins with the take-off of the aircraft and ends after landing;
- The aircraft's operational environment (influenced by factors such as high or low outside temperatures, humidity levels, and the amount of dust and salt in the air).

They help to detect and prevent fatigue, environmental wear, and degradation. Especially for scheduled maintenance, it is crucial to classify aircraft components according to one or more of these threshold parameters and to ensure that they are replaced or repaired before their limit is reached. However, once established, these intervals can be adjusted as operational experience is gained and the maintenance philosophy evolves (Aircraft Commerce, 2016). Such adaptations can have lasting effects on the maintenance estimation of technologies that are either yet to be introduced or for which there is limited practical experience (Meissner et al., 2023).

2.1.1. Line, base, and shop maintenance

Commercial aircraft maintenance classically encompasses line, base, and shop maintenance (Hinsch, 2019). Line maintenance involves regular tasks, such as visual inspections or minor repairs, to ensure aircraft airworthiness, performed on a daily or weekly basis at either an operator's home base or at outstations. The line maintenance contractor works closely with flight crews to resolve reported issues and to ensure the aircraft is in optimum condition for the next flight, with a focus on rapid turnaround times to meet scheduled departures. In contrast, base maintenance occurs less frequently, typically every few months or years, and involves comprehensive inspections and repairs that require the aircraft to be temporarily taken out of service. Base maintenance usually takes place in hangars, providing a controlled environment, good lighting conditions, and special equipment (Klußmann and Malik, 2018). The frequency and extent of shop maintenance operations, on the other hand, are closely linked to safety-critical components with defined lifetime constraints, known as Life Limited Parts (LLPs) (IATA, 2020; Ackert, 2015), being for example part of the jet engines or landing gears. The overhaul of these components is carried out in specialised facilities with certified technicians, while the aircraft often receives a replacement component for continuing its service during this time.

2.1.2. Maintenance checks

The execution of maintenance activities follows pre-defined intervals that serve as a guideline for the bundling of individual maintenance activities. These maintenance packages can be divided into different levels or letter[2] checks (e.g., A, B, C), with each letter defining a specific scope of maintenance activities (Wagner, 2009). A- and B-checks are part of line maintenance, usually shorter, and performed on a regular basis, while the C- and D-checks are more complex and performed less frequently. They are considered as part of base maintenance. The scope and frequency of these checks may vary based on aircraft type, manufacturer specifications, and regulatory requirements. In addition, aircraft maintenance includes a number of non-letter checks, such as pre-flight, transit, daily, and weekly checks, which contribute significantly to the overall airworthiness and operational readiness of the aircraft, especially within shorter time horizons. All checks are interrelated; for example, the weekly check includes the daily check tasks, thus eliminating the need for a daily check on a day when a weekly check has already been performed (Aircraft Commerce, 2006; Hinsch, 2019; Lapesa Barrera, 2022).

2.1.3. Maintenance planning document

The MPD contains the aircraft manufacturer's recommended maintenance program, providing essential planning information to individual aircraft operators for specifying their own maintenance schedules. In addition, the MPD provides detailed information on the execution of recurring maintenance tasks. This includes, for example, the exact description of the tasks, information on the average time required for execution (excluding time requirements for materials, resources, and document procurement), references to technical publications, access instructions, and the equipment to be used. In addition, each task is assigned a dedicated task code, which main description can be found in the MPD itself (Airbus, 2018).

2.2. Life cycle assessment of aircraft maintenance

In the field of environmental impact research in aviation, considerable attention has been given to conducting comprehensive LCAs of specific aircraft types or making comparisons between different aircraft configurations, modes of transport, and materials. The aspect of aircraft maintenance has typically been considered within the broader context of flight operations and assessed using various LCA methodologies, although in most cases in a simplified manner.

Several researchers (Chester and Horvath, 2009; Chester, 2008; Facanha and Horvath, 2006; Aihara et al., 2007) have used the Economic Input-Output Life Cycle Assessment (EIO-LCA) method to investigate the environmental impact of an aircraft's life cycle including maintenance activities. This method establishes a link between the economic performance of a specific industry and its corresponding environmental metrics. However, there are inherent uncertainties due to the lack of a dedicated aircraft maintenance sector within the EIO-LCA methodology (Chester, 2008). In the analysed studies, maintenance is approached in different ways. Aihara et al. (2007) combined maintenance with vehicle production, resulting in only a 1% contribution to CO_2 emissions in passenger transport. In the study by Facanha and Horvath (2006), the aircraft's end-of-life was additionally merged with maintenance activities and accounts for a total life cycle share of around 20%. Only Chester and Horvath (2009) presented separately assessed results showing that MRO activities account for approximately 2% of the total life cycle environmental impact when using the EIO-LCA method.

Other studies have used specialised LCA databases, such as the ecoinvent database (Lopes, 2010; Lewis, 2013; Bicer and Dincer, 2017; Su-Ungkavatin et al., 2023; Cox et al., 2018). These databases, though, solely offer data on airport maintenance and not specifically on aircraft maintenance, making them unsuitable as a basis for comparison in this study. Schäfer (2018) calculated the environmental impact of maintenance based on the energy consumption of individual processes and spare parts. The results of this streamlined LCA were only presented in terms of CO_2 emissions and represent merely 0.26% of the overall life cycle impacts. Other studies have examined the energy consumption of airports (Johanning and Scholz, 2013, 2014; Jordão, 2012; Sohret et al., 2016). Yet, without the ability to differentiate the consumed resources due to maintenance versus other airport or logistic operations, it is difficult to accurately calculate the environmental impact of maintenance with its wide range of tasks that can vary according to aircraft type, age, operating conditions, and other factors. Jordão (2012) further post-processed his findings by incorporating the calculated electricity consumptions with maintenance costs based on aircraft block hours. This approach results in an environmental share of 20% of the total life cycle, which is relatively high compared to other studies in the literature, but consistent with the share of direct maintenance costs in the total aircraft service life. Yet, the feasibility of a direct translation from costs to ecological factors remains a subject of debate (Eurocontrol, 2020).

Alternative approaches such as weight calculations (Fera et al., 2020), exergy analysis (Atılgan et al., 2013), or consideration of carbon pricing (Edwards et al., 2016) have been employed to assess maintenance impacts. However, none of these methods allows a detailed examination of specific maintenance aspects. Due to the lack of specific data on aircraft maintenance activities (Rupcic et al., 2023), it is not possible to assess the environmental impact on, for example, the component-level. As a result, some comparative studies have intentionally excluded the analysis of the environmental impact of maintenance activities (Vidal et al., 2018; Calado et al., 2019; Liu, 2013; Fabre et al., 2022). These studies assume that there is little variation in maintenance activities between aircraft types or due to different materials and configurations. Krieg et al. (2012), for example, argues that the relatively small environmental impact of maintenance does not justify the considerable effort required to collect and model the data. Conversely, a recent study by Barke et al. (2023) emphasised the critical role of maintenance, in particular the replacement of components, in environmental considerations during the use phase of the aircraft. The authors also highlighted the potential increase in maintenance effort, especially for emerging propulsion concepts, due to the shorter lifetimes of new technologies. In the study, especially batteries and fuel cells have a particularly large impact due to component replacements in the impact categories climate change, mineral resource depletion, and fossil resource depletion. The application of novel technologies and processes in maintenance, such as additive manufacturing for spare parts or repair technologies, should be further explored in terms of energy, material, and water requirements (Madhavadas et al., 2022; Keivanpour et al., 2017). In order to gain a better understanding of the impact of new technologies on the environment, maintenance must be given a more significant role (Rolinck et al., 2021).

This literature overview highlights the existing challenges and uncertainties associated with accurately capturing and analysing the specific environmental impacts of maintenance activities. While previous research has used a variety of methods and approaches to assess these impacts, a detailed and comprehensive approach that allows a granular analysis of MRO activities is currently lacking. Furthermore, it is often very difficult to compare results from the existing literature, as aviation maintenance is often not considered as a whole or is examined in varying levels of detail due to different boundary conditions and data availability.

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[2] It should be noted that the labels of the checks can vary, but many maintenance organisations and airlines use the letter checks mentioned above. The B-check is no longer used for most commercial aircraft, due to changes in maintenance practices and advances in aircraft technology (Klußmann and Malik, 2018; Wagner, 2009).

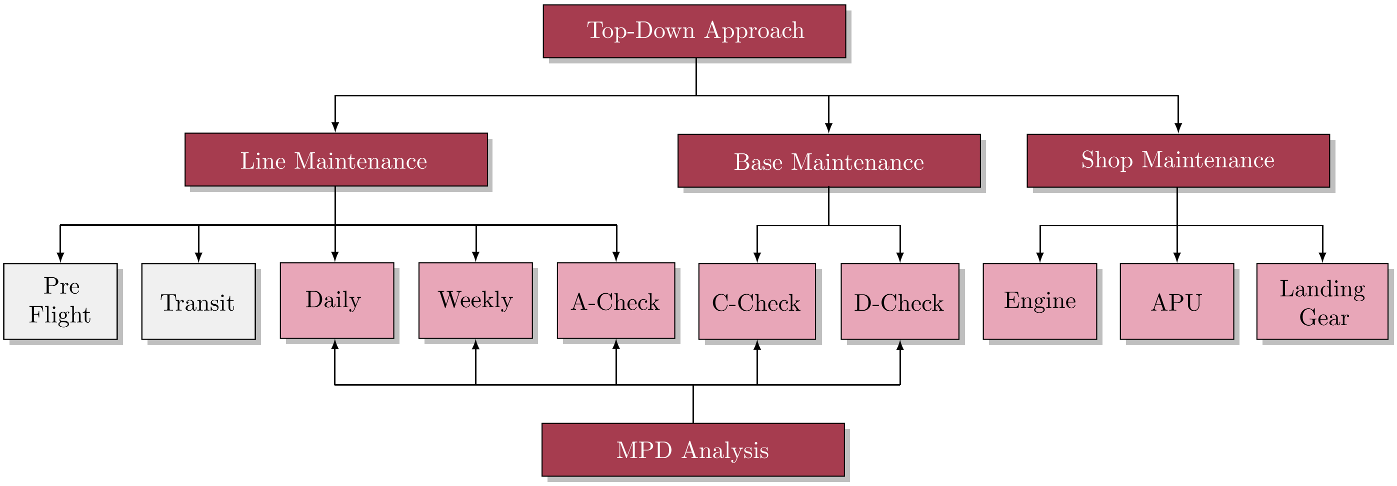

Fig. 1. Overview of the combined methodology for the assessment of aircraft maintenance.

3. Method

In the following section, an LCA approach, as defined by ISO 14040/44 standards (Deutsches Institut für Normung e.V., 2021a,b), is presented to investigate the environmental impacts of aircraft maintenance activities. Along with a description of the methodology, the goal and scope, including the system boundaries and functional units, are described. In addition, we provide a more detailed description of how the LCI is generated, both based on the maintenance checks and from the MPD.

3.1. Combined top-down and in-depth analysis

The methodology of this study is designed on the basis of two data sources. Firstly, a check-level approach is used to examine the overall maintenance processes. In this approach, maintenance activities are initially categorised into line, base, and shop maintenance, and then further aggregated. Line and base maintenance are then subdivided into checks, while shop maintenance focuses on the maintenance of large components. Secondly, to complement the top-down approach and provide a more in-depth analysis of single tasks, a detailed examination of the MPD is conducted. In addition, the MPD can be used to assign specific tasks to so-called ATA chapters. The ATA chapter system serves the unification and standardisation of aviation documents and subdivides groups and subgroups of aircraft components.

This integrated approach provides a more robust and comprehensive understanding of the ecological implications of aircraft MRO than previous studies. A schematic representation of this methodology is provided in Fig. 1. Pre-flight and transit checks routinely involve only visual checks by the pilot or flight crew and are therefore excluded from the analysis as they have no direct environmental impact. The MPD only includes tasks that are part of line and base maintenance (daily to D-check). Shop maintenance activities are also not included in the MPD.

3.2. Goal and scope definition

The goal and scope phase is an important step in the LCA, in which the purpose and the methodology of the study are defined. It sets the goals of the assessment and defines the system boundaries to focus on the relevant environmental impacts and activities.

3.2.1. Use case

The Airbus A320 was chosen as a use case due to the large data availability and the broad knowledge and experience in the industry resulting from its many years of operation. The DLR-internal discrete-event simulation framework named Life Cycle Cash Flow Environment (LYFE), which simulates the life cycle of an aircraft based on flight schedules and maintenance intervals, was used as a foundation to calculate the frequency of individual maintenance tasks over the whole lifetime of one aircraft. In addition, economic and environmental assessments can be applied to provide insight into operational and design trade-offs. In this study, an aircraft's service life of 25 years based on the International Civil Aviation Organization (2019) was assumed. A detailed description of how LYFE works can be found in Rahn et al. (2022) and Pohya et al. (2021). In the present study, flight schedules from Burschyk et al. (2023) were used to represent different operational scenarios. These consisted of schedules for different airline business models (so-called Full-Service Network Carriers (FSNCs) and Low Cost Carriers (LCCs)),[3] each with a short-haul and a long-haul schedule. The baseline for this study was the FSNC schedule with mainly short-haul flights and an annual average of 2,200 FH and 1,930 FC, which also reflects the average usage profile of an Airbus A320 (Aircraft Commerce, 2016).

The maintenance intervals and downtimes used in this analysis are shown in Table 1 and are based on multiple sources (Aircraft Commerce, 2006; Hinsch, 2019; Aircraft Commerce, 2001; University of Westminster, 2008; Ackert, 2012). For simplification, the FHs for the components, such as the jet engine or the Auxiliary Power Unit (APU), were set equal to those of the aircraft. Apart from the engine shop visit, engine maintenance also included the replacement of certain LLPs, which have their own maintenance intervals. These LLPs are single components, such as discs or shafts, which in turn are parts of component modules. For simplicity, only the modules and their respective lifetimes were considered here, which consisted of the fan (30,000 FC), the compressor (20,000 FC), the high-pressure turbine (20,000 FC), and the low-pressure turbine (25,000 FC) (Aircraft Commerce, 2006; IATA, 2020). For simulation purposes, the exchange of LLPs was included in the closest shop visit.

The study primarily examined preventive, planned, and routine maintenance activities. This focus was chosen due to the high unpredictability and variability associated with unplanned and non-routine

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[3] An FSNC is an operator that offers a comprehensive range of services, including multiple destinations, different cabin classes, and additional amenities to meet the needs of leisure and business travellers. LCCs differ from FSNCs in that they typically operate with shorter turnaround times and therefore offer more flights per day.

Table 1
Initial input for every maintenance check including durations and intervals (merged from Aircraft Commerce (2006), Hinsch (2019), Aircraft Commerce (2001), University of Westminster (2008), Ackert (2012)).

Check	Duration	Interval
Daily	2 h	1 day
Weekly	3 h	7 days
A-Check	10 h	450 FH
C-Check	168 h	5,000 FH
D-Check	672 h	6 years
Engine Shop	672 h	9,000 FH
APU Shop	336 h	7,000 FH
Landing Gear Shop	1,009 h	10 years

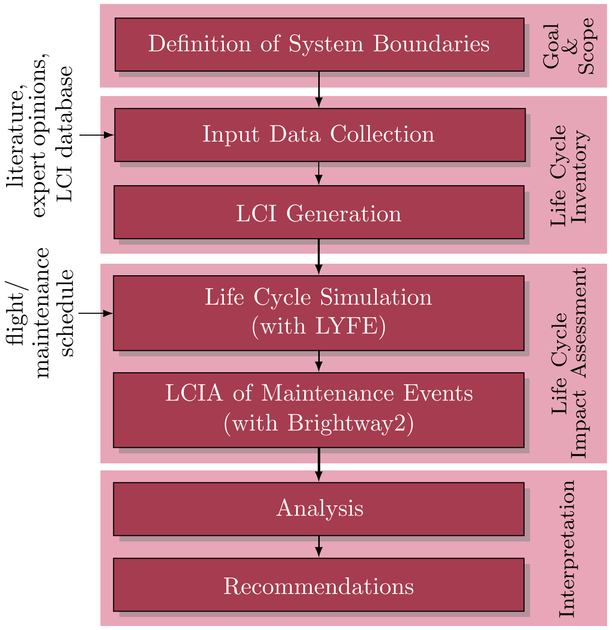

Fig. 2. Process flow of the LCA approach.

maintenance, which could significantly increase uncertainties. The LCA was conducted using the ecoinvent version 3.9.1 database, adhering to the allocation, cut-off by classification system model (Wernet et al., 2016) and the EF 3.0 LCIA methodology (Fazio et al., 2018). Fig. 2 illustrates a process flow diagram of the LCA approach. After defining the system boundaries, input data was collected from various sources, such as the ecoinvent database, scientific literature, and expert opinions, to form the basis of the LCI. The LYFE tool was then applied for the life cycle simulation. Therefore, specific input data was required, including maintenance and flight schedules, as well as additional aircraft-related information. This step was critical for a full understanding of all maintenance activities and their occurrence over the aircraft's lifetime. Following, the execution of the LCIA with the open-source python-based framework Brightway2 (Mutel, 2017) was performed to evaluate the environmental impact of these maintenance events. The final step was to interpret the results in order to assess the overall environmental impact of aircraft maintenance and identify areas for improvement. Additionally, the four standardised steps of the LCA are depicted on the right side of the figure.

3.2.2. System boundaries

The maintenance activities were mainly carried out in Germany, or where no further data available, in Europe.[4] The consideration of the location was critical in determining transport routes and logistical factors. The assessment excluded the end-of-life phase, and, therefore, waste treatment and recycling, due to the high complexity of this phase and the already very data-intensive inventory phase. Similarly, products and processes that have a secondary role in their use were not considered. For instance, the production of lamps, when assessing the energy consumption, or rags used for cleaning were not taken into account. Additionally, the manufacturing and maintenance of tools and equipment, as well as the transportation of products within the maintenance site, were excluded from the analysis. Moreover, impacts related to the maintenance staff, such as personal waste or commuting to the site, were not considered. These interrelations are illustrated in Fig. 3.

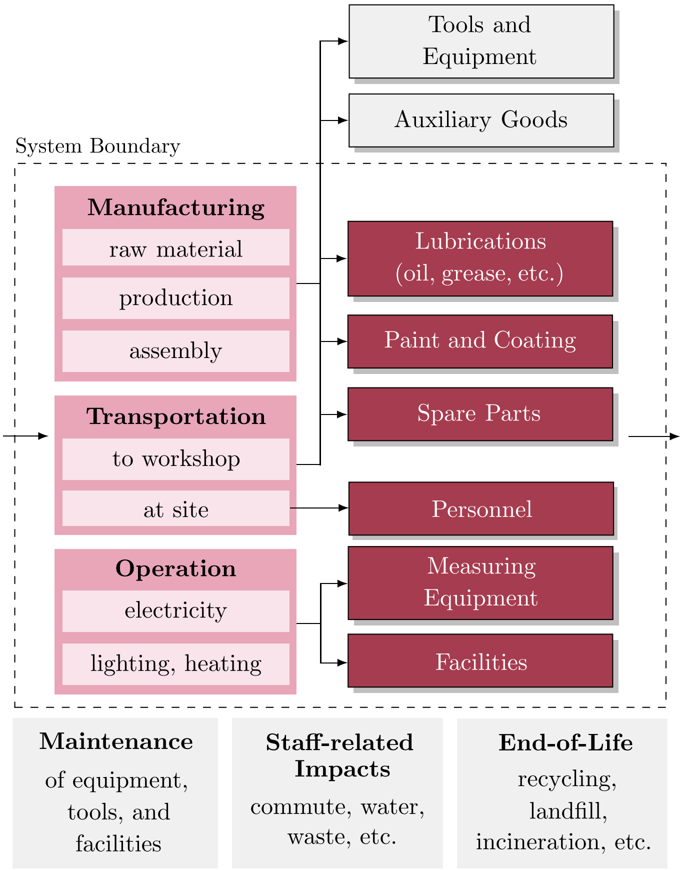

Fig. 3. Overview of the system boundaries of the presented study.

The assessment results are presented in both absolute terms and normalised according to the functional units *per FH* and *per Available Seat Kilometre (ASK)*. This approach facilitates comparisons of LCA outcomes across various operational scenarios.

3.3. Generation of the inventory

A preliminary analysis was required to create the inventory. The starting point was the analysis of the individual checks, which provided an overall view of the ecological implications of scheduled maintenance activities in general. The MPD analysis was then used to assess individual tasks in detail, but did not cover certain aspects such as the energy consumption of the hangar and equipment. This was supplemented by the results of the check analysis to provide a complete inventory. The generated LCI was compiled from a variety of literature sources, including brochures, training materials, and expert interviews. Due to the large number of references and to keep the paper concise, not all referenced sources are listed in this article. Instead, all sources, along

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[4] An overview of the used datasets and selected locations can be found in the supplementary information.

with additional details are provided in the supplementary material to this article.

The collected foreground data is linked with background data from the ecoinvent database. The ecoinvent database serves as a comprehensive collection of LCI data commonly utilised in LCAs and environmental evaluations; however, it is not specialised for aircraft-specific applications or materials. For instance, specialised aviation alloys, which also hold significance in MRO activities, are currently not covered in the database. To improve the quality of the background data in this study and illustratively enhance the methodology, an adapted dataset was employed for the titanium alloy Ti64, which is one of the most commonly used materials in the spare parts of engines, landing gears and APUs. The composition of the Ti64 alloy, along with the manufacturing energy consumption of approximately 60 kWh per kilogramme of a produced titanium component, is derived from Denkena et al. (2016) and the Office of Energy Efficiency & Renewable Energy (2017).

Inventory from maintenance checks

For the check-level approach, it was important to consider the main activities of each check in more detail. Pre-flight and transit checks performed at the gate involve only visual inspections and the correction of out-of-scope repairs, which have no apparent environmental impact (Aircraft Commerce, 2006). The daily check, on the other hand, includes visual inspections and engine oil servicing, which require the use of ground support equipment, such as a Ground Power Unit (GPU) and the transport of specialised personnel to the aircraft's location on the apron. Weekly and A-checks also include visual inspections and are typically carried out in a hangar, where the main contributor to their environmental impact is the operation of the facility. Base maintenance, which includes both C- and D-checks, is much more work-intensive than line maintenance inspections and requires the use of ground support equipment and electricity for the Heating, Ventilation, and Air Conditioning (HVAC) of the hangar. Beyond that, special equipment is used and parts of the aircraft are dismantled for inspection. In the case of workshop visits, certain components are first taken to a repair shop where they are cleaned and overhauled. An average transport distance of 500 km was assumed based on German maintenance locations and their average distances to the largest international German airports (Luftfahrt-Bundesamt, 2023). Cleaning and replacement of parts with a limited service life were calculated on the basis of the component dimensions. In addition, workshop activities such as lighting or special equipment were also taken into account.

This approach is illustrated by the example of the A-check, which was carried out on average every 450 FH (Aircraft Commerce, 2006) and took about ten hours. According to Hinsch (2019) and Augustine et al. (2007), the standard A-check includes typical tasks such as changing filters, checking and lubricating important systems (hydraulics of control surfaces, landing gears, etc.), and checking emergency equipment. The quantity of replaced filters, consisting of synthetic material fibres, was estimated at an average of 1 kg with the help of expert interviews and engineering guesses, while the oil change was calculated at 3.15 kg per check (Lufthansa Technik A.G., 1999). We assumed that the A-checks took place in the hangar, meaning the aircraft had to be towed into the hangar with the help of a towing vehicle. The energy consumption of the facility was calculated based on aircraft size and its proportional use. Energy consumption values for the hangar were determined from literature data (Ekoplan Energieberatung, 2023), giving annual values of 280,000 kWh for lighting and 246 kWh/m^2 per year for HVAC, scaled to the aircraft area (2500 m^2 for an Airbus A320 (Airbus, 2020)). An additional GPU supplies the aircraft with electrical energy when the engines are not running to operate the electrical systems on board, such as lighting, air conditioning, avionics, and other electrical equipment. Due to data availability, this study assumed that the GPU was diesel-powered (Airport Cooperative Research Program, 2012). With this approach, an initial inventory could be generated for all recurring maintenance checks, which was mainly limited to routine tasks such as oil changes and energy consumption of equipment and facilities. The full overview of all maintenance tasks with a list of used references can be found in the supplementary material. Information on maintenance tasks at the component-level was then supplemented with the help of data from the MPD.

Table 2
Overview of all MPD task codes and activities (Airbus, 2018).

Task code	Name	Activity (other than hangar and equipment)
CHK	Check	–
DET	Detailed inspection	–
DIS	Discard	Replacement of components
FNC	Functional check	Transportation to workshop
GVI	General visual inspection	–
LUB	Lubrication	Application of lubricants
OPC	Operational check	Transportation to workshop
RST	Removal/Restoration	Cleaning of components transportation to workshop
SDI	Special detailed inspection	Use of special measurement equipment transportation to workshop
SVC	Drain, Servicing, Replenishment	Exchange of fluids draining of components
VCK	Visual check	–

Inventory from maintenance planning document

In addition to the check-level LCI, the MPD was used to identify detailed maintenance actions. The MPD included checks with a minimum interval of three days, covering tasks from daily up to D-check. As the Airbus A320 MPD applies to all aircraft of the Airbus A320 family (e.g., A319, A321, or A320neo), it was first necessary to filter out all tasks related to the Airbus A320ceo with the CFM56-5 engine and modified wing that was considered in this study. The so-called *Applicability* could be used to specify further aircraft specifications that needed to be defined to avoid duplication of tasks, resulting in a total number of 1762 relevant tasks. Each task in the MPD was marked with a so-called task code, which provided sufficient information about the type of maintenance activity and could thus be used to bundle tasks. Further information on task codes could be obtained from the MPD (Airbus, 2018). Table 2 provides an overview of all task codes, their description, and the type of the derived environmental impact.

For the tasks with the codes *CHK*, *DET*, *GVI*, and *VCK*, the energy consumption of the facilities was found to be the main influencing factor since these tasks only require personnel and mechanical equipment. Repair task codes, such as *OPC*, *FNC*, *SDI*, and *RST*, were analysed individually, taking into account the mass and number of components, the transport distances to workshops, and the number of tasks per life cycle. Additionally, the *RST* tasks revealed a significant impact on cleaning tasks, with 91% of the measures being related to cleaning with compressed air and a water–alcohol mix (Sturwold, 1987). For the *SDI* tasks, the use of specialised measurement equipment, such as endoscopes, borescopes, and other battery-operated devices, was identified as the main source of environmental impact (Civil Aviation Authority, 2023). The *LUB* and *SVC* tasks involve the exchange of lubricants and fluids, and for the *DIS* tasks, the mass, material, and number of components to be replaced were determined. Expert knowledge was required to determine the type, density, and amount of lubricants and

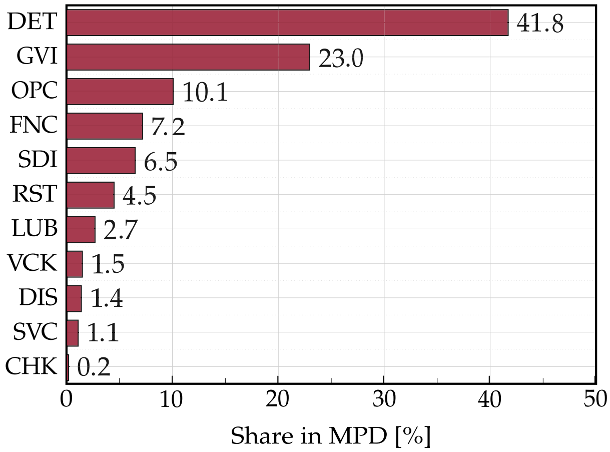

Fig. 4. Share of task codes in the number of maintenance tasks in the MPD.

fluids used in the *LUB* and *SVC* tasks. The bar chart in Fig. 4 gives an overview of the proportion of task codes in the MPD.

An example is given with task number 212141-01-1, which describes the replacement of filter elements that are part of the air conditioning recirculation system (ATA 21). The material of the filter element is polyester (Conrad, 2023) and a mass of 3 kg (Modstore, 2023) could be determined from the literature, which was then used to calculate the environmental impact of this discard task using the ecoinvent database. To calculate the total number of task executions over the life cycle of the aircraft, the lowest threshold or interval (in calendar time, FH, or FC) that applied in this study was first determined. The men hours and the number of mechanics could be combined to determine the duration of the task. Yet, the impact of the equipment or operation could not be considered at this stage as it was not possible to distinguish how many MPD tasks are performed in parallel. To take this into account, the number of men hours was presented as a percentage of the total maintenance time and compared with the equipment and hangar operating values from the check-level assessment. For the subsequent calculation, a factor of three has been used for the realistic number of men hours, based on expert opinions and information from Aircraft Commerce (2006). The results of this detailed approach could then be evaluated holistically at the ATA chapter-level.

4. Results

This section first presents the LCI, which has been compiled from the maintenance documents and can be fully accessed in the supplementary material. The results of the LCIA calculations are then presented in Section 4.2 for climate change and a selection of other impact categories. Finally, Section 4.3 provides a sensitivity analysis and shows the relative importance of maintenance activities in relation to the operational profile.

4.1. Life cycle inventory

The inventory consists of both the maintenance checks and the individual tasks in the MPD. Table 3 shows an example of the A-check (described in Section 3.3), including the relevant standard activities of this check and excluding some routine activities, such as visual tasks that are performed by the flight crew without equipment.

In addition, there were a number of activities that are not a direct requirement of the aircraft manufacturer but are nevertheless regularly performed by operators or MRO providers. Aircraft repainting and cabin refurbishment are typically carried out every six to eight years, which corresponds to the D-check interval. A regular engine wash is performed about every three months (Rahn et al., 2021) and a tyre replacement is conditionally carried out approximately every 250 FC for the nose wheel and every 350 FC for the main wheel (Aircraft Commerce, 2017). For the sake of simplicity and because the study did not distinguish between nose and main landing gears, tyre replacements as well as engine washes were integrated into the A-check. The full LCI including references is provided in the supplementary material.

Table 3
Extract from the inventory covering the activities related to the A-check.

Activity	Influencing factor	Quantity per check
Discard of filters	Synthetic material fibres	1 kg
Engine oil servicing	Engine oil	3.15 kg
Ground power unit	Diesel	30 l/h
Aircraft towing	Electricity	10 kW
Hangar operations	Electricity	76.7 kWh

Furthermore, the tasks listed in the MPD were thoroughly processed and categorised on the basis of their respective task codes. A selection of these datasets, including references, is provided in the supplementary material. These datasets comprises the full LCI data for all maintenance checks, together with a comprehensive analysis of the inventory for MPD tasks. As an representative example, we have only included tasks related to the air conditioning system (ATA 21), due to the extensive nature of the MPD and the fact that it is not publicly available. Whenever references are made to energy consumption associated with the hangar and equipment, the data is derived from the MPD's man hours and the top-down approach.

4.2. Life cycle impact assessment results

The results of the study provide a detailed analysis of the environmental impacts of aircraft maintenance activities at the check- and component-levels. This research highlights the specific areas where environmental improvements can be targeted. The following section presents the key findings derived from the LCA.

4.2.1. Global warming potential

The initial results focus on the impact category of climate change and the associated GWP, expressed in kilogrammes of carbon dioxide equivalents (kgCO_2-eq.), which is the most commonly used indicator as it allows the aggregation of greenhouse gas emissions from different origins. A selection of other impact categories of the LCIA EF 3.0 methodology and their results are also highlighted. An overview of all results can be found in the supplementary data.

Results for maintenance checks

An overview of all checks over the whole life cycle is shown in Fig. 5. After simulating the aircraft's operational life cycle with LYFE, the total environmental impact of maintenance events was aggregated for each year and plotted in the bar chart. There were significant differences between the years, particularly in connection with base maintenance and workshop visits. The greatest environmental effects occurred in the years 6, 12, 18, and 24, when the major D-check took place and the cabin was replaced. The sum of line maintenance checks remained almost constant each year throughout the aircraft's life. The daily check had the highest environmental impact among all checks, with more than 543.4 tCO_2-eq, accounting for 34.9% of the total impact. This was followed by the D-check, which included hangar operations, cabin refurbishment, aircraft repainting, and other activities, and resulted in a total impact of over 20.2%, causing a total environmental impact of 313.7 tCO_2-eq. The C-check had the lowest overall environmental impact of all the checks with only 5.0% and about 77.8 tCO_2-eq.

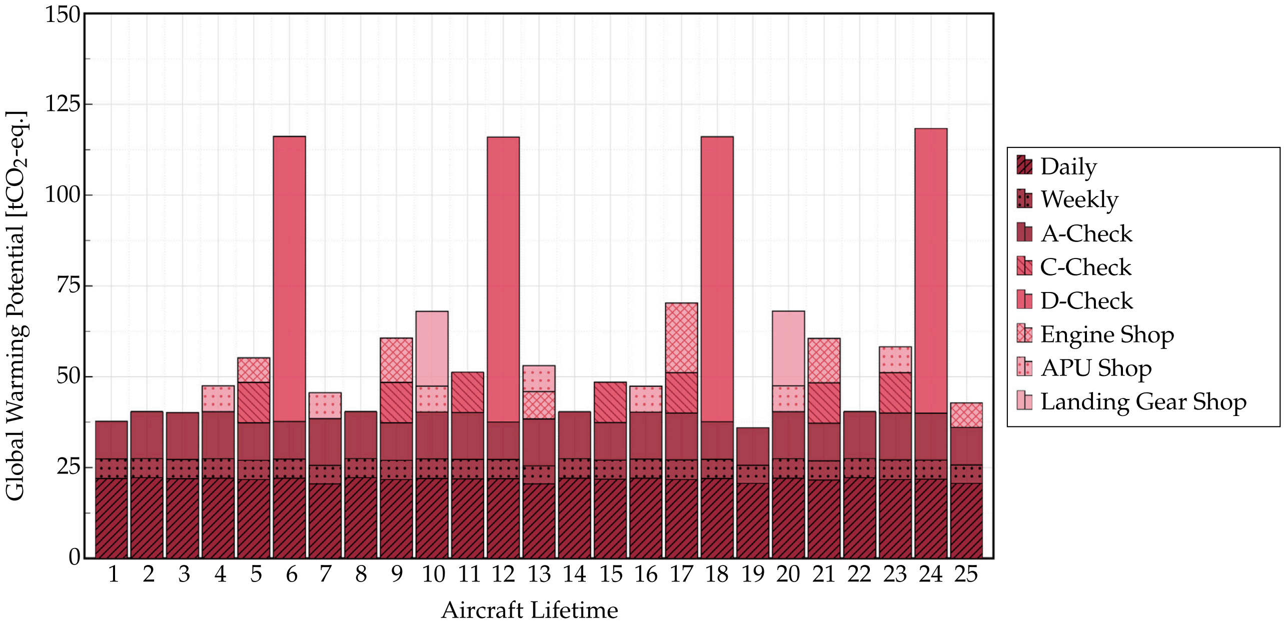

Fig. 5. Distribution of maintenance-related environmental impact over the whole life cycle of the aircraft.

Table 4
Overview of the environmental impact of maintenance types in terms of their GWP in relative, absolute, and normalised (in FH) values.

Maintenance type	GWP		
	[%]	[tCO_2-eq.]	[$kgCO_2$-eq./FH]
Line maintenance	64.1	996.1	18.1
Base maintenance	25.2	391.5	7.1
Shop maintenance	10.7	167.2	3.0

An overview per maintenance type can be seen in Table 4. Line maintenance accounted for about 64.1% in total, followed by base maintenance with 25.2%. Workshop visits accounted for a relatively small share of maintenance with only about 10.7% and a total of 167.2 tCO_2-eq. Looking at the environmental impact per flown hour, this ranged between 3.0 $kgCO_2$-eq./FH (for shop maintenance) and 18.1 $kgCO_2$-eq./FH (for line maintenance).

Results for component groups

The MPD uses the ATA chapter assignment to facilitate the systematic categorisation of maintenance tasks into specific component groups. Tasks that cannot be assigned to a single chapter are referred to as zonal tasks. Engine wash, tyre replacement, cabin refurbishment, and shop activities were allocated to the corresponding ATA chapters as appropriate. Aircraft repainting was excluded from the categorisation due to its association with several component groups. Fig. 6 provides a visual representation of the distribution of environmental impacts across all ATA chapters. However, not all ATA chapters are included in the MPD, as some component groups cannot be assigned maintenance tasks.

The figure illustrates the distribution of environmental impacts, with the landing gear having the highest impact of 198.0 tCO_2-eq., mostly due to regular tyre replacement and landing gear shop visits. Scaled to the functional unit, this amounts to about 3.6 $kgCO_2$-eq./FH. Similarly, the power plant and APU also contributed to the overall impact, with 150.8 tCO_2-eq. and 50.6 tCO_2-eq., respectively. Equipment and furnishing accounted for a significant portion of the environmental impact with 132.9 tCO_2-eq. and 2.4 $kgCO_2$-eq./FH, mainly because of the cabin replacement, which is typically performed during a D-check. Other notable component groups included air conditioning, electrical power, fuselage, and wings, which all had significant man hour allocations in the MPD. Overall, about 61.1% of the environmental impact of maintenance activities was attributed to aircraft systems, while tasks related to structural components represented 22.6%. Maintenance tasks at the power plant accounted only for 16.3% of the total impact.

Results for main environmental drivers

In this section, a deeper analysis of the LCA results was carried out to gain a more thorough understanding of the environmental impact of MRO. This detailed examination of each maintenance task and its accumulated impact over the entire life cycle has enabled the identification of the main contributors with the greatest ecological impacts. The results provide valuable insights for stakeholders in the aviation industry to highlight the biggest reduction potentials and to develop and implement effective measures to reduce their environmental footprint. Fig. 7 provides an overview of the identified main drivers of the ecological implications and their share of the overall impact.

Energy consumption for the operation of hangars and equipment accounted for approx. two thirds of the total environmental impact, making it the largest contributor. An average German energy mix was used as a baseline for the assessment of electricity consumption. The discard and replacement of components, including filter elements and major spare parts, contributed 21.0% of the impact. Other factors, such as the operation of test benches that follow specific maintenance procedures (especially for engines) or the repainting and cleaning of components represented only a minor share of the total ecological impact.

4.2.2. Other impact categories

Below, a detailed examination of additional impact categories at check-level is presented to gain a more detailed understanding of the environmental implications. Here, we focus specifically on three additional impact categories: Freshwater Ecotoxicity (FETP), Ozone Depletion Potential (ODP), and Minerals and Metals (MM). The results of all other impact categories can be found in the supplementary data.

A direct comparison (Fig. 8) shows that, although the daily check had the highest impact in the impact category of FETP, it did not dominate in the other categories. In particular, in the ODP, the D-check emerged as the most significant contributor, mainly due to the extensive cabin replacement and repainting activities. In contrast,

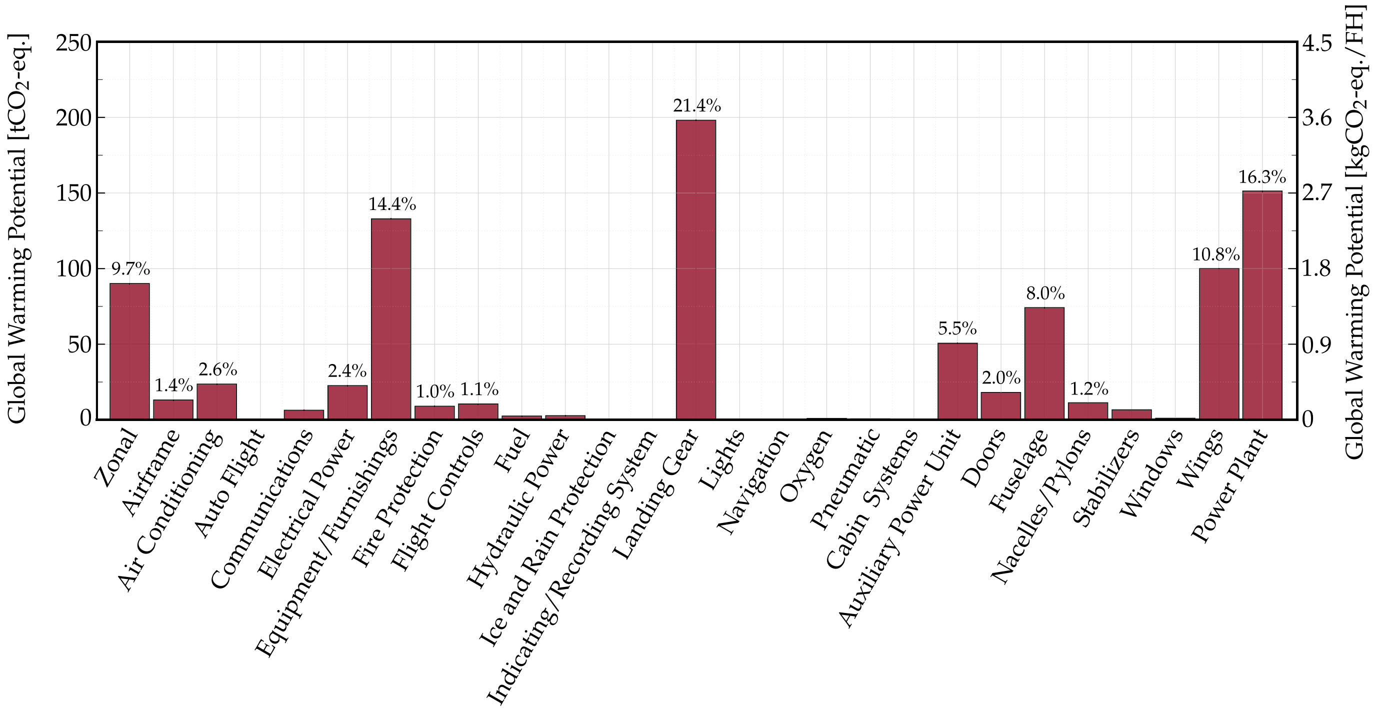

Fig. 6. Comparison of the environmental impact of maintenance tasks for different ATA chapters in terms of absolute values and normalised per flight hour. The share of the total impact is additionally indicated for each component for which the contribution accounts for more than 1.0% of the total share.

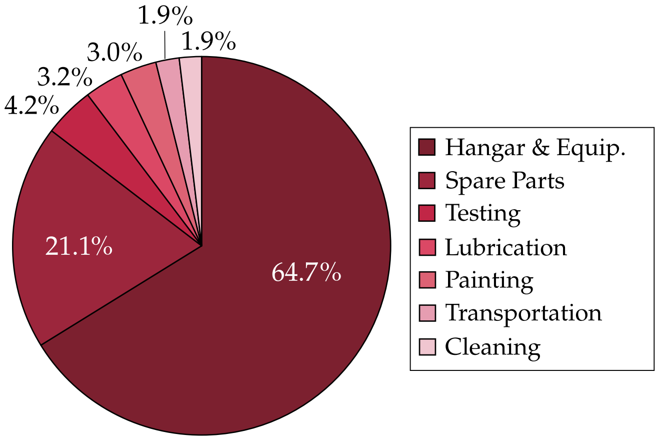

Fig. 7. Distribution of the main drivers of the ecological implications.

both A-check and D-check had a significant impact on the MM category, largely due to the frequent tyre changes and the aforementioned D-check activities. In comparison, the C-check had the lowest environmental impact of all line and base maintenance checks. When looking at the combined environmental impact, line maintenance emerged as the dominant contributor in almost all categories, with the exception of ODP. The impact varied significantly across the categories, ranging from 33.7% to almost 80.0%. Conversely, shop maintenance generally had the lowest impact in the analysis, with the highest contribution of just over 19% in the MM category. This notable impact in MM was mainly because of the extensive use of spare parts and related materials.

4.3. Scenario analysis

The frequency of maintenance tasks performed is strongly influenced by the operator's usage. Different operational scenarios (Burschyk et al., 2023) can be used to represent various ways in which the Airbus A320 class aircraft is used. The reference flight profile consisted mainly of short-haul flights with an average distance of approximately 741 km. In addition to this, another flight plan with long-haul flights (with an average distance of approx. 1,286 km) was analysed. The short-haul and long-haul schedules were simulated using two different business models (FSNC and LCC) resulting in a total of four different utilisation scenarios. Table 5 provides an overview of these scenarios, including the corresponding FC and FH per year.

Table 5
Overview of utilisation scenarios from Burschyk et al. (2023).

Scenario	Business model	Flight profile	FH/Year	FC/Year
Reference	FSNC	short-haul	2,200	1,920
Scenario 1	LCC	short-haul	2,530	2,219
Scenario 2	FSNC	long-haul	2,800	1,421
Scenario 3	LCC	long-haul	3,320	1,885

Fig. 9 shows the GWP in tCO_2-eq. for each check in each scenario, accumulated over a full lifetime of 25 years. In our analysis, the D-check was performed at fixed intervals of six years, resulting in no deviations compared to the reference. Similarly, the daily and weekly checks showed minimal variation as they followed fixed calendar intervals. The minor differences between them were due to their inclusion in other checks, resulting in slightly more or less frequent execution. The pattern was different when looking at tasks linked to FHs and FCs. If an operator mainly operates long-haul flights, maintenance tasks connected to flown hours will be performed more frequently, resulting in a greater environmental impact. This was evident in the case of the A-check, C-check, and certain tasks during the engine and APU shop visit. Conversely, since the landing gear shop maintenance was only twice in the aircraft's lifetime, there was no variation between the different scenarios.

To facilitate comparison between flight scenarios, the results were normalised in terms of FHs and ASK. The results for each scenario are shown in Table 6. The reference case (FSNC with short-haul) had, even though having the lowest total environmental impact, the highest ecological implication per flown hour with 28.3 $kgCO_2$-eq./FH, closely

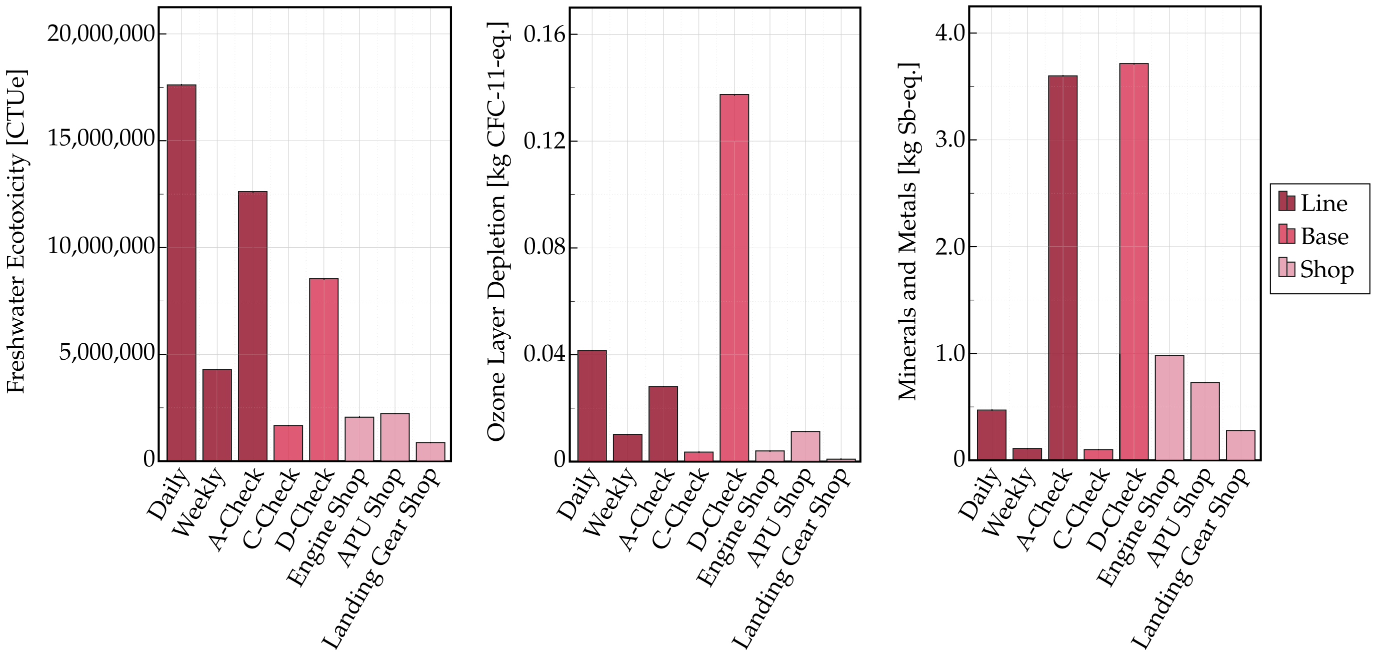

Fig. 8. Comparison of LCA results for the impact categories Freshwater Ecotoxicity (left), Ozone Layer Depletion (middle), and Minerals and Metals (right). The bars are divided by colour into line, base, and shop maintenance.

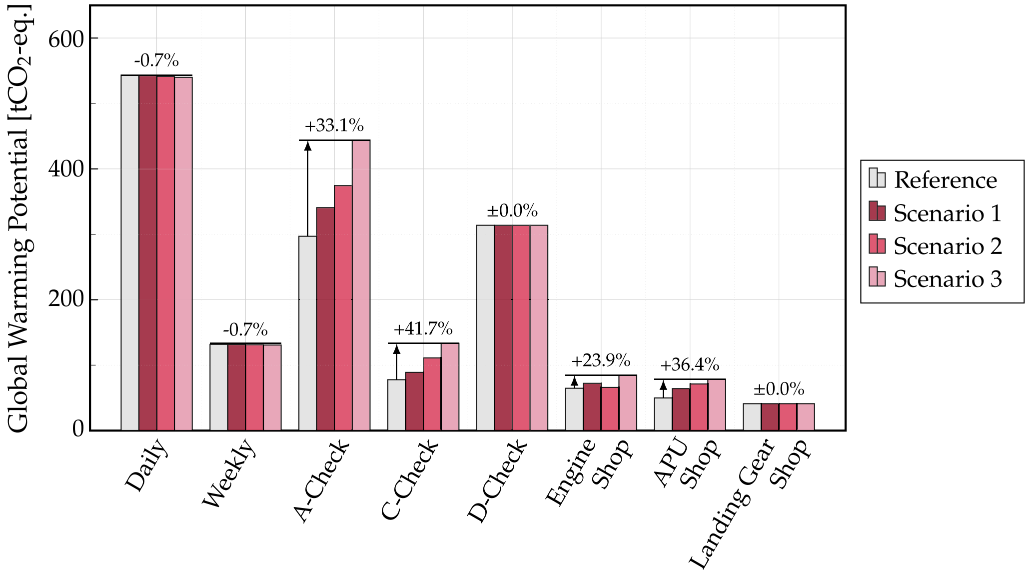

Fig. 9. Overview of the ecological impact (given in GWP) including the largest deviation from the reference case for each scenario (Reference: FSNC/short-haul; Scenario 1: LCC/short-haul; Scenario 2: FSNC/long-haul; Scenario 3: LLC/long-haul).

followed by LCC with a short-haul flight profile. Both flight scenarios with long-haul schedules led to lower environmental impacts, with 24.2 kgCO_2-eq./FH for the FSNC and 21.9 kgCO_2-eq./FH for the LCC. The higher environmental impact of the maintenance with short-haul flight schedules was mainly due to the significantly higher number of FCs over the life cycle of the aircraft and the more rapid degradation of LLPs.

In addition, the environmental value is provided in ASK in the last column of Table 6. The ASK normalises the environmental impact per flown kilometre per passenger seat over the lifetime of the aircraft. This unit is often used in environmental assessments of aviation (Rahn et al., 2022) and is therefore suitable for comparison with other studies. It also facilitates comparison with other modes of transport, such as cars or trains, as it includes the maximum number of passengers in the environmental value.

Table 6
Overview of results for the considered flight scenarios.

Scenario	GWP		
	[tCO_2-eq./lifetime]	[kgCO_2-eq./FH]	[kgCO_2-eq./ASK]
Reference	1,555	28.3	2.9 x 10^{-4}
Scenario 1	1,635	25.8	2.7 x 10^{-4}
Scenario 2	1,692	24.2	2.5 x 10^{-4}
Scenario 3	1,815	21.7	2.2 x 10^{-4}

5. Discussion

The results of this study provide insights into the environmental impact of aircraft maintenance and give an overview of potential improvements at check-level as well as component-level. Despite their relatively short duration, daily checks were found to have the largest overall impact due to their daily occurrence and contribute alone to more than one third of the total environmental impact in terms of GWP. Introducing longer service intervals for these kinds of maintenance activities may be an effective strategy for more sustainable MRO practices and could significantly reduce the environmental impact. In addition, the D-check, including cabin removal and repainting, was shown to be another major contributor to the overall impact. Future research efforts could focus on developing more durable furniture and coatings, and exploring the use of sustainable materials. The same is true for A-checks, where regular tyre replacements due to safety reasons introduce a big ecological impact because of the re-manufacturing of these tyres.

Our analysis at ATA chapter-level identified specific components that offer significant potential for further research, especially in complex systems, such as the landing gear or power unit. This is consistent with studies that have looked at the economic impact of maintenance for individual aircraft components. Using a cost-estimating model for aircraft maintenance, Fioriti et al. (2018), for example, showed that the landing gear (ATA 32) is by far the component with the highest maintenance cost at over 76 $/FH, being consistent with the present study.

A closer look at the main drivers of the ecological impact shows that more than 66% of the ecological footprint is contributed by the electricity required for lighting and heating or cooling the maintenance hangar and equipment. This represents a large reduction potential, e.g., by supplying the MRO facilities with renewable energy sources or by reducing energy consumption in general. In addition, due to the scarcity of aircraft materials and the large number of spare parts needed throughout the life of an aircraft, MRO providers as well as aircraft manufacturers should be encouraged to focus on research into extending the life of these components and improving the recyclability of materials, which could bring significant economic as well as environmental benefits.

However, there are several limitations in this study. Firstly, the limited number of comparable studies highlights the need for further research to validate the results and gain a better understanding of maintenance activities in general. In addition, this study only considered scheduled and routine maintenance for the calculation of environmental impacts. Other studies evaluating aircraft life cycle maintenance indicate that the economic costs of unscheduled maintenance are significantly higher, by a factor of up to 2.5 times, than scheduled maintenance (Wang, 2021). Future studies should therefore include additional unscheduled factors. In addition, the workshop visit activities were challenging to assess due to limited data availability, despite their significant contribution to the overall impacts. The ecological impact of shop visits could account for a much higher proportion of the overall impact than calculated here. Estimations were made when considering certain materials and masses as well as the intervals between different maintenance activities. Maintenance checks or tasks in the MPD usually have not one but several thresholds that the operator or MRO provider has to consider. This may lead to variations in the occurrence of tasks and checks.

The detailed MPD analysis is also not applicable on its own, as it does not include all maintenance activities and does not provide information on the operation of the hangar or the equipment, as the planning and clustering of simultaneous maintenance activities is the responsibility of the operator. In addition, various assumptions had to be made in order to model the LCI. For example, the choice of maintenance location has a significant impact on the environmental impact, as it depends largely on the regional energy mix. The lack of aircraft-specific data in conventional LCI databases introduces further uncertainties, which we partially addressed by introducing an aerospace specific titanium alloy. Future studies could focus on providing more aerospace specific LCI data to enhance existing LCI databases. Depending on the chosen LCIA, the results and their subsequent implications may vary, posing additional challenges, particularly when disseminating the results to different stakeholders.

6. Summary and outlook

This study presents a novel approach for conducting a comprehensive LCA of aircraft maintenance, using the case study of an Airbus A320 aircraft. Compared to other studies in the literature, this research method allows a much higher level of detail to be obtained. The results of the combined top-down approach and detailed analysis of the MPD provide valuable insights into the environmental impacts of aircraft maintenance and contribute to a more holistic understanding of the aircraft life cycle. While the check-level analysis provides a broad perspective on the overall environmental impact of maintenance, the detailed MPD analysis enables a more granular understanding of individual tasks. By breaking down maintenance activities into components and component groups (based on ATA chapters), this method enables the identification of components with the highest environmental impact associated with maintenance. The adaptability of this approach to different aircraft types and new maintenance tasks is a major strength. For the comparison with existing aircraft, the integration of existing or advanced MRO activities and intervals as well as multiple flight schedules into the LYFE model allows the simulation of environmental impacts over any given lifespan. In addition, a detailed analysis of new technologies, including their durability and shortcomings, enables the development of appropriate maintenance tasks. These findings can be used to target improvements in environmental performance when evaluating new aircraft concepts.

Although the impact of aircraft maintenance on the overall environmental footprint during the aircraft life cycle accounts is rather small (about 1%), it remains a crucial of aircraft operation. As aircraft technologies evolve to reduce in-flight emissions, the share of maintenance in the overall environmental footprint will grow. This is especially true for aircraft currently under research, which are both zero-emission in the use phase and are projected to have higher maintenance demands (Meissner et al., 2023). Therefore, transparency of the ecological footprint of individual MRO operations is crucial to establish a baseline against which innovations in maintenance can be evaluated. Additionally, maintenance is integral to regulatory compliance and ecological responsibility across the aircraft's life span. We note that advancing maintenance practices to minimise aviation's environmental footprint must be closely aligned with economic and social considerations that were out of scope in the current work.

Overall, this study highlights the importance of including aircraft maintenance activities in LCA studies, including the incorporation of specific aircraft materials or processes. The approach presented here provides valuable insights for researchers, industry practitioners, and policy makers to prioritise sustainability measures and improve the environmental and economic performance of aircraft throughout their life cycle. For future work, it is intended to adapt the developed methodology to other aircraft types — in particular to new aircraft concepts, such as hydrogen-aircraft. A study of the economic and environmental trade-offs could therefore be of particular interest.

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CRediT authorship contribution statement

Antonia Rahn: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Melissa Schuch:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Kai Wicke:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Benjamin Sprecher:** Writing – review & editing, Supervision. **Clemens Dransfeld:** Writing – review & editing. **Gerko Wende:** Funding acquisition.

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.

Data availability

Data is shared in supplementary material.

Appendix A. Supplementary data

Supplementary data to this article can be found online at

- **Life cycle Inventory:** Complete life cycle inventory at maintenance check- and component-level.
- **Life Cycle Impact Assessment Results:** Additional results at maintenance check- and component-level for all impact categories and scenarios.

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142195.

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