DLR-IB-MO-HF-2021-22

Life Cycle Assessment Methodologies for Aircraft Maintenance

Literature Review

Antonia Rahn

Deutsches Zentrum
für Luft- und Raumfahrt

Document Properties

Title	Life Cycle Assessment Methodologies for Aircraft Maintenance
Subject	Literature Review
Institute	DLR-MO
Compiled by	Antonia Rahn
Checked by	Kai Wicke
Release by	Kai Wicke
Date	26.11.2021
Version	1.0

Contents

Abbreviations

CFRP Carbon Fibre Reinforced Polymer

CI Cost Index

DOC Direct Operating Cost

EIO-LCA Economic Input-Output Life Cycle Assessment

GHG Greenhouse Gas

GSE Ground Support Equipment

LCA Life Cycle Assessment

LCC Life Cycle Costing

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

MPD Maintenance Planning Document

MRO Maintenance, Repair, and Overhaul

PKM Passenger-Kilometre

pLCA Process-based Life Cycle Assessment

1 Introduction

Environmental factors are playing an increasingly important role in today's society and politics. Currently, aviation is responsible for about 3.6 % of the total human-caused Greenhouse Gas (GHG) emissions [1]. However, with the steady growth of air transportation, the environmental impacts and challenges for all stakeholders in the aviation sector are expected to increase steadily.

The objective of this literature review is to identify methods for conducting a holistic environmental impact assessment of aircraft. A commonly used method in this context is Life Cycle Assessment (LCA), which considers and analyses different life cycle phases of a product or product system according to certain rules. Apart from the aircraft's production and end-of-life, the focus of this literature review will be on aircraft maintenance, as this is where currently the greatest uncertainties exist. In order to achieve the overall aim of this literature review, the report is divided into three steps:

The first part deals with the general basics that are necessary for a comprehensive understanding of this report. This involves explaining the key information of aircraft maintenance and subsequently providing the characteristics of LCA. Thereby, the individual phases of the LCA are considered and special types are described. The basic chapter is concluded with the strengths and limitations of an LCA.

The second part is the actual literature review in which existing methods for the ecological assessment of aircraft maintenance are identified and evaluated. A detailed discussion of the individual search terms introduces the research itself. Subsequently, the publications that appear most relevant are described and summarised.

In the third part, the information gathered from the literature search is considered in a research gap analysis. This can serve as a basis for further research and summarises the findings of this report.

2 Basics

This literature review is intended to focus primarily on the environmental impact of aviation maintenance over the entire life cycle of an aircraft or fleet. In the beginning, this chapter covers the basics of aircraft maintenance and gives an overview of main characteristics that can have an impact on maintenance - and thus on the environment. This is followed by an introduction to LCA, which is one of the most frequently used methods for environmental assessment of products or product systems.

2.1 Basics of Aircraft Maintenance

According to DIN-Norm 31051 [2], maintenance is described as

> *» a measure to preserve and restore the target condition and to determine and assess the actual condition.«*

It includes servicing, inspection, and repair of the aircraft. The reliability of every operating aircraft must be ensured with absolute priority and the aircraft availability must be guaranteed as a key factor of profitability for the airline. The respective scope of maintenance programs is defined for each aircraft type in form of scheduled maintenance work packages and unscheduled maintenance events covering necessary tasks and intervals. This includes national requirements, specific airline and aircraft manufacturer specifications, aircraft delivery configurations, and reliability issues in existing aircraft. [3, 4]

Aircraft maintenance can be divided into base and line maintenance. Line maintenance is generally carried out at a line station. Routine tasks such as cleaning, refuelling, or light inspections are performed at short intervals, while more time-consuming tasks are scheduled at the next base station if possible. Line maintenance tasks are limited both in terms of manpower and facilities. Base maintenance, on the other hand, is usually performed at the airline's home base station. Compared to the departure-oriented line maintenance, they are fix-oriented meaning that all manpower and facilities must be available to perform the required tasks. [5]

Typically, individual maintenance activities are divided into so-called maintenance packages in order to better plan and carry out each individual task [6]. This also facilitates the interaction between the involved stakeholders, including the mechanics, the maintenance facilities, the equipment, and the logistics behind the components and spare parts. Different inspection groups are:

Pre-Flight: The pre-flight test is a visual inspections at the beginning of each operation day, performed by maintenance mechanics and the pilot. Thereby, fluid levels, tires, brakes, emergency equipment etc. are inspected.

A-Check: The A-check consists of general inspections of the interior and exterior as well as the aircraft's power supply. In addition, a more detailed engine inspection is included. The A-check is performed approximately every 400 to 600 flight hours or every 200 to 300 flight cycles.

B-Check: The B-check includes mainly preventive maintenance tasks, such as oil change or inspection of the oil filters. The interval between these checks is about 750 flight hours. Nowadays the B-check is usually integrated in the A-check and not performed separately.

C-Check: This check contains detailed inspection of airframe, engines, and systems. Additionally, the flight controls are recalibrated and tested. This is performed approximately every 3,000 flight hours.

D-Check: This heavy check is the most intensive maintenance package which restores the aircraft to its original condition. For a more detailed inspection, the cabin interior, such as seats, galleys, furnishing, etc., is removed from the aircraft. This check takes about one month and is required every 6-8 years.

The pre-flight inspection as well as the A- and B-checks are carried out directly at the gate or apron, whereas the C- and D-check are usually performed in the hangar. All scheduled maintenance work required for an aircraft can be found in the operator's Maintenance Planning Document (MPD).

In addition to these scheduled maintenance activities, non-routine maintenance tasks occur when there is an unexpected issue with the aircraft or due to pilot complaints. These unscheduled maintenance activities must be addressed immediately to ensure safety and airworthiness. These and other unplanned events make maintenance planning a dynamic problem meaning that airlines often have to change their flight schedule within a relatively short time period [7].

This literature review will address the environmental aspects of aircraft maintenance. Hazardous waste and other emissions are released during maintenance and overhaul activities. In addition, numerous stakeholders are involved in the maintenance process, which in turn consume energy and resources and might as well have a negative impact on the environment [8]. In order to improve maintenance operations in terms of their ecology, their negative environmental impact must be identified and evaluated first. One methodology that is often used to calculate the environmental performance of products and processes is LCA, which will further be explained and defined in the next chapter.

2.2 Life Cycle Assessment

This chapter describes the meaning of LCA, a commonly used and widely applied analysis for assessing a product's potential environmental impact. In Chapter 2.2.1, the definition based on the ISO 14040 and ISO 14044 specifications of LCA is briefly given. Chapter 2.2.2 then lists special LCA types. Finally, the strengths and weaknesses of this assessment method are identified in Chapter 2.2.3.

2.2.1 Definition and Procedure

The term LCA is described in ISO 14040 [9] as

> *» a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.«*

LCA can mainly be used to better understand the environmental performance of a product or product system and to determine potential areas of improvement within a product's life cycle. Thereby, it uses a methodology framework (see Fig. 2.1), which consists of four phases: the *goal and scope*, the *life cycle inventory*, the *life cycle impact assessment* and the *interpretation* [10].

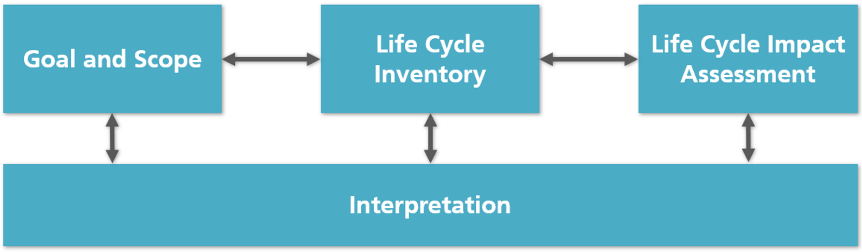

Figure 2.1: The four phases of life cycle assessment

Goal and Scope

The first phase is the goal and scope definition in which the purpose and the objective of the LCA is determined. This involves choosing the level of detail of the study, but also scoping the product system, including its system boundaries. There are different options to define the system boundary, e.g. *cradle-to-cradle*, *cradle-to-grave*, or *gate-to-gate* [11]. Fig. 2.2 schematically shows the life cycle of a product from raw material extraction, production, and transportation via use phase (which is usually the longest time period in a product's lifespan) to the end-of-life. Depending on the start and the end of the ecological evaluation, one of the above-mentioned consideration frameworks is applied. Hereby, *cradle* is the origin of a product, usually the raw material extraction, and *grave* represents the end-of-life. *Gate* can be any point in the life cycle.

One of the most commonly used options is the *cradle-to-grave* boundary, which considers all life cycle phases from raw material extraction to disposal. The *cradle-to-cradle* method additionally considers the recycling or re-utilisation of a product or component at the end of its life cycle, which in turn has a positive effect on the environment. Within a *gate-to-gate* option, the assessment from any defined point along the life cycle to another is possible. [12]

In addition to defining the system boundaries, the goal and scope phase includes the selection of a functional unit and the choice of different assessment parameters as well as geographical and temporal boundaries. The purpose of the functional unit is to provide a detailed product description. This is intended to give a reference to which inventory data can be applied to ensure that different systems are comparable on a common basis [13]. In the field of aviation, a product can for example be an aircraft that transports passengers on a defined route. A functional unit could therefore be one Passenger-Kilometre (PKM).

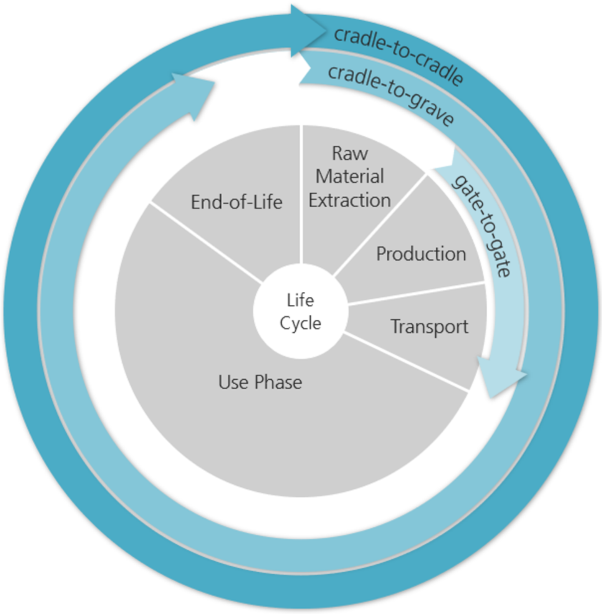

Figure 2.2: Cradle-to-cradle vs. cradle-to-gate vs. gate-to-gate

The decisions made during the goal and scope analysis determine the collection of data and the way the system is modelled and evaluated. The importance of this phase is often underestimated and does not receive sufficient attention [14]. However, it is a crucial factor for the entire LCA and has a very strong impact on the overall assessment.

Life Cycle Inventory (LCI)

The inventory analysis is the most time-consuming part of the LCA. It identifies all processes that belong to the product system and collects information on resource inputs, materials, and emission outputs. For this, the required data must be collected or calculated. These can be identified, for example, with the help of flowcharts of single processes. The data collection usually requires special emission databases, such as the ecoinvent database published by the Swiss Centre for Life Cycle Inventories [15]. The result of the inventory analysis is the Life Cycle Inventory (LCI) - a list of quantified elementary flows of the product system.

Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) then translates the collected inventory of the product system into environmental impacts. For this purpose, there are numerous methods that categorise and characterise the individual impacts of different processes and life cycle phases. The results are then multiplied by so-called impact factors and sorted into suitable impact categories, which groups different emissions into an environmental effect. [16]

An example of an impact category is *climate change*, which is expressed in kilograms of carbon dioxide equivalents (kg CO_2-eq). In this category, however, not only the gas carbon dioxide (CO_2) is included, but also other GHG emissions, such as methane (CH_4) or nitrous oxides (N_2O), which need to be converted into the unit kg CO_2-eq.

In addition to *climate change*, other impact categories can, for example, be *human and ecotoxicity*, *acidification*, *eutrophication*, *resource depletion*, etc. - depending on the chosen LCIA method. An overview and a description of major LCIA methods can be found in [17–19] or in their corresponding user guides, e.g. for the ILCD method [20], the ReCiPe method [21], and the IMPACT 2002+ method [22]. In summary, the LCIA consists of five steps according to ISO 14040 [9]:

- Selection of impact categories including a representative indicator and an environmental model
- Classification of elementary flows from the inventory by assigning them to an impact category
- Characterisation using the environmental model for the impact category to quantify the ability of each of the assigned elementary flows to impact the indicator of the category
- Normalisation to express all category indicator scores in the same metric
- Grouping or weighting to support the comparison across the impact categories

Interpretation

In the final phase, the results of the LCA are interpreted and conclusions as well as recommendations are made. The study is therefore analysed based on the goals and scopes of the first phase. This includes an evaluation regarding its completeness based on the assumptions and limitations [23]. To demonstrate the representativeness, robustness, and confidence in the LCI and LCIA within a given LCA study, a data quality analysis as well as a sensitivity and uncertainty analyses is recommended to strengthen the confidence in the findings. [24]

2.2.2 Special Types of Life Cycle Assessment

In addition to the traditional LCA, there are special types of LCA that have been developed for different application areas. Besides the very detailed Process-based Life Cycle Assessment (pLCA), there is a simplified and economy-based Economic Input-Output Life Cycle Assessment (EIO-LCA), which are often used in a hybrid combination. Additionally, a recent trend towards simplification has emerged to improve the communicability with society and which resulted in a streamlined LCA and different *footprinting* terminologies. A brief summary of these different methods is given below.

Process-based Life Cycle Assessment (pLCA)

A pLCA is a very detailed LCA form to perform an ecological assessment of a specific process step. It follows a bottom-up approach and takes into account all possible inputs (materials and energy resources) and outputs (emissions and waste to the environment). This enables a high level of granularity and a high degree of control over all material, energy, and substance flows. Uncertainties and the influence of individual process parameters can thus be assessed directly providing more insightful information on the overall process. Furthermore, a pLCA makes it possible to implement new processes and link them together [25]. However, the creation of the process-based inventory requires a high data collection effort and thus leads to high processing times for the pLCA.

Economic Input-Output Life Cycle Assessment (EIO-LCA)

Another variation of LCA, that is often used, is the so-called EIO-LCA, which is a simplified attempt to economise the traditional LCA. The EIO-LCA is a top-down approach that estimates the required materials and energy resources as well as the resulting environmental emissions for and from economic activities [26]. The advantage of an EIO-LCA is that no system boundaries have to be defined for the calculation and that no complex inventories have to be carried out. One of the main advantages is therefore, that an EIO-LCA does not require as much time as a traditional bottom-up LCA [27]. However, an EIO-LCA cannot guarantee a high degree of accuracy, since the cost of the product are estimated solely by the raw materials sector in national input-output tables. A comparison of two heterogeneous products or the consideration of new products is also not or hardly possible. In addition, this methodology only considers raw material acquisition and manufacturing processes, while use and end-of-life scenarios are largely neglected. [26]

Streamlined Life Cycle Assessment

Streamlined LCA is mostly used to make certain LCA activities more manageable. In this case, the traditional LCA is carried out in a simplified way. This can be applied, for example, when only a limited scope is of importance. One example of this is when certain life cycle phases are eliminated or certain processes have a negligible effect on the environment and are therefore not considered in detail. Similarly, one can use a streamlined LCA when only individual impact categories are to be considered in a given LCIA method. Especially for very complex products, a simplified method is often preferred when, for example, comparing different design options.

Footprinting

Another simplified way of expressing the results of an LCAs is to use so-called footprints. These are supposed to be particulary helpful for communication as consumers of a particular product can obtain information about the ecological performance with the help of one single value. The most important ones are the *carbon footprint*, which is a visualisation of GHG emissions, as well as the *water footprint*, which indicates the amount of water used during manufacturing of a particular product. The footprints are usually applied on daily goods or food in order to have an influence on consumer's behaviour and to offer more transparency. However, due to the simplification of a single value, there is a risk that consumers will not be able to make a judgement of the quality of the assessment. Besides, many rules are necessary in order to compare products directly with each other.

2.2.3 Strengths and Limitations

The strengths of an LCA are, above all, that a consideration of the entire life cycle is possible. It supports decision-making and informs stakeholders of the trade-offs that a decision will bring across all environmental impact categories. In this way, LCA can support the early design process and contribute to better environmental performances throughout the whole life cycle. Furthermore, an LCA can be used to compare different product systems or processes with each other. The variety of LCIA methods makes the tool robust and flexible by considering different perspectives. Additionally, different product systems can be compared with each other assuming the functional unit is the same in both systems. [10, 12]

This in turn can also count as a limitation, as product assessment without comparison is very difficult. An LCA does usually not measure the performance of a product or its constituents and cannot say whether a product is "sustainable enough", but only whether it is more sustainable than another. Accordingly, it does not tell stakeholders what they should do, but helps them to make better decisions based on the evaluated trade-offs. Furthermore, some simplifications and generalizations in the modelling of the product system have to be accepted. For instance – depending on the system boundaries - an LCA does not include any personnel requirements, e.g. the commute to and from work or lunch room waste. Any materials weighting less than one percent of the product are usually neglected as well. Another limitation is, that an LCA is usually very data-intensive and especially the inventory phase is relatively time-consuming. The assessment only provides a snapshot view meaning that changes over time are not accounted. One major difficulty for the performance of LCA of future technologies, also known as prospective LCA, is the lack of consistent inventory databases that matches the technology time frame [28]. By now, only background processes for future technologies can be modelled.

3 Literature Research

This literature research aims to provide an overview of existing papers dealing with environmental assessment in aviation - with a strong focus on aircraft maintenance. For this purpose, the search terms are first evaluated and the results from common search engines are analysed. This is followed by a detailed overview of the found publications.

3.1 Determination of Search Terms

The following section analyses the used search terms to conduct this literature review. Therefore, suitable synonyms were identified and the number of matches in the two databases Scopus and Web of Science was analysed. Elsevier's Scopus and Thomas Reuter's Web of Science both belong to the main sources of citation data and cover an interdisciplinary scientific field [29]. For this reason, they are seen as a good basis for this literature search.

Aviation - Search Terms

In order to identify the appropriate search term related to aviation, different aviation synonyms are analysed. The complete list of all search terms can be found in Appendix A. The five most frequent findings are shown in Table 3.1.

Table 3.1: Aviation search terms

Search Term	Scopus	Web of Science	Sum
aircraft	312,873	95,021	407,894
aerospace	146,539	44,477	191,016
aviation	91,557	23,694	115,251
aeronautic*	81,312	14,486	95,798
airplane	27,163	9,392	36,555

Looking at the number of matches in Scopus and Web of Science, one can notice that Scopus achieves significantly more results. The sum in the right column represents the total of the entries in the two databases, without taking any duplications into account. The most commonly used terms in literature are *aircraft*, *aerospace*[1] and *aviation*. These three search terms are in the following used in combined form:

[1] It should be noted that the term aerospace refers not only to aviation but also to the field of space mission.

Search Term
aircraft OR *aerospace* OR *aviation*
→ 483,526 publications in Scopus (11/2021)

Aircraft Maintenance - Search Terms

Similar to the aviation search term, a suitable search term for the associated maintenance is now determined. Table 3.2 shows the number of publications found when *maintenance* is used in a combined search with the previously defined aviation search terms.

Table 3.2: Aircraft maintenance search terms

Search Term	Scopus	Web of Science	Sum
aircraft AND maintenance	11,466	3,611	15,077
aviation AND maintenance	3,479	1,033	4,512
aerospace AND maintenance	3,297	959	4,256

In literature, the term *aircraft maintenance* is by far the most frequently used expression. Therefore, this term is also preferred in the course of this literature review. A combined search with the aviation search terms and maintenance in Scopus yields a total of 14,849 publications.

Search Term
(*aircraft* OR *aerospace* OR *aviation*) AND *maintenance*
→ 14,849 publications in Scopus (11/2021)

Life Cycle Assessment - Search Terms

In order to find suitable publications dealing with LCA in the field of aviation, the most appropriate notation must first be determined. Table 3.3 shows which search terms lead to how many results in Scopus and Web of Science.

Table 3.3: Life cycle assessment search terms

Search Term	Scopus	Web of Science	Sum
life cycle assessment	29,625	27,288	56,913
LCA	33,218	21,755	54,973
life cycle analysis	16,098	3,783	19,881
lifecycle assessment	660	397	1,057

Since *life cycle assessment* (equivalent to *life-cycle assessment*) achieves more hits than the joint written *lifecycle assessment*, this spelling is also applied in this literature report. Care should be taken with the abbreviation *LCA*, since this can also be used as an abbreviation for, e.g. light combat aircraft. The combined search term is:

Search Term
life cycle assessment OR *LCA* OR *life cycle analysis* OR *lifecycle assessment*
→ 47,962 publications in Scopus (11/2021)

Life Cycle Assessment - Synonyms

In order to not limit the literature research only to the search terminology LCA, more publications dealing with the ecological impact of aircraft maintenance were analysed. For this purpose, synonyms of LCA and their occurrences in Scopus and Web of Science were investigated. Table 3.4 shows the most frequently used search terms:

Table 3.4: Life cycle assessment synonyms

Search Term	Scopus	Web of Science	Sum
environmental impact	213,794	45,776	259,570
environmental assessment	24,733	8,521	33,254
carbon footprint	21,638	8,675	30,313
ecological impact	18,026	2,865	20,891
ecological footprint	4,521	2,393	6,914
environmental footprint	3,982	2,150	6,132

The Appendix B contains a complete list of all investigated synonyms. Although the main focus is on the search terms *life cycle assessment* and *LCA*, some other synonyms also seem to be very promising. Accordingly, the following search combination was used:

Search Term
life cycle assessment OR *LCA* OR *life cycle analysis* OR *lifecycle assessment* OR *environmental impact* OR *environmental assessment*
→ 260,248 publications in Scopus (11/2021)

The search yielded a total of 260,248 matches in Scopus. In the next section, the relevant results of this literature review are analysed statistically.

3.2 Statistics

In the beginning of this literature review, the existing relationship between aviation and LCA in the literature is determined. The following search term was used for this purpose:

Search Term
(*aircraft* OR *aerospace* OR *aviation*) AND (*life cycle assessment* OR *LCA* OR *life cycle analysis* OR *lifecycle assessment*)
→ 452 publications in Scopus (11/2021)

The search yielded a total of 452 results. Within the context of this literature research, the abstracts of these publications were read and analysed leading to a total of 150 results that can be regarded as irrelevant. There was either an insufficient connection to the aviation sector, for instance when aviation was only mentioned as an example or when the publication focused mainly on space missions. Furthermore, the abbreviation LCA was often used for light combat aircraft in the military context, especially in the 1990s and early 2000s, and therefore also provided misleading results. This left more than 300 remaining publications that are then clustered into different thematic fields. Figure 3.1 shows the main topics:

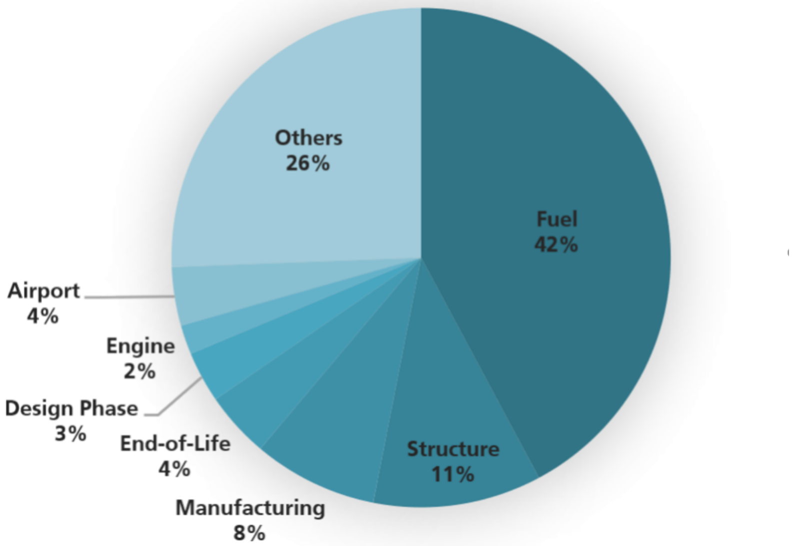

Figure 3.1: Life cycle assessment and aviation

The vast majority of publications combining LCA and aviation focuses on (alternative) fuels. Especially novel propulsion technologies are often assessed holistically with the help of ecological criteria over the entire life cycle. Besides that, several publications mainly deal with the ecological impact of structural components or the manufacturing process, and others consider end-of-life scenarios of aircraft components. Few address the environmental impact of ground infrastructure, such as airports. However, the non-flight operating phase, such as maintenance, is hardly mentioned in the literature.

Figure 3.2 gives an overview of the number of publications per year. It can be observed that LCA in the context of aviation is a relatively new field with a growing interest.

Figure 3.2: Publications per year

To get an overview of those publications also dealing with aircraft maintenance in the context of LCA, the results are further limited with the term *maintenance*.

Search Term
(*aircraft* OR *aerospace* OR *aviation*) AND (*life cycle assessment* OR *LCA* OR *life cycle analysis* OR *lifecycle assessment*) AND *maintenance*
→ 33 publications in Scopus (11/2021)

Within these 33 results, the so-called snowball method was applied in which the reference list of a publication is used to identify additional publications. This helps broaden the results list and is, according to Wohlin [30], an alternative way for a systematic literature study. An overview and summary of these publications is given in the following.

3.3 Detailed Literature Review

Howe [31] performed an LCA of an Airbus A320 for each life cycle phase (manufacturing, operation, and decommissioning) with a special focus on components, materials, and processes that significantly influence the environmental impact. The LCA software SimaPro with the ecoinvent database was used for the analysis and the result was evaluated with the LCIA method Eco-Indicator 99. The author found out that the operating phase accounts for 99 % of the total environmental impact and the manufacturing phase for only 0.01 %. According to Howe, disposal generates a positive return of 10 % meaning that some of the material and energy flows return to the overall system. However, maintenance was not discussed in detail.

Lopes [32] carried out a holistic LCA for an Airbus A330 from a cradle-to-grave perspective. To calculate the impact of the aircraft maintenance, the author used the ecoinvent database with an *operations, maintenance, airport* dataset. This means that maintenance is considered together with airport construction and infrastructure, which is due to the lack of datasets in the ecoinvent database and entails great uncertainties. As a result, the environmental impact of the aircraft maintenance comes with great uncertainties and does not include any calculations for specific maintenance activities.

In his dissertation, Chester [33] carried out a comparison between different transportation modes and their infrastructure in the US based on their energy and emissions impact. For air transportation, three different models of aircraft (Embraer 245, Boeing B737 and Boeing B747) were used to cover different vehicle sizes and operating ranges. Therefore, he developed a hybrid approach of a pLCA for the operation phase and an EIO-LCA for aircraft manufacturing and maintenance while neglecting the end-of-life phase. However, Chester mentioned that, for the aircraft maintenance, there are no sector entries in the EIO-LCA available to calculate reasonable environmental effects. Consequently, the impact for the aircraft maintenance was calculated with alternative best-fit EIO-LCA sectors. He concluded that the aircraft operational components, the manufacturing, and the jet fuel production are responsible for the majority of GHG emissions and energy consumption, whereas maintenance accounts for only a very small proportion of approximately 1 %. Looking at the different aircraft sizes, the short-haul aircraft had by far the biggest environmental impact compared to medium- and long-haul.

In a subsequent study, Chester et al. [34] further classified maintenance into aircraft maintenance and engine maintenance as non-operational components and airport maintenance as part of the infrastructure. Here as well, the proportion of maintenance both in terms of energy consumption and GHG emissions is very low (1 %) compared to the overall life cycle.

Similar to that, Facanha et al. [35] also compared road, rail, and air freight transportation based on the vehicle's life cycle, the infrastructure, and the fuel production with a hybrid LCA approach. Looking at a Boeing B747, the environmental impact of the aircraft maintenance was performed using the EIO-LCA *other maintenance and repair construction* sector due to its simplicity. Here again, the chosen inventory sector does not cover aircraft maintenance sufficiently and lead to high uncertainties in the overall LCA. The study did not provide single results for the aircraft maintenance itself but combined it with the vehicle manufacturing and the end-of-life, which in total account for 23 % of the overall CO_2 emissions.

Another publication that is often referred to is the one from Lewis [36]. In this master thesis, the author compared three different flight scenarios with different flight distances and aircraft types (Airbus A320, Airbus A330, and Airbus A380). He looked at the whole life cycle of the aircraft by using a combination of pLCA and EIO-LCA. In this study, only airport maintenance was considered whereby aircraft maintenance was neglected due to the lack of data.

Liu [37] also conducted an environmental comparison of two aircraft types, the Airbus A319 and the Boeing B737, primarily in terms of different composite material use rates. Therefore, the author divided the operation phase into three parts: the estimated fuel consumption of the aircraft, the construction of the airport, and its maintenance. However, due to the comparative nature of this study, it was assumed that only the fuel consumption will vary between different aircraft types while the airport construction and maintenance will remain the same and were not analysed further. In addition to that, aircraft maintenance was not considered in any detail. The used

LCA software was SimaPro with the ecoinvent and IDEMAT 2001 database and the LCIA method Eco-Indictaor 99.

In the publication of Dallara et al. [38], different LCA approaches and their applicability were discussed and compared with a tool called qUWick. With this tool, aircraft maintenance impacts were modelled using industry data and information from Boeing's aircraft maintenance manuals.

Jordão [39] calculated and compared the CO_2 emissions of an Airbus A330 and a Boeing B777. He estimated the environmental impact of the maintenance phase from the electricity consumption only. Therefore, a first assumption regarding the total maintenance time of an aircraft was made by equating it with the aircraft's minimum service life of 60,000 flight hours. With the associated cost per maintenance hour, the maintenance cost of an aircraft could be estimated over the entire life span. The energy consumption of the maintenance was then extrapolated with a specific kWh price. With a further assumption that all maintenance is carried out at London Heathrow airport and the total energy consumption as well as the CO_2 emissions from a fact sheet of this airport, the CO_2 emissions for the aircraft maintenance were then extrapolated. The total CO_2 emissions for the maintenance of the Airbus A330 thus amount to 500 kt and for a Boeing B777 to 700 kt CO_2-eq. Jordão thus calculates the share of maintenance to be around 20 % in relation to aircraft manufacturing and operation.

In a publication by Krieg et al. [40], the environmental impact shares of aircraft operations, infrastructure operations, and aircraft maintenance were calculated with a hybrid approach. While using a pLCA for aircraft and infrastructure operations, the authors noted that there are no sufficient environmental data available for the aircraft maintenance part and therefore had to use an EIO-LCA for that aspect. The inventory model was created with the GaBi software.

Using the fundamentals of [40], Johanning et al. [41], [42] conducted a study to integrate an LCA into the conceptual aircraft design. For this, they evaluated the ecological impact of the aircraft by a so-called single score and considered all phases of the aircraft's life cycle. Although they explicitly named Maintenance, Repair, and Overhaul (MRO) as a part of the operational phase, only the airport's energy consumption and the operations of Ground Support Equipment (GSE) were considered alongside the different flight phases. For the environmental impact of the airport, they focused on its energy consumption and converted the resulting emissions into PKM. The study revealed that 99 % of the environmental impact of an aircraft is contributed by the operational phase while the impact of the airport (represented by the energy generation and consumption as well as the ground handling) is only around 1 %.

Aihara et al. [43] published an inventory analysis of different modes of transportation (rail, road, air, and coastal shipping) in Japan focusing on CO_2, SO_X and NO_X emissions. They also looked at the ecological impact of the vehicles' maintenance, which was calculated using an input-output analysis. The authors concluded that, in the aviation sector, the operational phase (in terms of fuel consumption) is much higher than vehicle production and maintenance as well as infrastructure construction and its maintenance combined. However, the study looked at a period from 1985 to 2000 and is therefore comparatively old.

In a study by Timmis et al. [44, 45], an LCA of a Boeing B787 fuselage component was carried out including a comparison between aluminium and Carbon Fibre Reinforced Polymer (CFRP). The focus was on the manufacturing and disposal of the components as well as the fuel consumption during the aircraft operation phase. The results show that CFRP has a significant reduction in emissions due to the lower material weight. Maintenance was only considered by comparing maintenance cost.

Calado et al. [46] also conducted an environmental comparison of different aircraft materials and configurations over their entire life cycle. The authors used a combination of LCA and Life Cycle Costing (LCC) for a cargo aircraft elevator case study in which a total of six different laminate configurations and two carbon fibre prepreg materials were compared with each other. Here, due to the comparative study, the assembly of the elevator, maintenance cost, and operating cost other than the fuel consumption were neglected, as they seem to have no significant environmental difference between the configurations.

A similar approach combining environmental and economic assessment was carried out by Fera et al. [47]. In a literature review, the authors observed a lack both in maintenance cost estimation and, more significantly, in environmental assessment methods for aircraft maintenance. Therefore, they developed a new methodology to support the aircraft design process in terms of sustainability over the entire aircraft life cycle. A so-called green index was identified, which is intended to determine the greenest maintenance solution with lowest cost as well as lowest environmental impact. The environmental impact was calculated from a ratio of maximum payload weight and mean gasoline consumption.

Atılgan et al. [48] carried out an exergo-environmental analysis for a turboprop engine. The authors claimed that exergy is an effective indicator of the potential of an emission to impact the environment. In this study, an exergy analysis was performed in which inlet and outlet exergy flows of each engine component is calculated in order to determine the exergy destruction of the engine's components. Afterwards, an LCA of all relevant components was carried out. Therefore, the SimaPro software and the LCIA method Eco-Indicator 99 was used. Finally, every component exergy stream was environmentally assessed with the results of the LCA. By using this method, the authors were able to understand necessary mechanisms for more efficient aircraft propulsion systems. However, the authors did not distinguish between the operation and maintenance phase.

In a study by Bicer et al. [49], the relative environmental impact of each life cycle phase was examined and differences that occur when aircraft are operated with alternative fuels in the future were listed. The impacts caused by aviation maintenance were again taken from the ecoinvent database using SimaPro. However, the authors assumed that maintenance processes will not change due to new fuels and therefore did not consider maintenance any further.

The publication by Şöhret et al. [50] dealt specifically with maintenance on a Cessna 172 Skyhawk. For the evaluation of a piston-prop engine maintenance, the SimaPro software with the ecoinvent database was used again. The focus lied on electricity consumption and the gasoline demand during the maintenance process steps.

Vidal et al. [51] considered the maintenance of a single aircraft component. By comparing two interior panels, one made of conventional glass fibre-reinforced and one made of new, sustainable materials, not only the production and end-of-life scenarios were analysed, but also the maintenance process related to the panels. This process consists of the exchange of a decorative film on a routine basis. The environmental impacts resulting from the production of this film are the only factors that have an impact on the maintenance procedure.

The business model of an aircraft MRO company was the focus of a study by Cardeal et al. [52]. The study investigated the transformation from traditional maintenance activities to the use of additive manufacturing for the production of optimised spare parts. For this purpose, an LCA was carried out using the SimaPro software and the LCIA method ReCiPe with the spare part's relevant life cycle phases: production, transport, use phase, and end-of-life. The result showed that although the production of a spare part leads to an increased ecological impact, this is greatly outweighed by the savings in the use, end-of-life, and transport phase. After one year, for example, a positive impact of 210 kg CO_2-eq for the utilisation of one part was calculated.

Rolinck et al. [53] considered the use of blockchain as a promising approach for tracking and tracing life cycle data and therefore used a blockchain-based data management concept for LCA. The concept consists of five layers including a blockchain information system layer, an LCA database layer, and a user layer. The use case was a repair process of a high pressure turbine blade of a conventional aircraft engine. Each individual maintenance process was seen as an independent unit process, which was then stored into a block with a unique identifier. These unit processes together then lead to a comprehensive overview of all in- and output flows which allows each individual event of the aircraft's life cycle to be traced at part and system level.

An economic approach was done by Edwards et al. [54], who assessed the impact that the Cost Index (CI) could have on CO_2 emissions of air travel. Therefore, six aircraft models where compared. A variable carbon price was calculated and depending on the amount of burned fuel, added to the Direct Operating Cost (DOC). The maintenance was thus indirectly ecologically evaluated with the aid of the CI.

The authors van Beelen et al. [55] evaluated the maintenance process of a re-painting maintenance overhaul task. A so-called AVIOX CF primer, which is applied before the paint itself, was evaluated based on the paint layers required afterwards. The mass of the solvent emissions and the chromates caused by the re-paint were then calculated. The reduction of hazardous materials and emissions, which are both harmful to the environment and to the mechanic's health, could be reduced by the primer.

Koščák et al. [56] did not consider the aircraft maintenance, but rather the maintenance of the airport itself. Their aim was to optimize the winter maintenance at Kosice Airport, Slovakia, and to therefore reduce the negative environmental impact. They used an optimization model that transforms input data of the airport into output data to evaluate the environmental impact.

Besides that, the search revealed some publications that do not consider aircraft maintenance any further [27, 57–63]. Table 3.5 provides an overview of the relevant literature including a brief summary of the pursued objectives, the used methods, and the way maintenance was included.

Table 3.5: Aviation search terms (part 1 from 2)

Publication	Study Objective	Method	Maintenance Aspect
Howe [31]	life cycle assessment of an Airbus A320	LCA	maintenance not included
Lopes [32]	life cycle assessment of an Airbus A330	LCA	ecoinvent database
Chester [33]	comparison of different transportation modes based on vehicle, infrastructure, and fuel production data	hybrid LCA	EIO-LCA
Chester et al. [34]	comparison of different transportation modes including supply chain	hybrid LCA	EIO-LCA
Facanha et al. [35]	comparison of different freight transportation modes	hybrid LCA	EIO-LCA
Lewis [36]	comparison of different flight scenarios	LCA	ecoinvent database
Liu [37]	comparison of composite material use rate of an Airbus A319 and a Boeing B737	LCA	no consideration of maintenance due to comparative study
Dallara et al. [38]	comparison of different LCA approaches and applicabilities	streamlined LCA	aircraft maintenance model from industry data
Jordão [39]	life cycle assessment and comparison of an Airbus A330 and a Boeing B777	LCA	environmental impact via energy consumption of airport
Krieg et al. [40]	life cycle assessment of passenger aircraft operation phase	hybrid LCA	EIO-LCA
Johanning et al. [41, 42]	influence of life cycle assessment of an Airbus A320 on conceptual aircraft design	LCA	energy consumption of airport and GSE operation
Aihara et al. [43]	life cycle inventory analysis of different transport modes	LCI	EIO-LCA
Timmis et al. [44, 45]	life cycle assessment of different aircraft fuselage materials	LCA	only maintenance cost comparison

Table 3.6: Aviation search terms (part 2 from 2)

Publication	Study Objective	Method	Maintenance Aspect
Calado et al. [46]	comparison of different aircraft materials and configurations	combination of LCA and LCC	no consideration of maintenance due to comparative study
Fera et al. [47]	comparison of maintenance solutions for a Boeing B777, a Boeing B747, and a McDonnell MD-12	green index combining economic and environmental assessment	environmental impact of maintenance from ratio of payload weight and fuel consumption
Atılgan et al. [48]	exergo-environmental analysis of a turboprop engine	combination of exergy analysis and LCA	exergy analysis
Bicer et al. [49]	life cycle assessment of alternative aviation fuels	LCA	SimaPro software database
Şöhret et al. [50]	life cycle assessment of a maintenance process of a Cessna 172 Skyhawk	process-based LCA	environmental impact via energy consumption and gasoline demand
Vidal et al. [51]	life cycle assessment and comparison of aircraft interior	LCA	environmental impact of material and production after replacement
Cardeal et al. [52]	life cycle assessment of the utilization of aircraft spare parts	LCA	focus on an MRO company business model
Rolinck et al. [53]	blockchain-based data management for aircraft MRO	blockchain-based LCA	dummy-data to show methodology on a repair process
Edwards et al. [54]	assessment of CO_2 emissions of different aircraft models	CI model	calculation of a carbon price per flight hour and return conversation to CO_2 emissions
van Beelen et al. [55]	environmental assessment of an aircraft maintenance primer	no LCA	environmental impact via paint weight
Koščák et al. [56]	optimization of airport winter maintenance	input-output model	only airport maintenance

4 Research Gap

This literature review focused on publications assessing the environmental impact of aircraft. A special attention was given to aviation maintenance, which is very often neglected or simplified in the context of the whole aircraft life cycle. In total, more than 200 publications were read and analysed, most of which focused on other areas of aviation, such as alternative fuel systems or aircraft manufacturing. The studies that were considered to be relevant in the context of this literature review were described and analysed in detail in Chapter 3. The majority of these relevant publications carried out holistic LCAs of specific aircraft types, whilst some others compared, for example, different aircraft configurations, means of transport, or specific materials. The aircraft maintenance aspect was in most cases considered as a part of the operations using different environmental impact assessment methods.

Several authors [33–35, 40, 43] used the so-called EIO-LCA method to calculate the ecological impact of maintenance. EIO-LCA is based on the economic output of a given sector and associates it with environmental metrics. However, there are large uncertainties as there is no economic sector in the EIO-LCA that reasonably estimates the effect of aircraft maintenance [33]. In other publications [32, 36, 49] specific LCA databases such as the ecoinvent database were used. The problem is that these only contain datasets on the operation and maintenance of the airport without considering the aircraft maintenance, which also lead to inaccurate results. Other studies [39, 41, 42, 50] have used the energy consumption of the airport to calculate the environmental impact of maintenance. However, this is done using the energy consumption of the whole airport without specifically looking at maintenance only.

As many LCA studies are comparative studies, the environmental impact of maintenance has been intentionally excluded in numerous publications [37, 46, 51]. In these studies, the authors have assumed that maintenance activities will not change between different aircraft types or due to different materials and configurations.

In addition to these examples, a variety of other methods were used to calculate the maintenance impact, e.g. by weight calculations [47], exergy analyses [48], or carbon prices [54]. Nevertheless, none of the presented methods allows a detailed consideration of specific maintenance aspects. Rather, maintenance is often seen as an insignificant factor in the aircraft life cycle that is usually generalised and not subject to detailed analyses. Krieg et al. [40] for example mentioned as a reason that the small ecological impact of maintenance does not justify the huge effort to collect and model the data. Conversely, a report by Airbus Operations et al. [8] classifies maintenance activities and their corresponding environmental effect as important for both short as well as long life cycles.

As a result, these approaches lead to the problem that maintenance is not sufficiently considered. On the one hand, there are various types of maintenance that fulfil different aspects and requirements and thus may lead to different ecological impacts, which cannot be mapped using single datasets or rough estimations. On the other hand, maintenance activities usually lead to an improved performance resulting in a lower environmental impact during operation. However, this can only be analysed more precisely if details of the maintenance and corresponding ecological factors are known. In addition, maintenance also covers other activities, such as logistics. This includes, for example, the suppliers of spare parts or equipment, but also the facilities of the maintenance, mechanics, and the hangar, where mainly base and shop maintenance is carried out. The individual stakeholders and their interaction have not yet, at least to the author's knowledge, been considered in more detail from an environmental perspective in the literature.

Due to the identified research gaps, it is not yet possible to determine the overall ecological impact of maintenance, although it is an essential part of an aircraft's life cycle. Furthermore, it is expected that new and innovative technologies will affect areas such as maintenance [64]. In fact, a lower environmental impact during operation can lead to a larger share of maintenance in the overall life cycle, which in turn will give aircraft maintenance a new significance.

This summarizes the fact that environmental impact assessments of aviation maintenance are already being carried out, but by far not to the extent that would be necessary to look at the environmental impact in detail, e.g. based on individual maintenance tasks. In addition, there is a lack of parametric models that are able to consider a wide range of maintenance activities, their stakeholders, and modifications.

Appendix A

Search Term	Scopus	Web of Science	Sum
aircraft	312,873	95,021	407,894
aerospace	146,539	44,477	191,016
aviation	91,557	23,694	115,251
aeronautic*	81,312	14,486	95,798
airplane	27,163	9,392	36,555
air traffic	23,359	8,307	31,666
air transport*	25,571	4,895	30,466
aeroplane	2,114	9,392	11,506
air travel	4,825	2,559	7,384
airliner	2,361	893	3,254
jetliner	200	56	256
passenger jet	127	25	152
air sector	79	37	116

Appendix B

Search Term	Scopus	Web of Science	Sum
environmental impact	213,794	45,776	259,570
life cycle assessment	29,625	27,288	56,913
LCA	33,218	21,755	54,973
environmental assessment	24,733	8,521	33,254
carbon footprint	21,638	8,675	30,313
ecological impact	18,026	2,865	20,891
life cycle analysis	16,098	3,783	19,881
ecological footprint	4,521	2,393	6,914
environmental footprint	3,982	2,150	6,132
ecological assessment	2,249	1,327	3,576
life cycle approach	1,587	840	2,427
lifecycle assessment	660	397	1,057
lifecycle analysis	515	224	739
lifecycle approach	304	110	414
life cycle evaluation	217	116	333
lifecycle evaluation	31	17	48

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