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Using Discrete-Event Simulation for a Holistic Aircraft Life Cycle Assessment

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Abstract: With growing environmental awareness and the resulting pressure on aviation, ecological impact assessments are becoming increasingly important. Life cycle assessment has been widely used in the literature as a tool to assess the environmental impact of aircraft. However, due to the complexity of the method itself and the long lifespans of aircraft, most studies so far have made strong simplifications, especially concerning the operational phase. Using a combined discrete-event simulation framework, this paper aims to ecologically assess the individual life cycle phases of an aircraft. The method will be demonstrated in a case study of an A320 and subsequently compared with findings from the literature. Despite the significant environmental impact of flight operations, which covers almost 99.8% of the entire life cycle of the aircraft, a detailed consideration of all life cycle phases is essential to serve as a reference for the ecological assessment of novel aircraft concepts. The presented assessment method thus enables a holistic analysis at an early stage of the design process and supports the decision-making for new technologies and operational changes.

Keywords: life cycle assessment; discrete-event simulation; aviation

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1. Introduction

Aviation currently accounts for about 3.6% of the total anthropogenic Greenhouse Gas (GHG) emissions and is responsible for 13.4% of emissions in the transport sector [1]. However, with the steady growth of air traffic due to globalisation, this environmental impact is increasing, and consequently, so is the need for alternative and sustainable aircraft concepts. There are different approaches to determining the environmental impact of such new aircraft technologies and their corresponding effect compared to conventional aircraft. One of the most well-established methods is Life Cycle Assessment (LCA), which is defined according to DIN 14040/14044 and is used to assess the environmental impact of a product or a product system's overall life cycle phases [2,3]. An LCA can be divided into the following four steps:

- Goal and Scope;
- Life Cycle Inventory (LCI) Analysis;
- Life Cycle Impact Assessment (LCIA);
- Interpretation.

The first phase is used to define the goal and scope of the LCA. This includes, for example, the identification of system boundaries or a suitable functional unit. 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. In addition, important assumptions and limitations are selected and documented on which the study is based. This is followed by the LCI analysis, the data collection part of the LCA. In this phase, all processes that belong to a product system are identified, and the necessary resources, materials, and emissions are collected. The impact assessment then translates the collected inventory of the product system into environmental impacts. For this purpose, numerous methods that categorise and characterise the individual impacts of different processes and life cycle phases are available. The results are then multiplied by so-called impact factors and classified into suitable impact categories that combine different emissions into one or more environmental impacts [4]. In the final phase, the results of the LCA are interpreted, and conclusions, as well as recommendations, are drawn. The study is therefore analysed on the basis of the defined goal and scope of the first phase. This includes an evaluation regarding its completeness based on the assumptions and limitations.

There are a number of publications that perform an LCA for aircraft components or whole aircraft. These studies show that the operational phase, comprising both flight operations and maintenance of the aircraft, contributes to the highest environmental impact. Johanning and Scholz [5], for example, claim that the use phase completely dominates the environmental impact of an aircraft with a share of 99.8%, and many other authors come to similar conclusions [6–8]. In these studies, however, the operational phase is often analysed in a simplified way, e.g., by considering flight hours as an average value per year or per total lifetime and by often neglecting maintenance events. Yet, especially the latter, are essential for reliable flight operations and are themselves dependent on the flight schedule as their intervals are specified by, for instance, the number and duration of performed flights [9]. Additionally, overhaul or modification events can increase the lifetime of an aircraft's components or improve its in-flight efficiency, which in turn positively affects the environmental impact. To dynamically link individual flight and maintenance events and thus depict a realistic operational schedule, a discrete-event simulation is a valuable option. In a discrete-event simulation, isolated aircraft events (such as flights or maintenance activities) are generated with certain attributes and executed at specific times during the simulation. This enables a detailed and accurate simulation of an aircraft's life cycle and rapid implementation of operational changes. In the context of this study, an existing discrete-event simulation, developed at the DLR Institute of Maintenance, Repair and Overhaul, which covers the entire life cycle of an aircraft from an economic point of view, will be extended with an environmental assessment. Thereby, an individual LCA is performed for each event based on its operational parameters. This combined event simulation provides a detailed overall environmental impact for all aircraft life cycle phases, event categories, or time periods. Due to its generic structure, the simulation environment can be applied to different aircraft types, including both conventional and innovative ones. Especially with regard to the implementation of new technologies, possible environmental impacts can thus already be analysed in the development phase. In addition, the detailed analysis can indicate which design aspects still have the potential for improvement and thereby support re-design and further decision making.

The methodology is applied to a conventional aircraft comparable to an Airbus A320, which provides a solid data basis and can serve as a reference for the development of new aircraft concepts. The outcomes are then analysed and compared with existing findings from the literature. The study was carried out as part of, and by using, preliminary research from DLR's internal Exploration of Electric Aircraft Concepts and Technologies (EXACT) project, which aims, among other things, to assess the ecological effects of new aircraft technologies and their transportation systems. The structure of the paper is divided into the following sections: First, a detailed literature review identifies how existing LCAs for aircraft are conducted. Here, particular attention is dedicated to their considered life cycle phases. Furthermore, publications combining LCA and discrete-event simulation are examined in more detail. In Section 3, the discrete-event simulation is described and further framework conditions for modelling the life cycle are given. Section 4 then describes the environmental assessment for each life cycle phase in detail. The results are presented in Section 5 and compared with the findings from the literature.

2. Literature Review

The starting point of this study is a detailed literature review, providing an overview of existing LCA studies in the context of aviation. Thereby, a selection of suitable publications is identified to provide comparative data. Additionally, possible options for environmentally enhanced discrete-event simulation are highlighted and reviewed. As there is a lack of studies investigating discrete-event simulation and LCA in the field of aviation, the latter are related to various other industrial sectors.

2.1. Life Cycle Assessment in Aviation

The ecological assessment of aircraft and their operation using LCA is not entirely new. Several studies have dealt with the topic and carried out environmental impact assessments in a wide range of applications. In 2013, Atılgan et al. [10] conducted an environmental impact assessment for a turboprop engine using an exergo-analysis. The related environmental impact of each component of the engine was first calculated and then an individual environmental performance was assigned to each component using the exergo rate. The combustion chamber was identified as having the highest environmental impact in the engine. Vinodh et al. [11] published an LCA for a turbine blade. By focusing on the manufacturing phase, environmental issues could be identified as early as in the machining process, thus enabling the development of more environmentally friendly aircraft components. The environmental impact of the maintenance of an engine was assessed by Şohret et al. [12]. The author considered routine maintenance (based on electricity consumption and utilised fuel) of a Cessna 172 Skyhawk and concluded, among other things, that fuel is a significant contributor to impact categories such as the global warming potential, acidification, or photochemical oxidation, whereas electricity consumption dominates in the impact category of ozone layer depletion. Altuntaş et al. [13] considered the use of an Auxiliary Power Unit (APU) and Ground Power Unit (GPU) for a ground power supply and compared them based on LCA results. The study showed that the use of GPU at the airport has significantly lower impacts on human health, ecosystem quality, and resources compared to an APU. Another way to minimise the environmental impact of aircraft is to use lighter materials. A comparison of different materials in terms of environmental impact has been analysed, for example, using fuselage segments [14–16], elevators [17], aircraft interior panels [18], and lightweight trolleys [19]. These studies, however, usually only look at individual life cycle phases or materials in order to propose specific process improvements. Thus, they can only be considered as comprehensive LCA to a limited extent as the interactions and interdependencies between different phases are not taken into account.

For a holistic LCA, however, it is important to consider and assess the aircraft in all life cycle phases. Due to the extensive scope of such studies, many are based on master's theses or dissertations. Johanning [20], for example, investigated the integration of an environmental impact assessment into the conceptual aircraft design phase. The author concluded that the operational phase has by far the largest environmental impact, caused mainly by fuel combustion. Similarly, Howe et al. [21] conducted an LCA of an Airbus A320, looking specifically at the manufacture, operation, and end-of-life to calculate the respective share of the total environmental impact. In this study, the operational phase accounted for 99% of the total environmental impact, with no distinction made between maintenance and flight operations. The figures in this study are given in percentages only and do not provide exact numerical values. In 2006, Facanha and Horvath [22] calculated the environmental impact of a Boeing B747 freighter and compared the results with those of other means of transport. Not only was the entire life cycle of the vehicle considered, but also the construction and operation at the airport as well as fuel refining and distribution. In this study, however, only the inventory assessment was described in depth. The impact assessment was excluded from the study, resulting in a comparison of transport modes based only on air pollutants per freight activity. A similar approach to comparing aviation with other modes of transportation was used by Chester [23], who compared an Embraer

145, a Boeing B737, and a Boeing B747, and by Cox [24,25] (more details of this study can be found in the master's thesis by Jemioło [26]), assessing a variation of short-haul and long-haul aircraft, i.e., Short Narrow Body (SNB) and Large Narrow Body (LNB), representing the aviation sector. For the environmental assessment, the authors used an Economic Input-Output Life Cycle Assessment (EIO-LCA), which is a top-down approach that estimates the environmental impact based on economic activities [27], as the primary method leading to relatively high values. The reason for this is that the input-output approaches are rather approximate and usually contain wider system boundaries.

In a study by Lopes [28], a holistic LCA was carried out for an Airbus A330. The inventory for the manufacturing phase of the aircraft published in this master's thesis is used as a basis in many other studies. Another publication that is frequently referred to is that by Lewis [29], who compared three flight scenarios with different flight distances and aircraft types (Airbus A320, Airbus A330, and Airbus A380). The author considered aircraft manufacturing and operations using a hybrid approach combining Process-Based Life Cycle Assessment (P-LCA) and EIO-LCA. Jordão [30] applied an LCA study to the manufacturing, maintenance, and operational phases of an Airbus A330 and a Boeing B777 and compared these two aircraft types with each other. Noteworthy here is the relatively large ecological share of the maintenance phase of up to approximately 20%, which was calculated on the basis of the energy consumption of the airport and electricity price. In a recently published study by Fabre et al. [31], an LCA of an Airbus A320 was carried out. The manufacturing of the aircraft, airport construction, as well as operations using different fuel types, were considered. Maintenance activities and end-of-life were, however, neglected due to a lack of data. The authors likewise concluded that LCA is a suitable tool for the evaluation of new technologies, such as hybrid-electric or hydrogen aircraft. The study by Schäfer [32] aimed to develop a life cycle sustainability assessment methodology for the aircraft pre-design comprising an environmental and an economic assessment. For this purpose, all life cycle phases, including maintenance and end-of-life, were assessed based on CO_2, NO_X, and cumulated energy demand. In 2013, Dallara et al. [33] analysed the environmental impact of aircraft production and operations activities using a parametric Streamlined Life Cycle Assessment (S-LCA) tool called qUWick. The aircraft under consideration included an Airbus A320 and a Boeing B737 and were compared with LCA outcomes from the literature and EIO-LCA tools.

An overview of these mentioned LCA studies, whose outcomes are further applied as comparative values in Section 5, is provided in Table 1. Due to differences in aircraft types, additional information, such as aircraft weight or number of Passenger (PAX), is listed to normalise the results on a functional unit basis. The table furthermore provides information on the life cycle stages considered in each study as well as the applied LCA methods. These can mainly be categorised as a common P-LCA, an EIO-LCA, and a hybrid model combining these two approaches. An S-LCA is a simplified method that is particularly preferred for complex products. In this approach, often only individual impact categories are considered, for example, to compare different design options with each other. The studies by Howe et al. [21], Johanning [20], and Facanha and Horvath [22] are excluded from the table due to missing numerical values. Similarly, only a small selection of aircraft types was considered from the publications by Cox [24] and Dallara et al. [33].

In addition, a number of publications deal with the potential environmental impact of future aircraft concepts. These include hybrid-electric concepts [34], universal-electric powered concepts [35], or the use of Sustainable Aviation Fuels (SAFs) [36,37]. For these future technologies, a prospective LCA can be helpful for decision support in the design process or during engineering [38]. Johanning and Scholz [39], who compared electric, Liquid Hydrogen (LH_2), and SAF-powered aircraft, further indicated that additional renewable energy sources will be required to meet the increased energy demands of these concepts.

Table 1. Overview of comparable literature dealing with life cycle assessment of aircraft.

Study	**Chester [23]**	**Cox [24]**		**Lopes [28]**	**Lewis [29]**	**Jordão [30]**		**Fabre [31]**	**Schäfer [32]**	**Dallara [33]**
Aircraft Type	Boeing B737	SNB	LNB	Airbus A330	Airbus A320	Airbus A330	Boeing B777	Airbus A320	CeRAS	Airbus A330
PAX [-]	101	125	200	303	150	293	275	165	150	303
OEW [t]	37.1	31.0	51.0	124.4	42.1	106.2	134.8	37.2	42.1	124.4
Lifetime [years]	30	22	22	24	20	20	20	25	25	24
Manufacturing	●	●	●	●	●	●	●	●	●	●
Operation	●	●	●	●	●	●	●	●	●	●
Maintenance	●	○	○	○	○	●	●	○	●	○
End-of-Life	○	○	○	○	○	○	○	○	●	○
LCA Method	hybrid	P-LCA	P-LCA	P-LCA	hybrid	S-LCA	S-LCA	P-LCA	S-LCA	S-LCA

Note: ● included; ○ not included

In summary, the environmental assessment of aircraft is currently an emerging topic. Most publications refer to the operational phase as by far the most influential phase of the entire life cycle. However, changes in operation, correlations, or other resulting dynamic effects cannot be adequately represented with the above-mentioned conventional LCA approaches. An extension of the classical LCA with, for example, a discrete-event simulation can enable a dynamic operating schedule for aircraft and can thus provide an even more detailed insight into the different life cycle phases and better represent technological effects.

2.2. Combination of Discrete-Event Simulation and Life Cycle Assessment

Discrete-event simulation consists of state variables that change at discrete points in time during a simulation and thus model and execute a process as a series of individual events [40,41]. Advantages of discrete-event simulations include the ability to simulate complex systems wherein inputs and variables can be quickly exchanged to gain insight into their significance [42]. In addition, the simulated time can be easily varied and scaled without much effort. Due to the complex simulation setup, discrete event-driven simulations have thus far rarely been used for environmental issues [43]. However, according to Thiede et al. [44], a combination of LCA and discrete-event simulation is an effective solution that can overcome some of the problems of classical LCA, such as its static and disregard behaviour. Since there are no publications in the field of aviation dealing with a combination of LCA and discrete-event simulation, studies from other industrial sectors are considered in this section.

The authors de Oliveira Gomes et al. [45] compared the environmental impact of different fuels for forklift trucks in a production facility. Thereby, discrete-event simulation and LCA were carried out consecutively. The discrete events contained input data such as fuel type and consumption or the amount of products handled by the forklifts and were used to simulate different scenarios. After this simulation, the results were then used to perform an LCA by adopting the global warming method. A similar approach was followed by Bengtsson et al. [46], who analysed the energy and GHG emissions of Boeing machine tools to achieve benchmarks for sustainable manufacturing. The discrete-event simulation was performed with input data, such as cycle, setup, and down times for the machining tools. The results of the discrete-event simulation were then evaluated in an LCA focusing on direct and indirect energy consumption (kWh), carbon dioxide emissions (CO_2), and nitrogen oxide emissions (NO_X). Muroyama et al. [47] integrated discrete-event simulation input data into an LCA simulation to assess the environmental impact of a golf ball factory. Discrete parameters included the number of machines, type of polymer, and number of repair workers. The result of this simulation then provided the energy and material consumption, CO_2 emissions, and flow rate. The approach provided more effective resource management in the production process, but the authors were faced with large uncertainties due to the lack of LCI data. Comparable approaches were used, for example, by Sproedt et al. [48] to optimise the operational management of a factory, by Andersson [49] to analyse the material and energy consumption of an assembly line production, and by Löfgren and Tillman [50] to weight decision-making processes in a manufacturing process. These studies have in common that discrete-event simulation and LCA were carried out independently of each other. The results of the discrete-event simulation were hereby used as a basis for the LCA, with no possibility to intervene in the simulation itself due to ecological factors.

Apart from these sequential approaches, discrete-event simulation and LCA can be used simultaneously to enhance a combined model. Johansson et al. [51] focused on alternative solutions for a juice production plant. Using a discrete-event simulation enriched with LCA data, several factory configurations with different numbers of tanks and batches were compared. Each time an event was triggered, an LCA was automatically performed and the resulting environmental values instantly updated the model's output parameters. The focus of this study was to compare the carbon dioxide equivalents (CO_2-eq.) of the factory settings. The authors concluded that combining discrete events with LCA was much more time-efficient than applying independent analyses. A similar approach was used by Sigurðardóttir et al. [52] examining cod fishing in Iceland with a focus on the comparison of different vessel types. Each fishing activity represented a discrete event that was automatically updated with environmental impact parameters (e.g. CO_2 of the vessels) from an LCA. This allowed the environmental impact model to be traceable and easily scalable. In addition to these publications focusing mainly on the production and manufacturing phases of products, a study by Barletta et al. [53] addressed the management of electronic waste. In this context, different sorting methods were evaluated in order to obtain real-time data on energy consumption. Widok et al. [54] created a joint model for discrete-event simulation and material flow analysis, which was linked to environmental impact data to analyse different scenarios for manufacturing processes. The advantages mentioned here are again the possibility for precise analyses as well as simple and rapid adjustments of input data. Other publications have focused on construction processes in the building sector and examined the environmental impact of construction machinery and equipment [55,56] as well as the environmental performance of supply chains and on-site equipment [57].

Based on this literature review, a simultaneous approach was chosen for the present study in order to ensure a realistic variation in life cycle simulation based on ecological impacts. The methodology presented in the following sections is able to simulate an aircraft's life cycle in detail and environmentally assess it with the help of an LCA.

3. Description of Discrete-Event Simulation

The combination of LCA and discrete-event simulation described in this paper is based on an existing and generic Life Cycle Cash Flow Environment (LYFE) [58]. This modular framework was developed by the DLR Institute of Maintenance, Repair and Overhaul and provides a detailed simulation of the aircraft economic life cycle and the assessment and analysis of changes throughout the aircraft's operation. This chapter provides a more detailed introduction to the LYFE simulation environment (Section 3.1), describes the aircraft characteristics of the applied use case (Section 3.2), and presents the flight and maintenance schedule needed for the simulation of the operational phase (Section 3.3). The latter serve as the foundation for the subsequent ecological assessment of the aircraft over all life cycle phases.

3.1. Introduction to LYFE

So far, LYFE's main focus has been the economical cost-benefit evaluation of an aircraft over its entire life cycle. Thereby, all relevant cash flows (costs as well as revenues) are captured and analysed to obtain information on the profitability of the aircraft and its operator. The core of LYFE is the creation of an event calendar for the given aircraft, which covers all relevant events in the aircraft's life cycle, including aircraft purchase, performed flights, scheduled and, if necessary, unscheduled maintenance events, monthly recurring costs, as well as the sale of the aircraft at the end of its life. These specific events, particularly during operation, are processed sequentially according to a flight and maintenance schedule, resulting in a steadily growing event calendar over the duration of the simulation. Figure 1 shows an extract of the event calendar for a short-range aircraft with performed flights (blue) and maintenance events (red). Each event is an object with defined attributes depending on the event type. In general, all event types contain a unique timestamp and a specific duration that define the course of the event. Further event type-dependent parameters include the departure and arrival airport of a flight event including distance, fuel consumption, and related costs. For maintenance events, a distinction is made between the maintenance type (line, base, and shop maintenance) and the associated tasks. Boundary conditions such as turnaround times or curfew hours at certain airports are also taken into account.

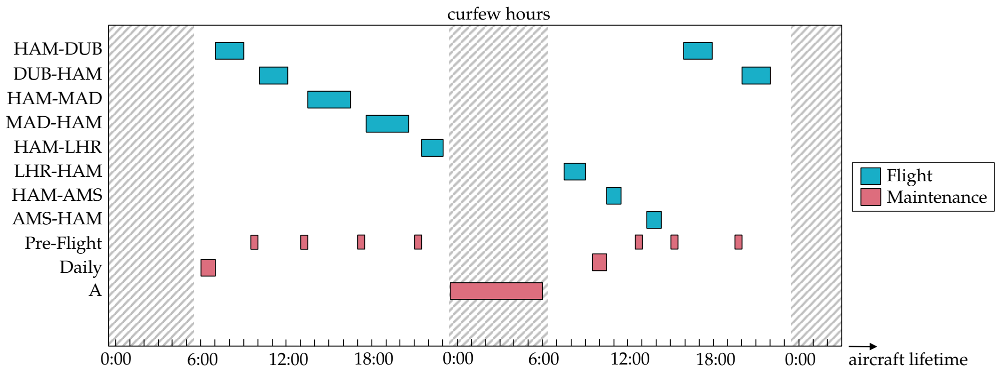

Figure 1. Operating schedule for two days including flight and maintenance events (based on [58]).

The structural design of LYFE enables the analysis of primary as well as secondary effects during the service life. Primary impacts are those that directly affect flight operations, whereas secondary impacts result from a more complex interaction network. For example, a modification to the aircraft may lead to a reduction in fuel consumption and thus has a direct impact on fuel costs and flight emissions (primary). However, maintenance activities associated with this modification may increase the ground time of the aircraft (secondary), which in turn may have implications for the operator.

Within the scope of this study, the economic focus of LYFE is expanded to include an LCA with ecological factors by performing an environmental assessment for each event or event type depending on its event-specific parameters. For instance, the ecological impact for each flight is calculated individually based on the flown distance, the number of PAX (depending on the aircraft seating and load factor), and the fuel consumption. The same applies for individual maintenance or modification events. Thus, each event is assigned an individual ecological impact, which is saved as an attribute, similar to those for costs. The generic extension with ecological factors thus enables optimisation of aircraft operations according to both economic and ecological aspects.

3.2. Aircraft Characteristics

The environmental extension of LYFE is exemplary applied to an Airbus A320 type of aircraft. The main aircraft characteristics, which are especially necessary for the environmental assessment and the simulation of the life cycle, are hereby taken from the project Central Reference Aircraft data System (CeRAS) [59]. CeRAS provides a variety of operational parameters, such as the average design range or the possible number of PAX. In addition, the detailed mass breakdown at the system level is particularly beneficial for the consideration of the manufacturing and end-of-life phase of the aircraft. The service life of the aircraft is assumed to be 25 years and it is powered by two conventional CFM56-5B engines and Jet A-1 fuel. An overview of the relevant characteristics of the aircraft can be found in Table 2.

Table 2. CeRAS aircraft characteristics (based on [59]).

Parameter	Unit	Value
Design Range	NM	2750
Cruise Mach Number	-	0.78
Passenger Capacity	PAX	150
Average Load Factor	%	80
Operating Years	years	25
Operating Empty Weight	kg	42,100
Manufacturer's Empty Weight	kg	38,200
Maximum Fuel Weight	kg	18,700
Engine Type	-	CFM56-5B
Number of Engines	-	2
Fuel Type	-	Jet A-1

3.3. Flight and Maintenance Schedule

The life cycle simulation is based on a flight and maintenance schedule for an Airbus A320 with the above-mentioned characteristics. Table 3 gives an extract of the exemplary flight plan and was created based on real flight operations of this aircraft type performed by different operators. Thereby, socio-economic air traffic forecasts, including airport capacity, aircraft performance data, and different flight routes were considered to simulate a real-world fleet utilisation. The flights are mainly short-haul with occasional medium-haul flights, resulting in an average utilisation rate of about four Flight Cycles (FCs) per day and an average flight duration of one and a half Flight Hours (FHs). Each flight is identified by a start and end time, including departure and arrival airport. In addition, the consumed fuel, as well as the flown distance, are indicated. Figure 2 illustrates the route network operated by the aircraft. The flight schedule was created as part of the EXACT project and a more detailed description of the creation of the flight plan can be found in Wehrspohn et al. [60].

Table 3. Extract from the flight schedule of an Airbus A320 with additional information on flight duration, distance, and fuel burn.

Origin	Destination	Duration [h:mm]	Distance [km]	Fuel Burn [kg]
Amsterdam (AMS)	Lissabon (LIS)	2:27	1848	5434
Lissabon (LIS)	London (LHR)	2:05	1566	4720
London (LHR)	Berlin (TXL)	1:16	948	3166
Berlin (TXL)	Zurich (ZRH)	0:53	660	2451
Zurich (ZRH)	Hamburg (HAM)	0:56	694	2533

Figure 2. Illustrated route network of the flight schedule performed by an Airbus A320 [60].

The maintenance schedule is based on a maintenance analysis of the Airbus A320 family from Aircraft Commerce [61] and consists of different categories, comprising line, base, and shop maintenance. Line maintenance checks are rather short and include mainly visual inspection tasks and oil or hydraulic fluid changes. Base maintenance checks, on the other hand, take much longer and are usually carried out during layovers and in a hangar. Large components, such as the engine or landing gear, are thoroughly inspected and overhauled in special shop visits. For these shop visits, the components are dismantled from the aircraft and transported to a special workshop. Meanwhile, the aircraft usually receives a replacement component to continue flight operations. Table 4 summarises a simplified version of the Airbus A320 maintenance schedule with associated downtimes and task intervals in FCs, FHs, or days. With these intervals, the corresponding maintenance events are integrated into the flight plan before one of these thresholds expires at the latest.

Table 4. Simplified maintenance schedule of an Airbus A320 (based on [61]).

Name	Type	Downtime [h]	Interval Thresholds [FH]	[FC]	[days]
Transit	Line	0.5	0	1	0
Pre-Flight	Line	1	0	0	1
Daily	Line	1	0	0	1.5
Weekly	Line	2	0	0	7
A	Line	10	450	0	100
C1	Base	68	4200	0	540
…	…	…	…	…	…
C16	Base	799	67,200	0	540
Engine	Shop	1008	10,000	8300	0
Landing Gear	Shop	1008	28,000	18,350	3652
APU	Shop	504	5500	4600	0

4. Life Cycle Assessment

The following section describes the approach of the implemented LCA, which is used to support the ecological extension of LYFE. After an initial goal and scope definition (Section 4.1), the preparation of the LCI (Section 4.2) is presented. Section 4.3 then provides more information on the chosen life cycle impact assessment methodology and its associated impact categories.

4.1. Goal and Scope Definition

In the goal and scope phase, the overall aim of the study as well as the assumptions and limitations are described. This is usually carried out before any data are collected and serves as the basis for the subsequent LCA steps. According to ISO 14040 [2], the objective of the study states the intended application, the reason for carrying out the study, or whether the results should be used for comparative purposes. The scope rather describes the product system of the study, including its function, system boundaries, the assumptions and limitations, as well as any data quality requirements. Additionally, one or more functional units must be selected to further describe the product system of the study in more detail and to provide a reference for future comparisons.

4.1.1. Study Goal

The goal of this study is a detailed holistic LCA of an aircraft similar to an Airbus A320 and to subsequently compare it with other literature findings. In particular, the operational phase is simulated with the help of a discrete-event simulation using the flight and maintenance schedule described in Section 3.3, thus providing a detailed basis for a thorough ecological assessment.

4.1.2. System Boundary

The analysed life cycle phases include the manufacturing, flight operations, maintenance, and end-of-life of the aircraft. In particular, the ground-based phases (production, maintenance, and end-of-life) are considered and calculated in detail. A graphical representation of the system boundaries is presented in Figure 3.

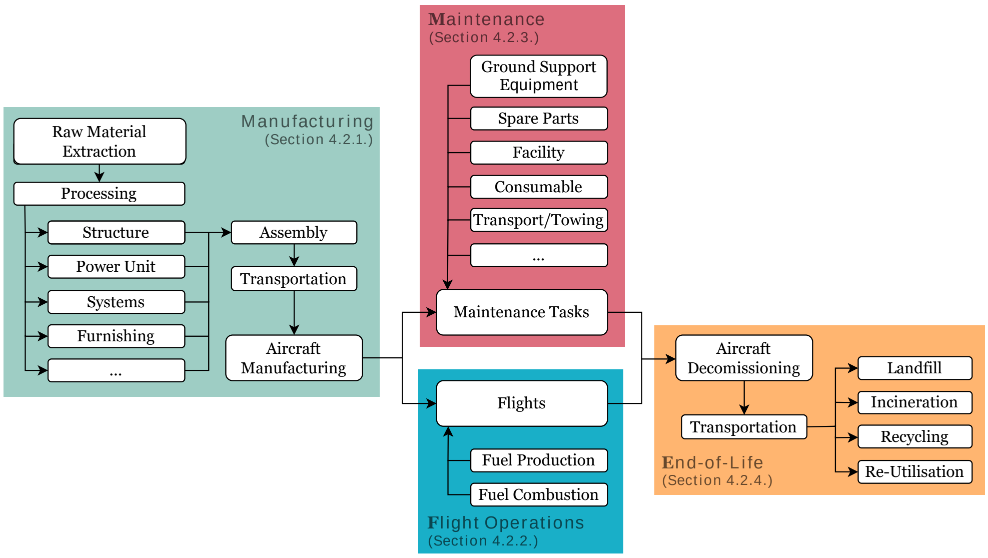

Figure 3. System boundaries of the presented life cycle assessment study.

In the manufacturing phase (green), raw material extraction, as well as manufacturing and assembly processes, are within the scope of the study. In addition, the transport of components from different manufacturing sites (similar to that of an Airbus A320) to the Final Assembly Line (FAL) is considered. Construction, maintenance, and operation of the manufacturing facilities are not included in this study. The flight operations (blue) include the production and transport of kerosene as well as the emissions resulting from combustion in flight. For the maintenance activities (red), equipment, materials, spare parts, transportation, and facilities are included in the system boundaries. The end-of-life of the aircraft (yellow) ends with the selection and transportation to different end-of-life scenarios (landfill, incineration, recycling, or re-utilisation).

4.1.3. Functional Unit

The functional unit is important for the interpretation and quantification of the LCA results. A very commonly used functional unit for aircraft in the literature is the unit *per Available Seat Kilometre (ASK)*. By choosing this unit, it can be ensured that the results of the calculations can be compared with other LCA studies, regardless of the chosen lifetime or the aircraft's utilisation. It is, however, dependent on the seating of the aircraft, as the flown kilometres are divided by the number of PAX. Another option for the functional unit is the *per Operating Empty Weight (OEW)*. This unit is particularly useful for comparing manufacturing and end-of-life processes, as these take place only once in a lifetime, irrespective of the operations phase, and are dependent on the aircraft weight. For the comparison with other literature findings (Section 5), both functional units are used, depending on each life cycle phase.

4.2. Life Cycle Inventory

The LCI analysis is essential for the implementation of an LCA. The inventory consists of inputs, e.g., resources and outputs, such as emissions (to air, water, and soil), waste, or other products. These inputs and outputs are summarised as flows and form processes that are linked to each other through exchanges of these flows. For the compilation of the inventory, the ecoinvent 3.7.1. cut-off database and several additional publications were used. A description of the LCI preparation for the different life cycle phases can be obtained below. An overview of the inventory can further be found in the supplementary data.

4.2.1. Manufacturing

Aircraft design and the associated manufacturing phase have a high level of complexity and thus a high potential for efficiency improvements for future aircraft. To gain an understanding of specific production stages and their current environmental impact, a detailed and component-based inventory is important. The manufacturing phase is divided into three sections: raw material extraction, processing and assembly, and transportation.

Raw Material Extraction

For the creation of the LCI in the manufacturing phase of the aircraft, a detailed mass and material breakdown at the component level is required. For this purpose, the aircraft under consideration must first be broken down into its structure and systems in order to consider them individually. An overview of the aircraft components and considered sub-components is shown in Figure 4.

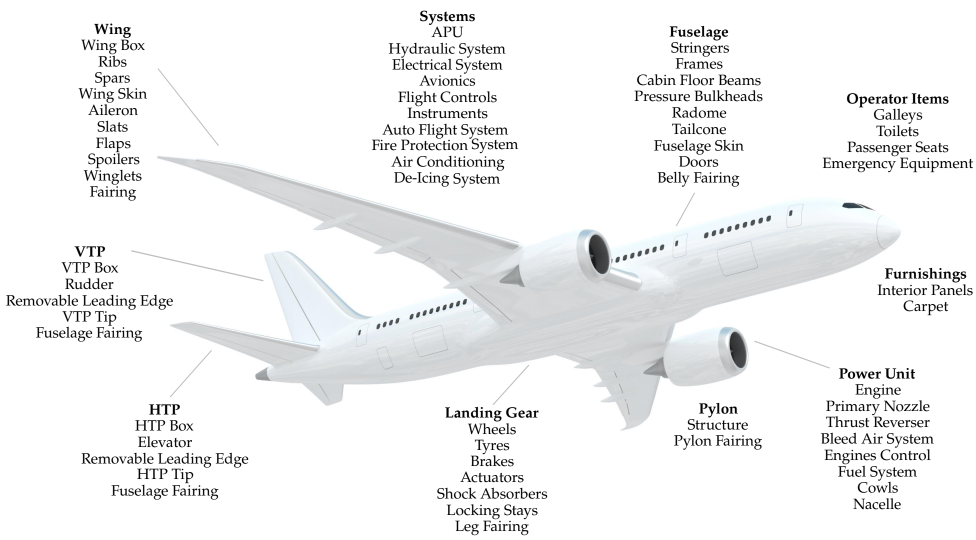

Figure 4. Component breakdown of the aircraft for the manufacturing life cycle inventory.

The aircraft structure comprises the wings, fuselage, Horizontal Tail Plane (HTP), Vertical Tail Plane (VTP), landing gear, and pylons with their respective compounds. Engines with nacelle, bleed air system, as well as the entire fuel system are counted as part of the power unit, whereas the systems category includes all other flight-relevant equipment. In addition, the mass breakdown for structure and system components is taken from CeRAS, as the values are comparable to those of an Airbus A320. Figure 5 illustrates the OEW distribution among the structure, systems, power unit, operator items, and furnishing. The aircraft structure accounts for about 58% of the aircraft weight, followed by the power unit with 19%.

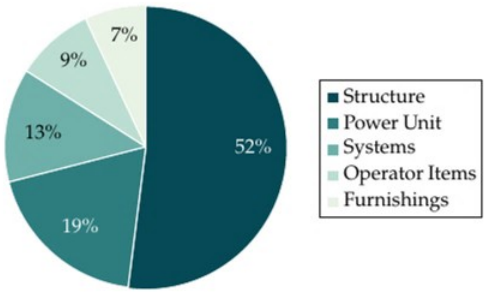

Figure 5. Mass breakdown of the considered aircraft based on CeRAS and own calculations and assumptions.

The structural components are assigned to one or more corresponding materials. For this, a variety of publications is used as a basis and, where necessary, adjusted with appropriate estimates. In the case of the wing, for example, the spars, ribs, and wing skin are mainly made of aluminium, resulting in a total material content of about 85% [62]. Other structural elements, such as ailerons, winglets, or fairings for landing gear or flap tracks are made of Carbon Fibre-Reinforced Plastic (CFRP) [63]. In addition, some components of the aircraft, such as the belly fairing or the VTP leading edge, are made of Aramid Fibre-Reinforced Plastic (AFRP) and Glass Fibre-Reinforced Plastic (GFRP). As the ecoinvent database does not contain these material datasets, CFRP is assumed for these components as well. For the power unit, a material and mass breakdown from Lopes [28] was used as a basis and expanded with an EASA Type-Certificate Data Sheet [64]. Based on these assumptions, the most commonly used materials in the engine are titanium (27%), which is, for instance, used for the turbine blades, CFRP (19.5%), mainly applied for nacelle and cowls, as well as nickel (17%), which is used under high operating temperatures in the engines due to its considerable strength and corrosion resistance [65]. The material breakdown for the systems is subject to many uncertainties and assumptions. By using product data sheets and a variety of other publications, materials and weights are assigned to each individual system component. Aluminium, steel, and copper are identified as the most common materials for system components. An overall breakdown of the materials used in the aircraft can be seen in Figure 6 and is confirmed with data from the literature.

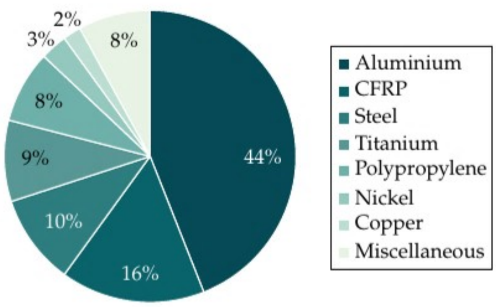

Figure 6. Material breakdown of the considered aircraft based on CeRAS and own calculations and assumptions.

The calculation of the environmental impact from raw material extraction $EI_{extraction}$ at the component level is carried out using Equation (1), where $EI_{material}$ is the ecological impact of the extraction of a material M and the mass m of a component C.

$$EI_{extraction,C} = \sum_{M} EI_{material,C,M} \cdot m_{C,M} \quad (1)$$

Processing and Assembly

Manufacturers usually keep the manufacturing processes in aircraft construction highly confidential in order to maintain their competitiveness. To estimate the respective manufacturing process, precise knowledge of the component geometry is needed, which is not feasible within the scope of this study. For this reason, an average value for the processing energy consumption was used for each material, regardless of the specific component. Aluminium sheets for the wing skin, for example, have to be milled in shape and hardened through various heat treatment processes before utilisation. The processing of one kilogram of aluminium is assumed to have an energy consumption of 89.3 MJ/kg [66]. For the manufacturing of CFRP components, several processes, including fibre winding, tape laying, and injection moulding can be applied. Based on a study by Bohlender [66], an energy consumption value of 40.2 MJ/kg is therefore selected. For titanium, a significantly higher energy consumption of on average 216 MJ/kg was reported in the literature [67,68], as very high amounts of specific energy inputs are required, e.g., for milling or machining, due to titanium's poor thermal conductivity properties. For each component, the corresponding ecological impact $EI_{processing}$ is calculated with the energy consumption during processing $E_{processing}$, based on its specific material composition.

$$EI_{processing,C} = \sum_{M} E_{processing,C,M} \cdot m_{C,M} \quad (2)$$

For the environmental impact of the assembly $EI_{assembly}$, material-specific joining methods were determined. For metallic materials such as aluminium, possible joining methods include rivets or screws. CFRP, on the other hand, is often assembled via adhesive bonding. The energy consumption for the assembly $E_{assembly}$ is 23.8 MJ/kg for metals and 14.2 MJ/kg for CFRP components.

$$EI_{assembly,C} = \sum_{M} E_{assembly,C,M} \cdot m_{C,M} \quad (3)$$

Transportation

As this study focuses on an aircraft similar to an Airbus A320, the transport between different production sites is included in this environmental assessment. For this purpose, all distributed components must first be identified and assigned to a suitable transportation vehicle V. The ecoinvent database contains a number of different datasets for calculating the ecological impact of the transportation $EI_{transportation}$ of a given component, depending on the mass m and the distance travelled d (see Equation (4)). This study assumes that the FAL is located in Hamburg, Germany. The wings are manufactured in the UK and in Germany, while for the fuselage, some parts are manufactured in France whereas others are fabricated directly at the FAL. Within Europe, the Airbus A330-700L (also known as Beluga [69]) and trucks are the main means of transport.

$$EI_{transportation,C} = \sum_{V} EI_{transportation,C,V} \cdot m_{C,V} \cdot d_{C,V} \quad (4)$$

The total environmental impact of aircraft manufacturing $EI_{manufacturing}$ is then calculated with the sum of raw material extraction, processing, assembly, and transportation for all considered components C.

$$EI_{manufacturing} = \sum_{C}(EI_{extraction,C} + EI_{processing,C} + EI_{assembly,C} + EI_{transportation,C}) \quad (5)$$

4.2.2. Flight Operations

The ecological impact of flight operations depends on the aircraft's specific fuel consumption, the distance flown, and the number of completed flights. A distinction can be made between the production of the fuel and the effects and emissions during combustion in flight. These two factors are taken from the literature and database information and are discussed in more detail below.

Fuel Production and Supply

Jet A-1 kerosene is mainly used in aviation for a variety of different turbine-powered aircraft and must meet strict international regulations. The fuel is mainly produced from crude oil and must go through various production processes. These include, for example, extraction through drilling. The crude oil is then broken down into its constituents by distillation, purified, and finally processed for transportation and utilisation [70]. According to Koroneos et al. [71], the refining process is the most environmentally harmful operation due to its highly energy-intensive process. Depending on the region, crude oil source, and refinery process, the environmental impact of the fuel production can vary greatly. Various studies have calculated the carbon intensity of the whole kerosene production process to be 12–22 gCO_2-eq./MJ [72]. With a specific energy value of 43.2 MJ/kg [36], this results in 0.5–0.95 kgCO_2-eq./kg fuel. These values are consistent with the ecoinvent database for the *market for kerosene* dataset, which includes kerosene production and supply, and is therefore used as a basis for this assessment.

Flight Emissions

Emissions emitted during the flight phase account for the main part of the ecological impact of aircraft in all the considered LCA studies. For a detailed calculation of the climate impact, not only CO_2 emissions but also so-called non-CO_2 climate effects have to be taken into account. The most common non-CO_2 effects are caused, for example, by the production of water vapour, NO_X emissions, or contrail-induced cloudiness [73]. Unlike CO_2 emissions, which are location-independent because of their long lifetime in the atmosphere, these effects are strongly correlated with altitude and geographical longitude and latitude. Due to this complexity and the fact that there is no direct linear dependency between overall climate impact and fuel consumption, there are significant uncertainties in the ecological calculation of aircraft emissions [74]. There are already existing frameworks and studies (e.g., by Grewe and Stenke [75]) that incorporate all these parameters and thus provide a detailed and reliable statement on the climate impact of aviation. However, the results of these calculation tools are often limited to a few impact categories, for example Global Warming Potential (GWP) or Average Temperature Response (ATR), and are only applicable to certain flight schedules. For a holistic LCA analysis, as is the aim of this paper, the GWP alone is not sufficient. Therefore, a simplified approach is chosen in this study to at least consider the magnitude of flight operations.

The ecoinvent database provides ecological datasets for the *market for transport, passengers, aircraft* over a certain distance. These datasets are divided into very short-haul (<800 km), short-haul (800–1500 km), medium-haul (1500–4000 km), and long-haul flights (>4000 km). The distinction in these categories can be explained by the fact that, for example, short-haul flights are particularly harmful per ASK, as the emissions during the kerosene-intensive climb phase are exceedingly high [76]. A closer look at the ecoinvent dataset, however, reveals that these datasets proportionally include both the production and transport of kerosene and the construction and operation of the airport. Due to the lack of data availability on the flight phase of aircraft and their environmental impact, the corresponding activities that lie outside the system boundaries of this study and that are already covered in fuel production are removed from every impact category. The high complexity of the interconnection between individual inventory datasets entails further uncertainties that have to be critically discussed in the analysis of the results.

The ecological impact of the operation phase is thus derived from the modified ecoinvent transportation dataset ($EI_{PAX.transport}$) as a function of the flight distance d and the number of PAX n_{PAX}, as well as the ecological impact of kerosene production $EI_{kerosene}$, depending on the amount of burned fuel m_{fuel} per flight F.

$$EI_{operation} = \sum_{F} (EI_{PAX.transport,F} \cdot d_F \cdot n_{PAX,F} + EI_{kerosene,F} \cdot m_{fuel,F}) \tag{6}$$

4.2.3. Maintenance

Maintenance is very often neglected or simplified in LCA studies. However, due to the event-based nature of this environmental assessment, independent consideration of each maintenance event in the maintenance schedule (see Section 3.3) is essential. For this purpose, the activities in each check are analysed and ecologically assessed according to their specific boundary conditions. The most important factors for the ecological assessment of maintenance activities are:

- The manufacturing and transportation of spare parts;
- The energy consumption of maintenance equipment;
- The operation of the maintenance facilities.

In particular, the latter two aspects are strongly dependent on the duration of the respective check. For simplification, the existing maintenance activities listed in the maintenance schedule are divided into line, base, and shop maintenance.

Line Maintenance

Line maintenance includes the maintenance work that must be carried out before a flight to ensure the airworthiness of the aircraft. This usually includes pre-flight, transit, daily, weekly, and A-checks [77]. Short and frequent maintenance tasks, such as pre-flight checks and transit checks, usually only involve visual checks directly on the ramp. As this is assumed to be carried out by the aircraft crew and thus no transport or special equipment is involved, the environmental impact for these tasks is neglected. Other line maintenance checks include activities that cause, for instance, emissions generated by Ground Support Equipment (GSE), maintenance vehicles, or general service tasks, such as engine oil servicing. Equation (7) describes the calculation for the environmental impact of line maintenance EI_{line} for each maintenance task T, with the impacts of the equipment EI_{GSE}, the vehicles $EI_{vehicle}$, and the consumables $EI_{consumable}$.

$$EI_{line} = \sum_{T} (EI_{GSE,T} + EI_{vehicle,T} + EI_{consumable,T}) \tag{7}$$

Base Maintenance

The maintenance schedule presented in Section 3.3 comprises various C-checks, which are characterised by a high level of detail and a comparatively long duration [77]. During the C-check, safety-relevant systems and components are checked in detail. In addition, intensive cleaning and an overhaul of the cabin are carried out [78]. For base maintenance, the aircraft usually has to be transferred to a maintenance base, where the maintenance work is performed in a hangar. Using data from the literature [79], energy consumption for the hangar per hour (for lighting, heating, or ventilation) was calculated related to the aircraft size [80]. The environmental impacts of base maintenance EI_{base} is similar to those of line maintenance (see Equation (7)), with the additional environmental impact of operating the facility EI_{hangar} and the towing of the aircraft EI_{towing}.

$$EI_{base} = \sum_{T}(EI_{line,T} + EI_{hangar,T} + EI_{towing,T}) \quad (8)$$

Shop Maintenance

Certain complex components, such as the engine, landing gear, and the APU, are replaced during the course of the aircraft's life to be thoroughly overhauled. The aim of so-called shop visits is to detect corrosion, fractures, or other defects that are not visible during a regular line or base check [77]. Therefore, the components are first removed from the aircraft and transported to a special workshop. There, they are disassembled, cleaned, stripped of paint, if necessary, and then examined via non-destructive testing methods using special equipment. Information on the quantity of replaced sub-components (i.e., scrap rate) is very difficult to obtain. Based on an article by Aircraft Commerce [81], stating that 25% of engine shop visit costs are related to spare parts, this assumption has been adapted to the environmental perspective. It is therefore assumed that one quarter of the respective shop components needs to be fully replaced. For the calculation of the ecological impact, the energy consumption of the workshop is determined similarly to that of the hangar. The transport from the aircraft to the workshop is calculated using the component mass and the travelled distance. An important environmental aspect of the engine's workshop visit is a final engine test run in a test cell, where the engine is operated in different modes for several minutes to ensure full operational capability. The ecological impact of the shop visit EI_{shop} is calculated with Equation (9) and includes the operation of the workshop ($EI_{workshop}$), special workshop equipment ($EI_{equipment}$), the manufacturing of spare parts (EI_{spare}), testing procedures ($EI_{testing}$), and the transportation to the workshop itself ($EI_{transportation}$).

$$EI_{shop} = \sum_{T}(EI_{workshop,T} + EI_{equipment,T} + EI_{spare,T} + EI_{testing,T} + EI_{transportation,T}) \quad (9)$$

In addition to these mentioned maintenance categories, there are other recurring tasks that may also influence the environmental impact. These include, for example, the regular replacement of tyres and brakes or engine washes, as further explained in Rahn et al. [82]. However, these maintenance tasks are considered as non-scheduled tasks, which is why they are not included in the calculation of the environmental impact in this study.

4.2.4. End-of-Life

The final phase after the aircraft's service life is the end-of-life. Typical end-of-life scenarios are landfill, incineration, recycling, or re-utilisation, although there is very little information on the disposal scenario for individual aircraft components. The most comprehensive study in this area to date was carried out as part of the Process of Advanced Management of End-of-Life of Aircraft (PAMELA) [83] project, a joint study by the EU and aircraft manufacturers. The results of this study are applied as a basis for this end-of-life assessment, albeit individually adjusted. For example, the distribution of end-of-life scenarios for structural components, such as wings, fuselage, HTP, and VTP, is taken from the PAMELA study. However, own assumptions were made for the landing gear and engine. Due to their high residual values and the fact that they are subject to regular overhauls during their lifetime, a certain re-use factor of 75–80% is assumed for these components. For the systems, on the other hand, it is more difficult to find adequate information, which is why the end-of-life treatment is estimated individually based on the material scarcity. For small parts, such as heat exchangers or electrical and hydraulic valves, a landfill rate of 100% is assumed, while the APU, batteries, or flight control actuators are considered to be partly recycled or re-used. An overview of the proportion of the individual end-of-life scenarios for the entire aircraft based on the mass is shown in Figure 7. Landfill and recycling each account for the largest share of the aircraft end-of-life, namely 34% and 41%, respectively, whereby only 12% of the total aircraft is directly re-used.

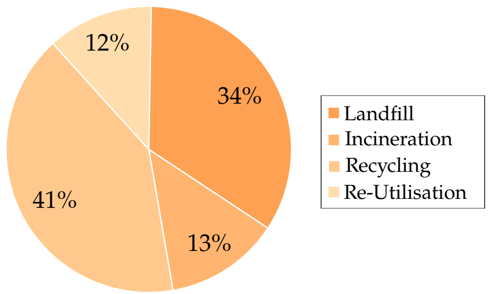

Figure 7. Distribution of the end-of-life scenarios of the entire aircraft based on the aircraft weight.

After creating an individual disposal scenario for each component, the respective environmental consequences of these scenarios are calculated. For instance, if a component is sent to a landfill, no impact was assumed except for the transportation to this landfill site. Incineration, on the other hand, is considered a possible waste-to-energy method, which can be used to generate energy in the form of electricity and heat by burning the waste. Depending on the material, incineration can generate up to 44 MJ/kg, which has a positive effect on the overall environmental impact of the aircraft. The ecological impact of the incineration scenario $EI_{incineration}$ is calculated with Equation (10), where $E_{incineration}$ is the energy generated from incinerating a material.

$$EI_{incineration,C} = \sum_{M} E_{incineration,C,M} \cdot m_{C,M} \tag{10}$$

Significantly more benefits can be created by the recycling of components, as energy can be saved, and water, soil, and air pollution can be reduced by proper treatment [84]. A so-called credit for avoided virgin production was assumed for the proportion of recyclable material. This assumes that the recycled material of a given product substitutes virgin material for future products [85]. The Equation (11) is used to calculate the environmental impact of recycling a component $EI_{recycling}$. Since the energy of a recycled material $E_{recycling}$ is usually lower than that of the virgin material E_{virgin}, the energy consumption of the recycling process is usually negative. $\eta_{recycling}$ is the specific recycling rate of a component.

$$EI_{recycling,C} = \sum_{M} (E_{recycling,C,M} - E_{virgin,C,M}) \cdot \eta_{recycling,C,M} \cdot m_{C,M} \tag{11}$$

Re-utilisation assumes that a component can be re-used without further processing. In this calculation, a specific re-utilisation efficiency $\eta_{re-utilisation}$ of 90% is assumed. This means that 10% of the original energy is necessary due to, for instance, a new recertification or minor adjustments. With Equation (12), the environmental impact, that is saved when a specific component can be used again, is calculated.

$$EI_{re-utilisation,C} = \sum_{M} E_{virgin,C,M} \cdot \eta_{re-utilisation,C,M} \cdot m_{C,M} \tag{12}$$

In addition to these calculations, it is assumed that for each component, transportation ($EI_{transportation}$) is required for the respective end-of-life scenario, either to the landfill, incineration site, or back to the manufacturer or operator for re-utilisation. The total environmental impact of the aircraft end-of-life EI_{eol} is calculated with:

$$EI_{eol} = \sum_{C} (EI_{incineration,C} + EI_{recycling,C} + EI_{re-utilisation,C} + EI_{transportation,C}) \tag{13}$$

4.3. Life Cycle Impact Assessment

The LCIA is the third step of the LCA in which the elementary flows from the LCI are transferred into their potential impact on the environment [4]. For this purpose, the inputs and outputs of the inventory are assigned to various impact categories, e.g., climate change, ozone layer depletion, toxicity, acidification, etc. These impact categories must first be selected for the respective LCA and usually concern the three areas: natural environment, human health, and natural resources. In this study, the Environmental Footprint (EF) 2.0 methodology [86] was chosen as impact assessment methodology. Table 5 lists the selected impact categories of this methodology as well as their indicators and units.

Table 5. Impact categories for the life cycle impact assessment (taken from [86]).

Abbr.	Impact Category	Indicator	Unit
CC	Climate Change	Global Warming Potential	kg CO_2-eq.
AP	Acidification	Accumulated Exceedance	mol H^+-eq.
FETP	Freshwater Ecotoxicity	Comparative Toxic Unit for Ecosystems	CTUe
FEP	Freshwater Eutrophication	Fraction of Nutrients Reaching Freshwater End Compartment (P)	kg P-eq.
MEP	Marine Eutrophication	Fraction of Nutrients Reaching Marine End Compartment (N)	kg N-eq.
TEP	Terrestrial Eutrophication	Accumulated Exceedance	mol N-eq.
HHC	Carcinogenic Effects	Comparative Toxic Unit for Humans	CTUh
IR	Ionising Radiation	Human Exposure Efficiency	kBq U^{235}-eq.
ODP	Ozone Depletion Potential	Ozone Layer Depletion	kg CFC-11-eq.
POF	Photochemical Ozone Formation	Tropospheric Ozone Concentration Increase	kg NMVOC-eq.
PM	Respiratory Effects	Human Health Effects Associated with Particulate Matter	disease incidences
WS	Water Use	User Deprivation Potential	kg world eq. deprived
ECF	Energy Carriers	Abiotic Resource Depletion	MJ
LU	Land Use	Soil Quality Index	m^2a
MM	Minerals and Metals	Abiotic Resource Depletion	kg Sb-eq.

In the EF 2.0 methodology, the material and energy inputs and outputs are first assigned to one or more associated impact categories. The subsequent characterisation evaluates the contributions of the inputs and outputs in the respective impact categories. For this purpose, so-called characterisation factors are used with which the emission impacts are multiplied. Two further optional steps are weighting and normalisation of the categories [87]. The LCIA is usually carried out automatically with appropriate LCA software. In this study, the open-source and python-based LCA framework Brightway2 is applied to perform the LCIA.

5. Results

In the following, the LCA results for all considered life cycle phases are presented. Due to the study boundary conditions and different functional units, the comparison with the literature is carried out separately for each life cycle phase (Section 5.2). This is followed by a brief interpretation of the results (Section 5.3) and, based on this, the strengths and weaknesses using discrete-event simulation are discussed (Section 5.4).

5.1. Total Results

At the end of the discrete life cycle simulation, all events are summarised according to their respective life cycle phase. Table 6 provides an overview of the calculated values in the impact category Climate Change (CC). The results are given in absolute values and normalised per ASK, as well as in their respective percentage share, of the life cycle. Considering the environmental impact of the aircraft over 25 years, the flight phase has, by far, the largest ecological contribution with more than 99%.

Table 6. Life cycle assessment results of the climate change impact category for all considered life cycle phases of one aircraft with a lifespan of 25 years.

Life Cycle Phase	GWP		
	[$kgCO_2$-eq.]	[$kgCO_2$-eq./ASK]	[%]
Manufacturing	1,401,164	2.25×10^{-4}	0.19
Flight Operations	733,789,318	1.18×10^{-1}	99.70
Maintenance	789,165	1.27×10^{-4}	0.11
End-of-Life	−707,239	-1.13×10^{-4}	−0.10
Total	735,272,408	1.18×10^{-1}	-

Additionally, the impact categories Freshwater Eutrophication (FEP), Ozone Depletion Potential (ODP), and Minerals and Metals (MM) are exemplarily shown as pie charts in Figure 8, as the largest effects and variations (especially regarding the fuel production and combustion) can be seen here. However, the operational phase clearly represents the greatest impact in these analyses as well. The results of all other impact categories for each life cycle phase can be found in the supplementary data.

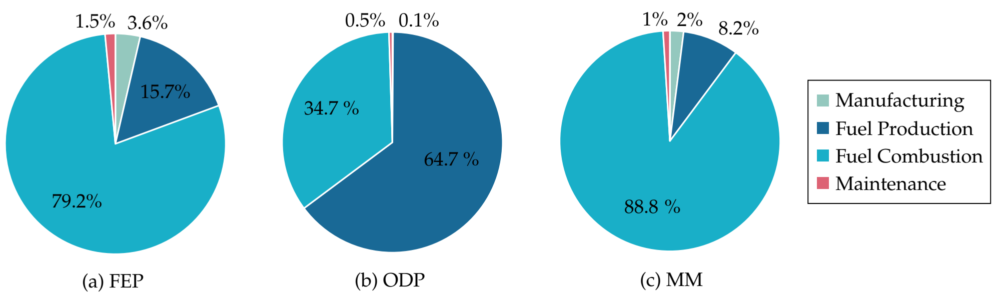

Figure 8. Life cycle assessment results for the freshwater eutrophication (**a**), ozone depletion potential (**b**), and mineral and metal (**c**) impact categories.

5.2. Individual Results for the Life Cycle Phases

5.2.1. Manufacturing

According to the CC impact category, the production phase of an aircraft has a total impact of about 1401 tCO_2-eq. calculated with the GWP. The largest share of this is related to raw material extraction (51%) and processing and assembly (48%). The transportation of the components to the FAL accounts for only 1%. Based on the created inventory (Section 4.2), the corresponding environmental impact for each category can be analysed at the component level, which is visualised in Figure 9. The power unit has the largest share in the majority of the impact categories. The selection of high-quality and robust materials is a decisive factor in this context. In the CC impact category (first bar in the chart), its share is about 30%, closely followed by the wings (19%) and fuselage (18%), whose ecological impact is mainly caused by their structural weight and material composition. The contribution of the different components is similar in almost all impact categories. An exception is the impact category of materials and metals, where systems have the largest share with almost 60%. The reason for this high share is the considerable proportion of valuable metals, such as nickel, copper, and invar, which are particularly significant in the MM category. Pylons, landing gear, HTP, and VTP, as well as the operator items and furnishings have the lowest impact in most impact categories, mainly because of the relatively small mass of these components.

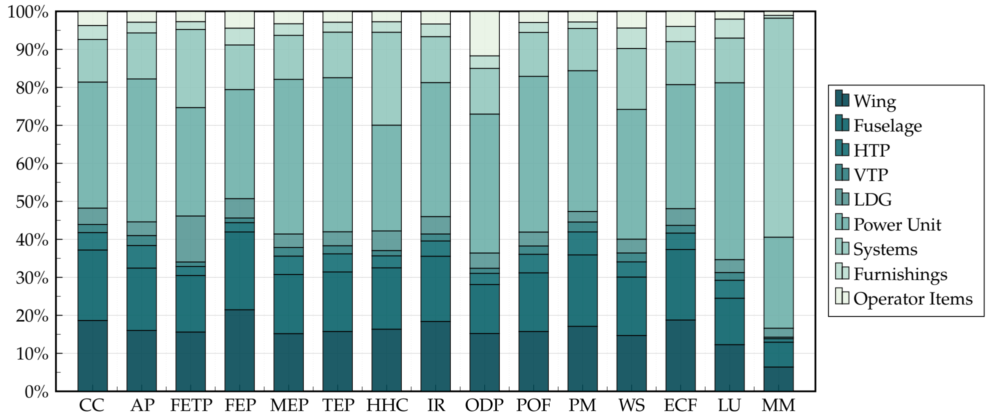

Figure 9. Life cycle assessment results for the manufacturing phase across all impact categories.

Comparison with Literature

For the aircraft manufacturing phase, the functional unit *per OEW* is most suitable for comparing the environmental impacts of the manufacturing phase with those from the literature. Figure 10 depicts the GWP of all considered studies in relation to the assumed OEW of the aircraft applied therein. A comparison is only applicable for GWP, as most studies only report their results in kgCO_2-eq. or use other LCIA methods, which makes a comparison for all of the impact categories used here impossible. The results of the LCA for the manufacturing phase differ significantly in the individual studies. The main reasons for these variations are different assumptions regarding the aircraft weight and its material composition. Nonetheless, the result of the present study falls within the average of all publications.

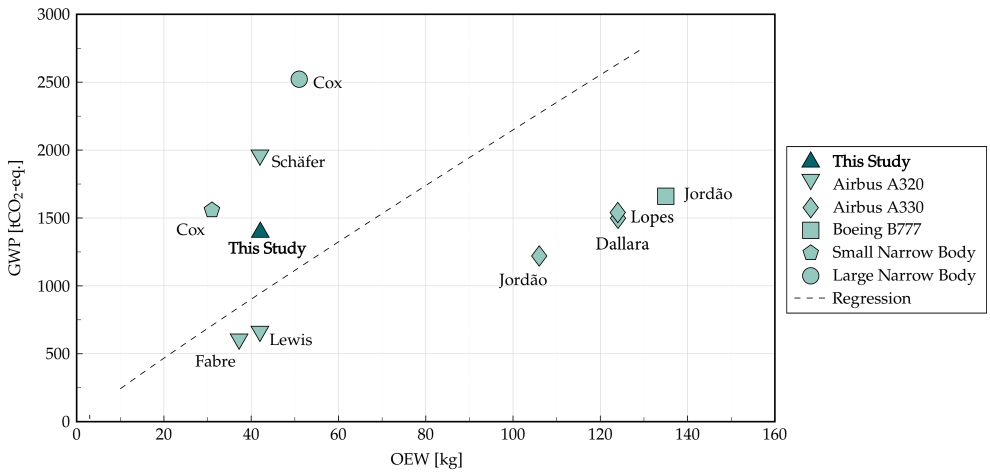

Figure 10. Overview of the ecological impact (GWP) of this study and other publications over the associated operating empty weight. (Cox [24], Lopes [28], Lewis [29], Jordão [30], Fabre [31], Schäfer [32], Dallara [33]).

This is particularly visible when the values from the literature are normalised for direct comparison. A further comparison of the normalised ecological impacts in kgCO_2-eq. per kilogram of aircraft OEW is illustrated in Figure 11.

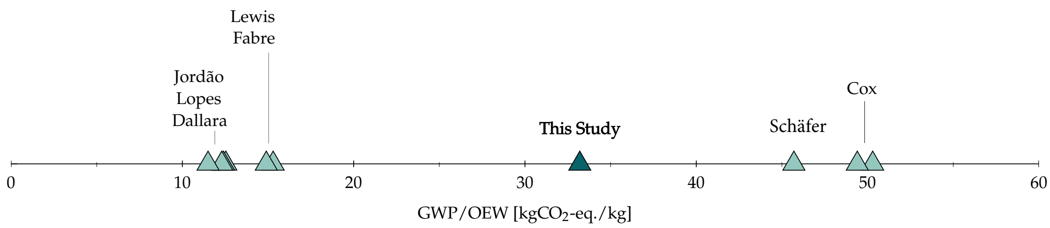

Figure 11. Comparison of the manufacturing impact of this study with outcomes from other publications (normalised by aircraft operating empty weight) (Cox [24], Lopes [28], Lewis [29], Jordão [30], Fabre [31], Schäfer [32], Dallara [33]).

5.2.2. *Flight Operations*

The ecological value of the flight phase depends primarily on the total lifetime of the aircraft and thus on the number of flights performed. This means that the longer an aircraft is in operation, the greater the ecological impact. Due to the different assumptions and boundary conditions in the published studies, the functional unit *per ASK* is used to compare the results. In this paper, the calculated average value for an ASK based on a service life of 25 years and a passenger capacity of 150 PAX is 0.118 kgCO_2-eq. The total environmental impact of the operation is subsequently divided by the number of PAX and kilometres. Figure 12 illustrates the ratio of fuel production and combustion in all impact categories.

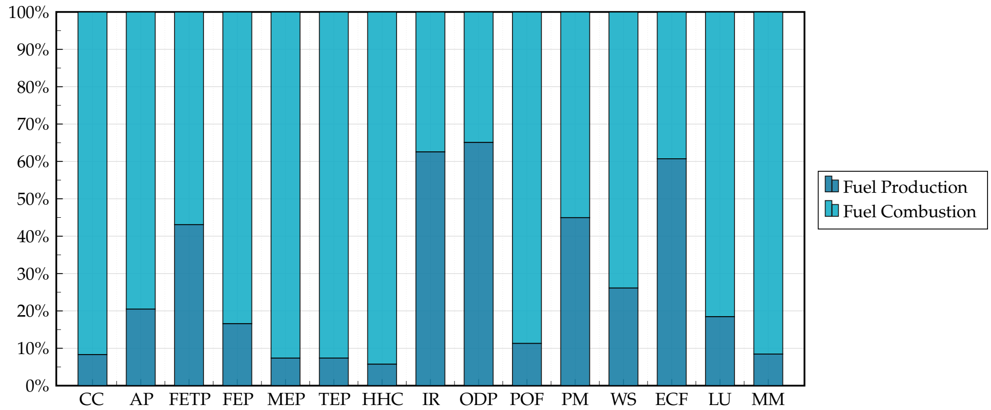

Figure 12. Life cycle assessment results for the operation phase across all impact categories.

Fuel combustion has by far the highest share in almost all impact categories compared to the production of kerosene. In the CC category, for example, in-flight combustion causes an impact eleven times higher than the fuel production. This is primarily due to emitted GHG emissions, particulate matter, and NO_X, which are the main drivers in certain impact categories [88]. In other categories, such as ionising radiation and energy carriers, however, the share of fuel production exceeds that of its combustion for different reasons. Crude oil production contributes a share of more than 60% to these impact categories. For the ODP impact category, instead, the high impact of kerosene production results, for example, from the chemical element halon 1301 (bromotrifluoromethane), as this is recorded in the ecoinvent database as an emission from petroleum production [89].

Comparison with Literature

Despite the complexity mentioned above, the operational phase is the most analysed life cycle phase in the literature. The reason for this is primarily the immense impact that it has on aviation. Most studies in this field only look at fuel-specific emission indices for CO_2, NO_X, HC, or CO emissions, for which there are special engine emission databases [90] or calculate the environmental impact of the flight phase based on GWP or ATR. However, this approach does not represent an environmental LCA and should therefore be treated with caution, which is why a comparison of the results is only possible to a limited extent. The unit CO_2-eq. per ASK serves as the basis for this analysis. The greatest similarities can be observed with the results of the studies by Chester [23] and Cox [24]. An overview of the comparative studies can be found in Figure 13. Again, it can be seen that the calculated environmental impact for the operation phase of this study (dark blue) fits in well with outcomes from other publications.

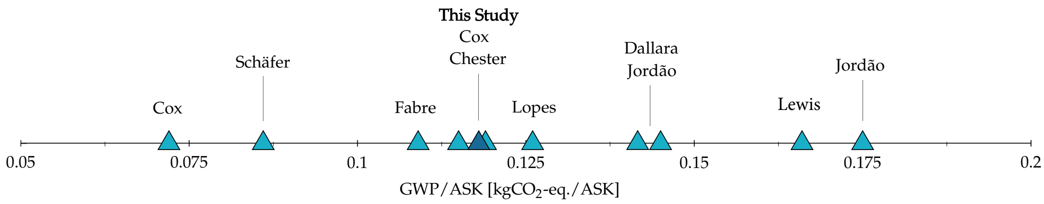

Figure 13. Comparison of the operations impact of this study with outcomes from other publications (normalised by available seat kilometres) (Chester [23], Cox [24], Lopes [28], Lewis [29], Jordão [30], Fabre [31], Schäfer [32], Dallara [33]).

5.2.3. *Maintenance*

Similar to operations, the maintenance phase also depends on the lifetime and utilisation of the aircraft. The total environmental impact in the CC impact category for all maintenance activities is 1.27×10^{-4} $kgCO_2$-eq./ASK, whereby the largest share is caused by C-checks and shop visits (especially for the engine). C-checks occur rather rarely, but have a comparably high impact caused by their long maintenance duration. Moreover, these checks are carried out in the hangar, which represents an additional environmental impact because of the electricity consumption of the facility and equipment. The engine shop visit has a significant environmental impact due to its complex maintenance processes and the high number of spare parts that is needed for the overhaul.

An overview of all other impact categories is shown in Figure 14. Besides the CC, workshop visits have a very high impact in several other categories. For example, in the MM, the effect of component shop visits represents more than 65% compared to all other maintenance checks. This is mainly due to the materials needed to manufacture the spare parts for the engine, landing gear, and APU. In the impact category ODP, daily and weekly checks in combination lead to a comparatively high environmental impact. One of the largest ozone-depleting substances is N_2O, which is produced, for example, by the operation of diesel-powered ground-based GSE, which are mainly used for ramp maintenance checks. This shows that the results for different impact categories can be rather diverse, which is why it is important to take them into account and analyse them accordingly.

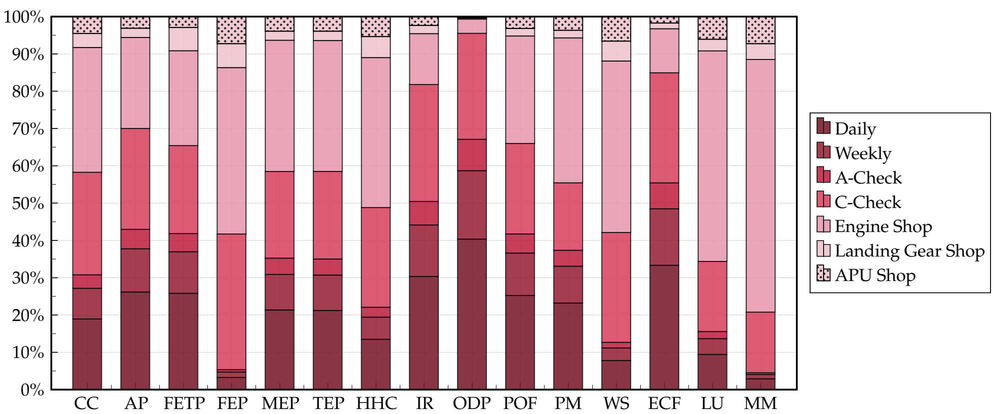

Figure 14. Life cycle assessment results for the maintenance phase across all impact categories.

Comparison with Literature

Comparative values from the literature are rare. Many publications disregard the maintenance phase or integrate it into the operations phase in a simplified way. There are only very few values for the environmental impact of maintenance, which are all calculated on the basis of economic values. One of these is the consideration of the maintenance phase by Schäfer [32]. The author calculated the environmental impact (expressed in CO_2 emissions) based on the energy consumption of the maintenance processes and the resources needed for spare parts. The environmental impacts were calculated on the basis of direct maintenance costs for labour and materials and amount to 0.26% of the overall life cycle (in comparison, this study has an ecological maintenance share of around 0.11%). Chester [23] used various EIO-LCA sectors for manufacturing processes, including *aircraft engine and engine parts' manufacturing* for the environmental assessment of the maintenance phase, and obtained an overall value of about 2% of the total life cycle. Another publication that examines maintenance independently is that by Jordão [30]. The author calculated the environmental impact of maintenance using the total energy consumption of the airport, the electricity price per kWh, and the maintenance costs based on aircraft block hours. The environmental share of maintenance is about 20% of the total life cycle impact, which is significantly higher than other literature values due to the calculation using the economic approach.

5.2.4. *End-of-Life*

This study's end-of-life result is composed of the negative environmental impacts of aircraft dismantling and transportation to the end-of-life site, as well as the much higher positive environmental benefits driven by incineration, recycling, and re-utilisation. The ecological impact is strongly dependent on the material composition and mass distribution of the aircraft (see also manufacturing phase in Sections 4.2.3 and 5.2.1). For analysing the end-of-life phase of the aircraft, the functional unit *per OEW* is applied again. Taking into account the end-of-life scenarios presented in Section 4.2.4, the environmental benefits from proper recycling and re-use amount to a total of -1.13×10^{-4} $kgCO_2$-eq./OEW, which corresponds to about 40.8% of the environmental impact of the manufacturing phase. In Figure 15, the positive environmental impacts in relation to the manufacturing of the aircraft are compared across all impact categories. The values are presented as negative values because they reduce the overall impact of the aircraft. The effect is particularly high for the impact categories of climate change, freshwater eutrophication, ionisation radiation, and energy carriers.

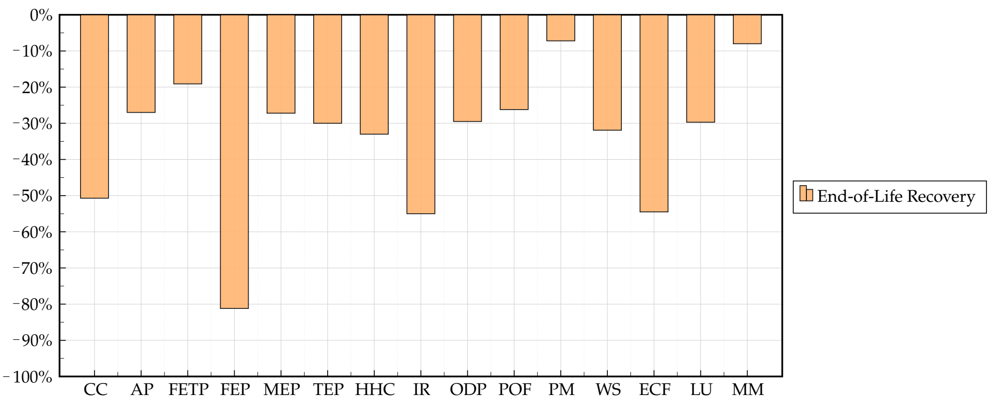

Figure 15. Ecological benefit due to the end-of-life phase (compared to the manufacturing phase) across all impact categories.

Comparison with Literature

Similar to maintenance, end-of-life is a phase that is often neglected in the literature. Only Schäfer [32] and Howe et al. [21] have considered an end-of-life scenario in their LCA studies. The environmental benefit calculated by Schäfer is based purely on CO_2 values and amounts to 5.7% of that of the manufacturing phase. The author also conducted a parametric study with a 0% and a 100% recycling scenario (excluding CFRP) and obtained a negative impact of 1.1% for the pessimistic and a benefit of 10.9% in the optimistic scenario. In Howe's study, the total environmental savings based on GWP are 10%. These are significantly lower than the values calculated here. One reason for this could be the rather optimistic view of the end-of-life scenarios with their relatively high recycling rates. As in the case of maintenance, there are large differences between these results and literature values caused by different assumptions and system boundaries.

5.3. Interpretation

The interpretation phase concludes the four steps of the LCA. In this study, especially the manufacturing, maintenance, and end-of-life phases, have a very high level of detail based on the granular inventory. In this context, the lack of data availability led to difficulties in creating detailed mass and material breakdowns of the aircraft, which were therefore complemented with numerous assumptions and estimations. In addition, insufficient datasets in the ecoinvent database, especially regarding aviation materials or processes, led to further uncertainties. An expansion of the ecoinvent database or the creation of aviation-specific datasets is inevitable for future assessments in aviation. The comparison with values from the literature showed that the alternative solution of the EIO-LCA, which determines the ecological impact based on economic values, often delivers a significantly higher ecological outcome. The main reason for this is that the system boundaries are often drawn much wider in the economic analysis, as entire industrial sectors serve as a basis. In contrast, the environmental effects of the flight phase were determined using rather simple approaches, such as the ecoinvent database *market for kerosene* and *market for transport, passengers, aircraft*. Due to the combination of CO_2 and non-CO_2 effects, which have different impacts depending on geographic location and altitude, the pure consideration of emissions is not sufficient. Targeting more emission-friendly combustion that can be expected from SAFs or LH_2 and the introduction of new production processes for fuels, a shift between ground-based and flight-based environmental impacts can be expected, which makes the environmental assessment of the operational phase especially complex. In particular, because of these potential improvements, it is important to establish an aviation-specific LCIA methodology with different impact categories. Yet, the ecological assessment of flight emissions in the context of a holistic LCA is still fraught with many uncertainties. An uncertainty and sensitivity analysis was not performed in this LCA due to the complexity of this study. Possible uncertainty methods such as the pedigree method [91] can, however, help to identify additional potentials for improvement, especially in the field of aviation.

5.4. Strengths and Weaknesses of a Discrete-Event Life Cycle Assessment Simulation

By combining LCA with discrete-event simulation, a more detailed analysis is possible compared to other rather streamlined LCA studies found in the literature. For example, it allows the ecological impacts to be calculated and analysed both based on individual event types and over the whole course of the life cycle. Figure 16 underlines that the temporal consideration of individual events during the operation time can have inherent advantages for the LCA values, which are otherwise calculated on the basis of average flight or maintenance hours per lifetime. The total environmental impact of flights (top) and maintenance events (bottom) is estimated based on the sum of the annual flight and maintenance events. Compared to the average value (black line), clear differences between the individual years can already be seen, as the flight and maintenance schedule result in individual variations in the operating phase. Especially when analysing the maintenance events, the effects become visible when major maintenance checks are carried out. Particularly in the years in which a longer C-check takes place (2025, 2031, 2037, and 2043), an increased ecological impact due to maintenance on the one hand, and a lower impact in the flight operations on the other, can be seen. This is due to the fact that the aircraft remains on the ground for the duration of the C-check. This effect is omitted in the case of the shop visits, as the aircraft usually receives an alternative component in order to continue flight operations during these checks.

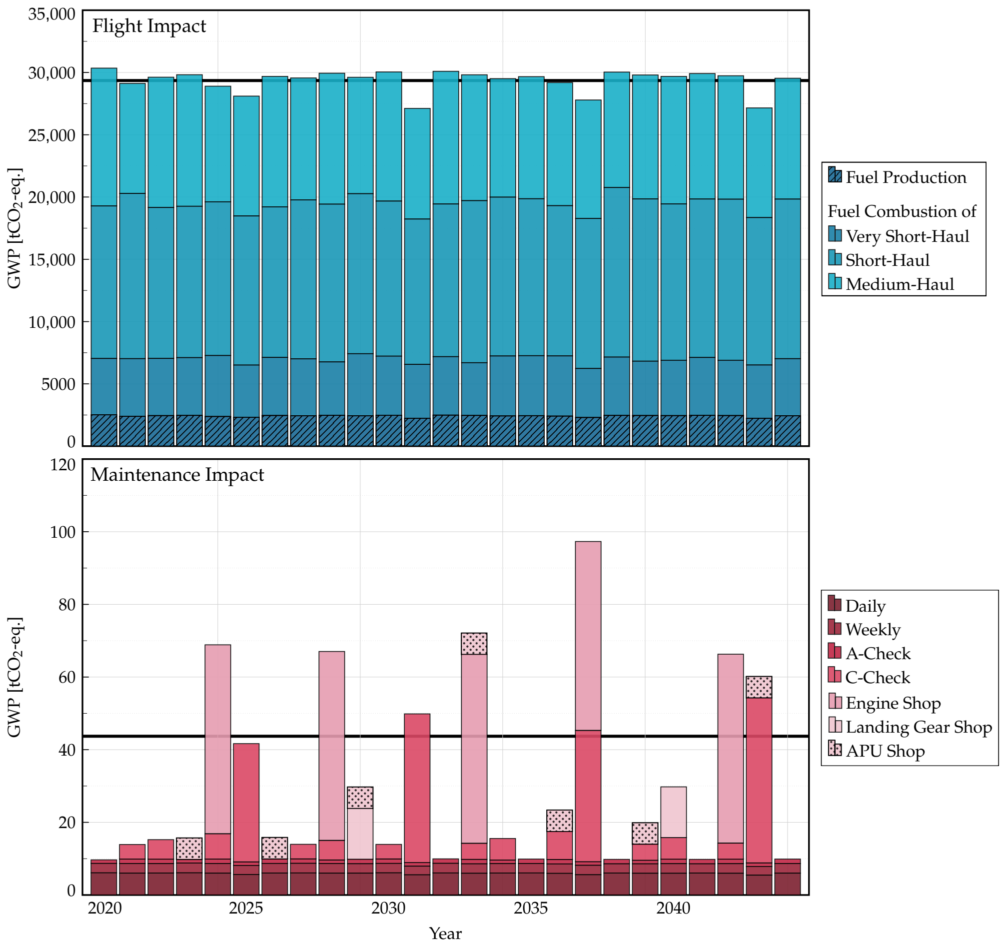

Figure 16. Effects of annually considered flight (**top**) and maintenance (**bottom**) events compared to usually on-average-determined ecological impacts (black line).

Another advantage of discrete-event simulation is the possibility to analyse aircraft modifications and their effects on the remaining life cycle. Modifications can be manifold and are usually carried out to improve the aircraft efficiency. The impact on the environmental footprint is illustrated subsequently using an exemplary modification in the tenth year, leading to a hypothetical improvement in fuel efficiency of 10%. Figure 17 shows the cumulative environmental impact of the unmodified aircraft (solid lines) compared to the modified one (dashed lines) for the flight and maintenance events. The modification event leads to an additional annual inspection event for the considered component. Although the environmental impact increases due to the additional maintenance tasks, this is outweighed by the savings resulting from the improved performance. At the end of the service life, this hypothetical modification can save almost 38,378 tCO_2-eq. and thus 5.2% of the total impact over all life cycle phases. The applicability and advantages of a discrete-event simulation are thus multifaceted and offer a wide range of analysis possibilities compared to previous LCA studies in the field of aviation.

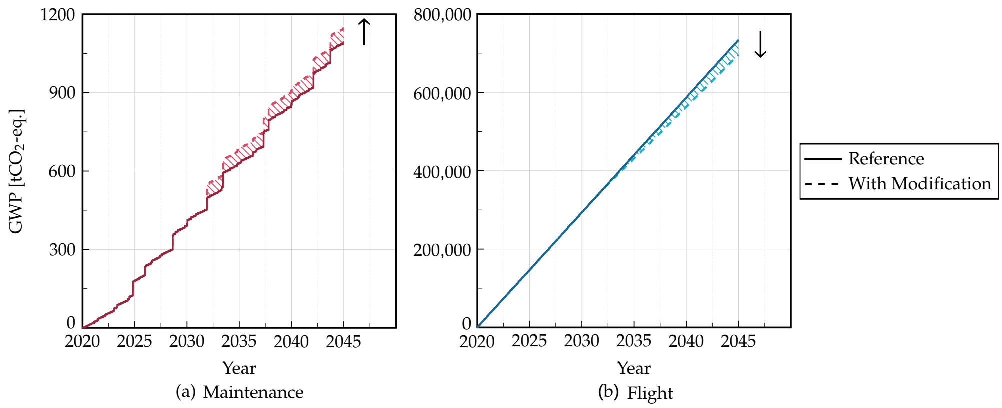

Figure 17. Cumulated changes in the environmental impact after a modification for maintenance (**a**) and flight (**b**) events.

Moreover, the discrete-event simulation enables a detailed analysis of an aircraft's life. Changes in the flight schedule can be implemented and analysed at any point in the life cycle and the granular decomposition of the aircraft into different components provides additional details. A summary of the advantages that the combination of discrete-event simulation and LCA offers compared to conventional ones is listed below:

- The ecological consideration of the discrete events allows a detailed analysis of the entire life cycle at both aircraft and event type level.
- Changes in the flight or maintenance plan can be made at any point in the life cycle, immediately reflecting the impact on subsequent operations.
- Integration of new aircraft technologies and associated maintenance tasks or modifications can be embedded into the life cycle without major effort.
- Each event provides temporal and geographical information for deeper analysis.

This is in contrast to the fact that a significantly higher data availability must be guaranteed and more laborious preparation is required. The need for a specific aviation database thus becomes even more apparent and makes uncertainty and sensitivity analysis more important as a large amount of parameters can cause misleading results.

6. Summary and Outlook

This paper presented an advanced combination of LCA and discrete-event simulation that is used to simulate and to environmentally assess the life cycle of an aircraft in detail. For this purpose, LCA was implemented in an existing life cycle simulation environment (LYFE) developed at the DLR Institute of Maintenance, Repair and Overhaul. Using the example of an aircraft similar to an Airbus A320 with an operating life of 25 years, each life cycle phase of the aircraft was thus evaluated individually on the basis of the existing parameters. Based on a detailed literature review and a selection of suitable comparative studies, it was further possible to validate the results of this LCA.

The findings of the extended LCA presented here fit well into existing publications and can serve as decision support for product development and operational planning. The study also showed the potential for further developments in the field of environmental assessment in aviation, for example, in the creation of an aircraft-specific database or LCIA methodology for more accurate assessment of the ecological impact of flight operations. In addition, an uncertainty analysis is essential to identify uncertainties. Within the DLR-internal project EXACT, the generic nature of this simulation is used to perform the evaluation of different aircraft types and the implementation of new aircraft technologies or modifications. Furthermore, it is planned to integrate time-dynamic aspects in subsequent studies in order to further strengthen the positive effects of the discrete-event simulation model and to enable a variety of additional analysis options.

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Author Contributions: Conceptualization, A.R. and K.W.; methodology, A.R.; software, A.R.; validation, A.R.; formal analysis, A.R.; investigation, A.R.; resources, K.W.; data curation, A.R.; writing—original draft preparation, A.R.; writing—review and editing, A.R. and K.W.; visualization, A.R.; supervision, K.W. and G.W.; project administration, K.W.; funding acquisition, K.W. and G.W. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

APU	Auxiliary Power Unit
ASK	Available Seat Kilometre
ATR	Average Temperature Response
CC	Climate Change
CeRAS	Central Reference Aircraft data System
CFRP	Carbon Fibre-Reinforced Plastic
EIO-LCA	Economic Input-Output Life Cycle Assessment
FC	Flight Cycle
FEP	Freshwater Eutrophication
FH	Flight Hour
FAL	Final Assembly Line
GHG	Greenhouse Gas
GPU	Ground Power Unit
GSE	Ground Support Equipment
GWP	Global Warming Potential
HTP	Horizontal Tail Plane
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LH_2	Liquid Hydrogen
LNB	Large Narrow Body
LYFE	Life Cycle Cash Flow Environment
MM	Minerals and Metals
ODP	Ozone Depletion Potential
OEW	Operating Empty Weight
PAX	Passenger

P-LCA	Process-Based Life Cycle Assessment
SAF	Sustainable Aviation Fuel
S-LCA	Streamlined Life Cycle Assessment
SNB	Small Narrow Body
VTP	Vertical Tail Plane

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