Life Cycle Assessment in Aviation

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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. In the following, a brief overview of the existing research on the topic of life cycle assessment in aviation is given. This is concluded with a short summary and an introduction to a possible combination with discrete-event simulation.

life cycle assessment discrete-event simulation aviation

1. Life Cycle Assessment

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 research 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 research 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.

2. 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.[5] 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.[6] 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.[7]. 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.[8] 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 research 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[9][10][11], elevators[12], aircraft interior panels[13], and lightweight trolleys[14]. 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[15], 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.[16] 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 research, the operational phase accounted for 99% of the total environmental impact, with no distinction made between maintenance and flight operations. The figures in this research are given in percentages only and do not provide exact numerical values. In 2006, Facanha and Horvath[17] 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 research, however, only the inventory assessment was described in depth. The impact assessment was excluded from the research, 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[18], who compared an Embraer 145, a Boeing B737, and a Boeing B747, and by Cox[19][20] (more details of this research can be found in the master's thesis by Jemioło[21]), 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[22], 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[23], 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[24], 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[25] 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.[26], 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[27] 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.[28] 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 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.[16], Johanning[15], and Facanha and Horvath[17] 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[19] and Dallara et al.[28].

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

Study	Chester[18]	Cox[19]		Lopes[23]	Lewis[24]	Jordão[25]		Fabre[26]	Schäfer[27]	Dallara[28]
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 addition, a number of publications deal with the potential environmental impact of future aircraft concepts. These include hybrid-electric concepts[29], universal-electric powered concepts[30], or the use of Sustainable Aviation Fuels (SAFs)[31][32]. For these future technologies, a prospective LCA can be helpful for decision support in the design process or during engineering[33]. Johanning and Scholz[34], 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.

3. Summary and Combination with Discrete-Event Simulation

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. 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.

The study by Rahn et al.[35] presents 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 is 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. The findings of this extended LCA fit well into existing publications and can serve as decision support for product development and operational planning. The research also shows 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.

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