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Life cycle inventories for aviation: Background data, shortcomings, and improvements

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ABSTRACT

In the context of growing environmental awareness and a drive towards sustainable aviation, Life Cycle Assessment (LCA) emerges as a pivotal tool for evaluating the environmental impacts of current and novel technologies. This paper focuses on Life Cycle Assessment within the aviation sector, with a specific emphasis on Life Cycle Inventories (LCIs) and databases. Recognizing a relevant data gap in existing databases regarding aircraft maintenance, our study seeks to address this limitation. A maintenance, repair and overhaul use-case is proposed as an illustrative example to enrich underrepresented data in LCIs. Our methodology considers the entire service life of aircraft, building a cumulative life cycle inventory in a cradle-to-gate approach. Geographical representativeness is ensured for maintenance activities conducted in Germany, with extrapolation applied across Europe where necessary. Our findings underscore the need to differentiate maintenance activities between aircraft components and engines, as well as the importance of considering various flight scenarios, ranging from short to long haul. This paper contributes to the advancement of LCA in aviation by providing insights into improving data accuracy and completeness. It also delves into how and why data generation is possible and what are the necessary data improvements within the topic. This paper is aimed at LCA practitioners in both research and industry, thus fostering sustainable practices in aviation.

1. Introduction

Despite the impact on air transportation and air passenger numbers posed by the Covid-19 travel restrictions during recent years, the sector is expected to recover and grow steadily and in a faster rate than efficiency improvement. The European Commission estimates that emissions would more than double by 2050 (EU, 2020). With raising environmental awareness and efforts towards sustainable aviation, accurately assessing the sector's influence in transportation sustainability has been proved central. Although the greatest share of aviation emissions occur during the flight operations phase (e.g., taxiing, takeoff, cruise, descent, and landing), life cycle phases such as manufacturing and maintenance are also relevant when holistically assessing environmental impacts (Chester, 2008; Facanha and Horvath, 2006; Jordão, 2012). Life Cycle Assessment (LCA) is a method used to comprehensively assess the environmental impacts of products throughout their entire life cycle, i.e., from raw material extraction, production and use phases, to end-of-life (Finnveden et al., 2009). LCA can assist decision-makers in choosing products or processes that yield the least environmental impact, making it applicable in the achievement of environmental targets and policy objectives. As defined by the ISO 14040/44 standards (ISO, 2006a,b), it is a holistic tool comprised of four steps: 1. Goal and Scope Definition, 2. Life Cycle Inventory (LCI), 3. Life Cycle Impact Assessment (LCIA), and 4. Interpretation.

The goal of an LCA must state the intended application, the reasons to perform the study, and the intended audience. The scope, on the other hand, includes the product system to be analysed, the functions of such system, the Functional Unit (FU), the system boundary, the selected impact categories, data requirements, limitations, and initial data quality requirements (ISO, 2006a). The LCI analysis is an inventory of input/output data regarding the system in scope, and involves the compilation of data necessary to meet the goals of the study. The main objective is to collect and compile the data on elementary flows from all processes on a combination of different sources (Hauschild et al., 2017). The object of study in an LCI analysis is the product system - a set of processes which are connected by energy or material flows and should perform the functions defined during the goal and scope definition phase. In LCA, an FU is established during the goal and scope step, serving as the reference for all inputs and outputs in LCI (ISO, 2006a).

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Acronyms

APU	Auxiliary Power Unit
CFRP	Carbon Fibre Reinforced Polymer
EIO-LCA	Economic Input-Output Life Cycle Assessment
FC	Flight Cycle
FEP	Freshwater Eutrophication
FETP	Freshwater Ecotoxicity
FH	Flight Hour
FU	Functional Unit
GFRP	Glass Fibre Reinforced Polymer
GPU	Ground Power Unit
GWP	Global Warming Potential
IRP	Ionising Radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LLP	Life Limited Part
MPD	Maintenance Planning Document
MRO	Maintenance, Repair, and Overhaul
PKM	Passenger-Kilometre
POCP	Photochemical Ozone Creation Potential
SA	Sensitivity Analysis
UPR	Unit Process

Within aviation, the prevailing FU is the Passenger-Kilometre (PKM), representing the transportation of one passenger over a distance of 1 km. The system boundary is the border between a product system, the natural environment, and other product systems, i.e., it delimits the product system to be studied (Ciroth and Arvidsson, 2021).

Subsequently, the LCIA phase provides a holistic interpretation of the elementary flows provided in the LCI phase and translation into relevant impact scores, representing the product's system impact different impact categories. This can support decision-making as well as answer the questions stated in the goal and scope definition phase (Hauschild and Huijbregts, 2015). The LCIA phase translates inventory data into impact categories (such as climate change, ozone layer depletion, among others) and areas of protection (e.g., human health, natural environment, and natural resources). The interpretation is the final phase, in which the results of LCI and LCIA are summarized and analysed for conclusions, recommendations and decision-making in line with the goal and scope definition.

LCA facilitates a comprehensive analysis of a product or service life cycle, preventing burden-shifting across phases, regions, or environmental issues (Finnveden et al., 2009). This is particularly pertinent when evaluating different aircraft technologies within the context of evolving configurations for sustainable aviation. This technique can take either an attributional or a consequential approach, with the former focused on describing environmental properties of a product or a system and the latter aimed at outlining the effects (consequences) of changes within the life cycle (Laca et al., 2011).

The relevance of LCA studies in aviation has been growing, allowing hotspot identification, comparison between different aircraft technologies, and fulfillment of environmental targets. International initiatives such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) developed by the International Civil Aviation Organization (ICAO) aim at reducing CO_2 emissions for international flights. To that end, the conduction of LCA has been pivotal as the first internationally adopted approach for the calculation of life cycle greenhouse gases emissions of aviation fuels (Prussi et al., 2021). At regional level, the Federal Aviation Research Programme (LuFo) by the German Federal Ministry for Economic Affairs and Energy highlights the relevance of LCA when assessing innovative technologies over the entire product life cycle (BMWI, 2024).

However, LCA is highly data-intensive, especially during the LCI stage, requiring both foreground (study-specific) and background data (generic). Background LCA databases, as ecoinvent, provide inventory information on a wide range of economic activities and industrial sectors, relevant for most product systems. Nonetheless, there are data gaps and shortcomings in aviation-specific activities such as aircraft maintenance. In order to achieve comprehensive LCA studies, consistent, sector-specific, and detailed LCI datasets are needed (Rupcic et al., 2023).

Since process-based LCA significantly depend on background data availability, aviation-related studies are conducted using Economic Input-Output Life Cycle Assessment (EIO-LCA) (Chester, 2008; Lewis, 2013), prone to high levels of uncertainty inherent to the method itself. Process-based LCA usually has a bottom-up approach, in which data are collected for all processes within the chosen system boundary, whereas EIO-LCA data collection approach is top-down, accounting for product flows between different economy sectors (Kjæ r et al., 2015; Hendrickson et al., 1998). Due to data scarcity, authors also make simplifications such as considering only airport infrastructure maintenance (Bicer and Dincer, 2017; Su-Ungkavatin et al., 2023). The complexity and high level of confidentiality associated to the aviation sector often represent an obstacle in building representative datasets.

This paper aims to address the research gap in LCI in aviation using the case study of aircraft maintenance. Through timely and proper maintenance, vehicle degradation due to flight operations is reduced (e.g., engine wash reduces fuel consumption, which in turn decreases flights environmental burdens). Conversely, the use of hazardous materials during different Maintenance, Repair, and Overhaul (MRO) activities may pose hurdles in areas of protection such as human health and ecosystem quality (Halpern and Graham, 2018; Aerospace Technology Institute, 2021). Lastly, hangar operations are highly energy-intensive and represent a key driver in environmental impacts (Rahn et al., 2024). Despite the importance of this phase in the overall product's life cycle, MRO datasets are not yet available in leading LCI background databases such as ecoinvent (Rupcic et al., 2023; Keiser et al., 2023; Melo et al., 2020). The goal is to improve life cycle data coverage in air transportation datasets. Additionally, the aim is to present the process of translating foreground data to background databases, considering assumptions, data gathering, aggregation levels, and cut-off criteria when generating LCI datasets. A comparison of findings from literature-based research and insights derived from interviews with LCA experts within the aviation industry offers a nuanced examination of the inherent limitations of LCIs as well as LCA conduction in the sector.

The novelty of this paper is the translation of detailed, foreground to aggregated, background data. Such process is exemplified via an MRO use-case, as aircraft maintenance activities are not yet present in LCA background databases (Rupcic et al., 2023). The development of such dataset is especially relevant since MRO processes are energy-intensive and includes scarce or hazardous materials in many activities (Aerospace Technology Institute, 2021), thus allowing for more comprehensive LCA conduction.

The paper is structured into the following sections: Firstly, it introduces fundamental concepts of LCA, with a special focus on LCIs and prominent background databases. Next, an overview of LCA in the context of aviation is provided, addressing current gaps and shortcomings. Subsequently, a MRO use-case serves as the foundation for constructing background datasets. Finally, the paper discusses relevant aspects and considerations necessary for creating such representative data. The conclusion and outlooks highlight the importance of addressing data gaps in sectors like air transportation, especially in the context of advancing sustainable aviation and emerging technologies.

2. Life cycle inventories (LCIs)

The LCI step, a critical yet time-consuming stage in LCA, involves a mass-energy balance, quantifying both input and output flows within the analysed system (Islam et al., 2016; Ferrari et al., 2021; Laca et al., 2011). This stage serves as the central point for data collection to achieve the study's defined goals, encompassing energy and raw material requirements, atmospheric and water emissions, solid waste, and other releases throughout the entire life cycle (ISO, 2006a; Curran, 2008). Given that LCA studies often demand a significant amount of data, the accuracy of this information greatly influences the quality of the obtained results (Ciroth et al., 2019).

In LCA, the connection of numerous interlinked human activities, each with associated exchange flows, is necessary. These flows are quantified through Unit Processes (UPRs), the smallest element in LCI analysis (ISO, 2006a). Together, these UPRs form product systems, consisting of interconnected processes in a highly complex network (Hellweg and Milà i Canals, 2014; Reinhard et al., 2019; Bourgault et al., 2012). Input flows encompass materials, energy, and resources, while output flows include products, waste to treatment, and emissions. Typically, UPRs maintain mass balance, where the sum of input flows equals the sum of output flows. Additionally, outputs from one UPR can serve as inputs to subsequent processes within categories such as materials and energy. Resources and emissions, denoted as elementary exchanges, are not exchanged between UPRs (Hauschild et al., 2017). Fig. 1 illustrates a UPR example for aircraft maintenance, demonstrating flows within each of the six categories. During aircraft maintenance activities, environmental impacts are mostly caused by energy consumption, maintenance products (e.g., cleaning agents) and spare parts (e.g., landing gear, airframe, systems, and engine components) production as well as waste and wastewater generation (Shirinfar et al., 2022; EASA, 2022).

LCI models typically consists of two systems, commonly referred to foreground (under direct control/influence of the company or decision-maker) and background system. The former is specific to the modeled system and can represent directly measured or study-specific data. In contrast, background data are generic and usually sourced from third-party LCI databases, often presented with high aggregation levels (Goedkoop et al., 2016). Distinguishing between these data types is not always straightforward and depends on the subject of the LCA study (European Commission, 2013). LCA practitioners commonly collect foreground data on selected activities relevant to a specific project, while the remaining activities (referred to as background data) are modeled using generic LCI databases such as ecoinvent (Wernet et al., 2016). Fig. 2 illustrates the differentiation between foreground data, which comprises engine and airframe (structure and components), and background data, which encompasses raw materials, resources, and utilities for an aircraft MRO use-case.

Furthermore, the characteristics of LCI databases can vary depending on their intended use. Whether employed for a detailed LCA study or company-internal inventories, industry-specific analysis, or as a background LCI database, these databases exhibit differences in data quality, parametrisation, and aggregation levels of UPRs. The audience, be it experts, industry insiders, or general LCA users, plays a crucial role in shaping these variations. For instance, company-internal LCI databases may feature a lower level of aggregation, focusing on individual process steps, whereas background LCI databases, like ecoinvent, adopt a modular approach. This modularity allows for the application of different allocation methods based on study goals and enables the aggregation of UPR to meet the needs of diverse audiences.

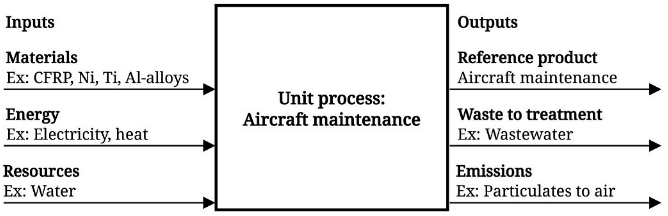

Fig. 1. A potential UPR for an aircraft maintenance activity (adapted from Hauschild et al. (2017)).

The use of LCA databases brings advantages to the end-user, such as reduced efforts and resources for data collection and improved representativeness of complex supply chains when conducting comprehensive and accurate environmental analyses (Ciroth et al., 2019). In the context of aviation studies, ecoinvent is recognized as the most extensively utilized database, followed by sphera (formerly GaBi), and European Reference Life Cycle Database (ELCD) databases (Keiser et al., 2023). For the end-of-life phase, the Granta Database provides materials data and can be applied as background database considering recycling and upcycling of materials, enabling streamlined-LCA conduction and quick environmnetal hotspots identification. The database includes information on embodied energy and CO_2 emissions (Mayyas et al., 2012). Given the high level of confidentiality required in the aviation sector, improving data availability poses a challenge, leading to potential data gaps (Rupcic et al., 2023). To address this challenge, research and industry partners, along with leading LCI databases providers, are encouraged to collaborate closely while maintaining transparency within the bounds of data sensitivity.

3. LCI and background data shortcomings in aviation

The following section provides an overview of LCA conduction within aviation (3.1), focusing on data availability and other challenges faced by both industry and research sectors. For that end, a literature review was conducted. Given that of LCIs are the backbone of LCA studies, the discussion delves into LCI data requirements and shortcomings (3.2) for specific stages such as production (3.2.1), operation (3.2.3), maintenance (3.2.2), and end-of-life (3.2.4). It also highlights assumptions, results, data gaps, shortcomings, and potential improvements in existing LCIs.

3.1. LCA in aviation

Incorporating insights from industry experts, especially from aircraft manufacturers, maintenance providers, and airline operators, holds a big potential for improving completeness and representativeness for LCIs. In aviation, LCA is a relatively new discipline, lacking sufficient knowledge for providing data in a format suitable to build datasets. The available information are often only provided in raw data. Above that, it is not clear for suppliers what data is actually needed, as the industry is used to assess key performance indicators for economic considerations, which sometimes differ drastically to ecologically-driven parameters.

Indeed, LCA practitioners in industry often encounter challenges with LCI data collection. In order to properly assess complex process chains, they need to extensively review the raw data gathered from suppliers and restructure such data. This is a highly resourceful and time-expensive process, often overlooked by industry partners who hold different understandings of aspects such as ecodesign and LCAs in general. Initiatives such as the Digital Product Passport (DPP) hold the potential of prompting efforts on product data traceability and availability (Götz et al., 2022). Furthermore, DPPs provide primary, granular data of a product over its life cycle, thus increasing LCA outcomes accuracy given that LCIs would be built upon primary data rather than secondary or generic data (Protokol, 2024; Haupt et al., 2024). The LCA development in aviation industry has been tenuous in the last decades; however, with raising environmental awareness, concepts such as ecodesign and Design for Environment (DfE) have become increasingly relevant for different stakeholders, such as manufacturers, service providers, and operators (Boeing, 2023; Pigosso et al., 2013). In such context, LCA represents a well-established tool for measuring impacts

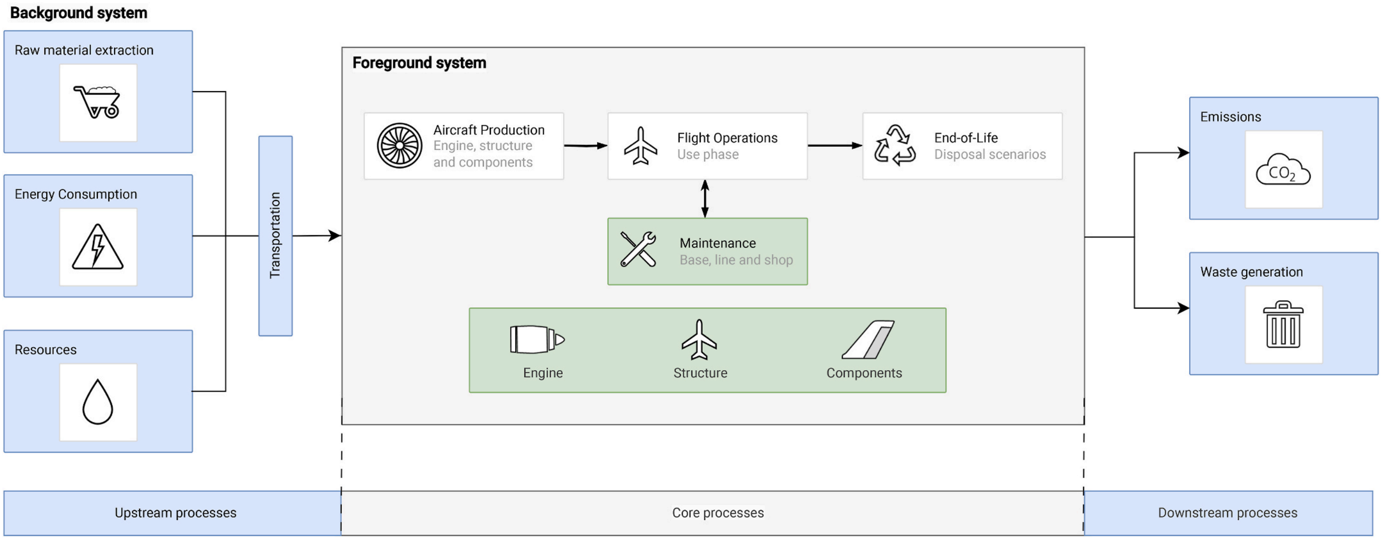

Fig. 2. The fore- and background data for the aircraft life cycle, with special focus on the MRO use-case. Foreground data are categorized into engine and airframe (structure + components), whereas background data are obtained from LCI databases.

over the product's life cycle for informed decision-making.

Both production and maintenance activities are highly dependent on specific aviation alloys and materials, highlighting the relevance of data enrichment efforts within LCI databases. Either taking a detailed approach (e.g., component level) or a general perspective in manufacturing and maintenance activities, LCA practitioners within the aviation industry benefit greatly from upstream and downstream impacts across process chains. Such impacts are provided by secondary inventory data, usually in an aggregated manner.

As for research, Chester (2008) focused on various transportation modes (i.e., air, rail, and road), employing a hybrid-LCA approach, which integrates process-based LCA with EIO-LCA, connecting economic outputs with environmental metrics. Lopes (2010) conducted a cradle-to-grave assessment of an A330-200, utilizing foreground data from the aircraft's weight and balance manual along with confidential airline data, and ecoinvent as the background database. Challenges in obtaining detailed information for alloyed materials and Carbon Fibre Reinforced Polymer (CFRP) production emphasize the importance of representative inventories.

Dallara et al. (2013) introduced a streamlined LCA tool for multidisciplinary aircraft design optimization and compared results to previous LCA studies by Chester (2008), Lopes (2010), and Howe (2011). For aircraft manufacturing and operation, the author utilized the ecoinvent database and made assumptions regarding material composition and buy-to-fly ratio,[1] acknowledging that these assumptions can significantly impact the resulting environmental assessments. Jordão (2012) compared the emissions of an A330–200 and B777-200 using embodied CO_2 emissions during manufacturing and maintenance and CO_2-eq emissions during the operational phase. Lewis (2013) examined flight scenarios for the A320, A330, and A380 models, including airport construction and operation. The author compared results obtained by process-based LCA (using ecoinvent as background database) and EIO-LCA. Howe et al. (2013) primarily examined the breakdown of materials and components examining the life cycle of an Airbus A320. The study employed ecoinvent databases to characterize materials such as aluminum, steel, and titanium. For CFRP and aviation biofuel production, custom UPRs were built based on Duflou et al. (2009) and Suzuki and Takahashi (2004).

Cox (2018) performed an LCA of 72 common aircraft types for different flight distances. The LCI for both airport construction and aircraft production, operation, maintenance, end-of-life as well as fuel production (kerosene) is built upon ecoinvent datasets, however these are adjusted considering annual passenger data and scaled aircraft operating empty weight for different production years (1970–2050). As for aircraft operation, the exhaust emissions are based on EEA (2013). Fabre et al. (2022) assessed an overall aircraft design using the A320 as a reference, focusing on the manufacturing phase with data from Lopes (2010), Verstraete (2012), Johanning and Scholz (2013), Jemioło (2015). The ecoinvent database was used to consider the extraction and transportation of raw materials. The study also addressed the operational phase, covering fuel production, combustion, and tyre and brake wear from landing and takeoff.

3.2. LCIs for aviation: requirements and improvements

In the following sections, a summary of LCA research in aviation is provided, along with detailed analyses of the different stages of the aircraft life cycle (from production to end-of-life), and a discussion of the specific data requirements and challenges for each stage, given their distinct and intrinsic characteristics.

3.2.1. Production

The aircraft production phase is comprised of several key stages, starting with the extraction of raw materials. These materials are then transported to production sites, where various manufacturing processes take place to create different components. Due to their high level of complexity, strict regulations, and specific requirements, aviation materials are typically more expensive than those of other sectors (e.g., the automobile industry) and require highly complex manufacturing processes.

While the EIO-LCA method is applied using the aircraft and engine parts manufacturing sectors (Chester, 2008; Lewis, 2013), other authors (Lopes, 2010; Howe, 2011; Jordão, 2012; Lewis, 2013) focus on the material breakdown of different aircraft components (e.g., structural components and sub-assemblies) for the most common aviation alloys. As for CFRP, custom UPRs were created based on various sources (Duflou et al., 2009; Suzuki and Takahashi, 2004) since no activity dataset was available at the time of the studies. On the other hand, recent research (Cox, 2018; Fabre et al., 2022) utilizes the ecoinvent aircraft production dataset, which provides a good basis for comparing

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[1] The weight ratio between the raw material (buy) used for a part and the weight of the finished part (fly).

transportation modes and conducting general studies. However, some datasets of aviation-specific materials, such as special alloys, CFRP, and Glass Fibre Reinforced Polymer (GFRP), lack adequate representativeness and represent potential for data enrichment efforts. In the following, the main shortcomings regarding aircraft production inventories are outlined and the motivation for enhanced datasets is presented.

Alloyed materials. Aerospace materials are a core aspect of aircraft component design and must meet strict requirements such as high strength, lightweight characteristics, excellent corrosion resistance, and high performance at wide temperature ranges. Different alloys are used for various aircraft parts, such as the airframe, engine, and landing gear, to meet specific mechanical requirements and environmental conditions (Tech Briefs, 2019). The material generation of special alloys is highly energy-intensive, particularly when compared to alloys used in other industry sectors. Moreover, the manufacturing processes also represent significant energy demand and are highly complex (e.g., blisk manufacturing). Due to the lack of aviation-specific alloys, such as aluminum, magnesium, nickel, cobalt, and titanium-based alloys, in leading background databases, some researchers (Vinodh et al., 2017; Fricke et al., 2022; Rahn et al., 2022) have created their own datasets on material generation, considering the raw material composition and energy intensity.

Composite materials. In recent aircraft development, as seen in models such as A350 and B787, there is a growing utilization for lightweight composite materials such as CFRP and GFRP (Dolganova et al., 2022). This trend allows for decreased fuel consumption compared to conventional aircraft, which are predominantly constructed with metals. Hence, a greater share of composite materials in aircraft manufacturing has a high potential for reducing emissions during operation.

Fibre reinforced plastics consist of reinforcing fibres and a polymer matrix that surrounds the fibres. Without the matrix material that surrounds the fibres, the high specific strength and stiffness of the reinforcing fibres cannot be utilized (Melby and Castro, 1989). Typical fibres used in aviation are carbon, glass, and aramid fibres. The matrix can be thermoset, such as epoxy and phenolic resin, or thermoplastics such as those from the polyaryletherketone family (Ogin et al., 2016). For some applications such as interior linings and flooring, a metallic or polymeric sandwich core is added. Bio-based materials, including natural fibres, have been researched for years but have not yet been integrated into commercial aviation (Bachmann and Yi, 2020). Recycled carbon fibres are under consideration as a potential replacement for glass fibres in interior linings or in secondary structures (Gardiner, 2014).

Due to the lack of primary data, the assessment of potential environmental impacts from the production phase (cradle-to-gate) of composite materials leads to considerable uncertainty. Available LCI data for composites contain mainly information on energy consumption in literature (Suzuki and Takahashi, 2005; Dér et al., 2021) or aggregated data in commercial databases (sphera, 2022).

Most virgin carbon fibres produced today are made of a petrol-based polyacrylonitrile precursor in continuous process including stabilisation, oxidisation, carbonisation, and surface treatment (Groetsch et al., 2021a; Lengsfeld et al., 2020). While energy consumption is a main influence on the comparatively high environmental impacts of virgin carbon fibre production compared to other materials, most published LCAs only include energy demand data and neglect other sources of environmental impacts such as equipment, consumables, or direct emissions (Suzuki and Takahashi, 2005). Due to confidentiality, primary data are currently not available. Therefore, many studies use assumptions (Hermansson et al., 2019) or laboratory data (Dér et al., 2021) instead. Within the example of virgin carbon fibre, a considerable range of energy consumption data can be observed, differing in several orders of magnitude (Dér et al., 2021). Further unclarity occurs due to the limited information on type of energy used, yield of conversion, emissions (Groetsch et al., 2021b), and general uncertainty on which process steps are included in the data.

Realistic LCI data are also rare for the production steps of composite materials in aviation. Aircraft structures, roughly divided into interior, primary, and secondary structures are produced in distinct processes. Data for typical processes, e.g., automated fibre placement or autoclave curing is rare (Ogugua et al., 2023; Atescan Yuksek et al., 2024). Fibre cut-offs, consumable material, and tool preparation are only seldom included (Silva et al., 2024). Equipment and direct process emissions are usually neglected, leading to potential incomplete data. Proxy datasets for composites containing CFRP produced by injection moulding are present in leading databases such as ecoinvent (Notten et al., 2018a). However, injection moulding, while utilized often in the composite industry in general, is not a typical production step for primary aircraft composite-based structures. Therefore, global aircraft production models have a high uncertainty based on missing data or proxy datasets, leading to a potential over- or underestimation of environmental impacts (Rahn et al., 2022; Vivalda and Fioriti, 2024; Lopes, 2010; Verstraete, 2012). An improvement of LCA databases regarding aircraft structures is necessary and should contain the addition of transparent and representative UPRs for typical materials and production steps.

3.2.2. Maintenance

Aircraft maintenance is often included in LCA in a simplified way, with different methodologies such as EIO-LCA or specialized LCA databases leading to different results regarding the share of maintenance in the total environmental impact. Several researchers (Chester and Horvath, 2009; Facanha and Horvath, 2006; Krieg et al., 2012) have used the EIO-LCA method to assess the environmental impact over the entire life cycle of an aircraft. Other studies (Bicer and Dincer, 2017; Su-Ungkavatin et al., 2023) have utilized specialized LCA databases, for instance the ecoinvent database, which, however, provide data related to airport maintenance rather than specifically to aircraft maintenance. Generally, in the studies that have analysed maintenance, it was often allocated to different life cycle phases and merged (usually together with production or infrastructure), which led to a wide variation in the magnitude of its contribution to the overall environmental impact and therefore made the results difficult to compare (Rahn et al., 2022).

Further, some studies evaluated the environmental impact of maintenance based on the energy consumption of individual processes and spare parts, where differentiating the resource consumption for maintenance from other airport or logistic operations proves difficult. While this approach facilitates comparability under set conditions, none of these methods allow a detailed investigation of specific maintenance aspects. Due to the lack of specific data on aircraft maintenance activities, it is not feasible to evaluate the environmental impacts at, for example, the component level. Hence, some LCA studies (Calado et al., 2019; Liu, 2013) have deliberately omitted the analysis of environmental impacts of maintenance activities. Lopes (2010), Lewis (2013), and Cox (2018) simplified the MRO aspect considering only airport maintenance.

This literature overview underscores the difficulties and uncertainties associated with precisely capturing and examining the specific environmental impacts of maintenance activities in the aviation sector. Although existing research has utilized a variety of methodologies and approaches to assess these impacts, there is currently no comprehensive approach that enables a detailed analysis of MRO processes. Moreover, comparing results from existing literature often proves challenging, as maintenance in aviation is not always considered holistically in studies, or the investigations vary depending on available data and specific conditions. A more detailed literature review on LCA studies regarding aircraft maintenance can be found in Rahn et al. (2024).

3.2.3. Flight operations

Many factors are relevant when determining the environmental impact of flights. The first is the choice of fuel, which has to be produced, distributed and stored before it can be burned. For conventional kerosene, there are already many datasets available in LCI databases, such as GREET or the ecoinvent database. However, current research is particularly focused on advanced fuel types such as sustainable aviation fuels or hydrogen (Mussatto et al., 2022; Fernanda Rojas Michaga et al., 2022). For combustion, emission factors (Aihara et al., 2007; Chester, 2008) or data based on the European Environment Agency (EEA) and European Monitoring and Evaluation Programme (EMEP) Inventory Guidebook (Johanning and Scholz, 2013; Jordão, 2012) are often used. However, a common challenge is to translate these results into non-CO_2 impacts or other impact categories (Cox, 2018). Most studies often divide the studied flights into different phases, such as the landing and takeoff cycle and the cruise phase. This segmentation is done to relate emissions to flight phases of different lengths, as the distance flown can significantly influence environmental impacts.

The life cycle phase of flight operations receives by far the most attention in current research, not least because the environmental impact during the flight has the largest impact when considering the contribution to global warming. However, non-CO_2 effects play a major role, especially in the cruise phase of flights. Unlike CO_2 emissions, non-CO_2 effects depend on parameters such as the flight altitude and geographical location. Due to distinct lifetimes and spatial dependencies, non-CO_2 induced climate change by aviation is not proportional to CO_2 emissions and are prone to significant uncertainty (Scheelhaase et al., 2016). Covering flight operations with other metrics or impact categories, apart from, for example, the Global Warming Potential (GWP), is therefore still a major topic of discussion (Megill et al., 2024).

3.2.4. End-of-life

Given the rising trends in air transport and the expected retirement of aircraft within the next decade, the end-of-life phase is becoming increasingly relevant for a comprehensive analysis of an aircraft life cycle (IATA, 2024). Initiatives such as the Aircraft Fleet Recycling Association (AFRA) and the research project Process for Advanced Management of End-of-Life Aircraft (PAMELA) have prompted efforts on aircraft end-of-life. The PAMELA project focused on recycling and dismantling and aimed at developing and establishing the safe and sustainable management of aircraft end-of-life. AFRA is a global network of different sectors such as waste management, raw material production, aircraft maintenance and manufacture, parts suppliers, and service providers (Dwulet, 2016; Maaβ, 2020). The PAMELA project demonstrated components recyclability potential, i.e., between 80 and 85% of an aircraft's weight (Dolganova et al., 2022).

Most LCA studies (Chester, 2008; Jordão, 2012; Lewis, 2013), however, do not cover this life cycle phase. Dallara et al. (2013) uses automobile industry data to represent aircraft end-of-life, while the analyses by Lopes (2010) and Howe et al. (2013) are based on Airbus' PAMELA (Airbus, 2008).

End-of-life is intrinsically considered in studies by Cox (2018) and Fabre et al. (2022), as both authors use the ecoinvent dataset to represent the aircraft production. The assumption employed is that all materials (aluminium, titanium, nickel, steel, and CFRP) are to be scrapped during the end-of-life stage (Notten et al., 2018b). In addition, composite materials pose challenges in end-of-life treatment due to their complex composition. Recycling efforts for CFRP primarily focus on carbon fibre, with pyrolysis being the established method (Oliveux et al., 2015). However, recycled carbon fibres often undergo downcycling, limiting closed-loop recyclability, especially in aviation (Hermansson et al., 2022). Implementing end-of-life recycling credits requires careful consideration due to limited data availability, highlighting the need for further research.

Table 1 outlines the analysed LCA studies. In summary, the environmental assessment of aircraft is an emerging field, with most studies indicating that the operational phase has the greatest impact on the entire life cycle. The manufacturing and flight operations phases are the most thoroughly defined, whereas maintenance and end-of-life represent the greatest gaps in terms of life cycle coverage. Maintenance activities are either partially included by considering only airport infrastructure maintenance or not included at all. End-of-life is either intrinsically examined via simplifications in LCI background datasets or excluded from the scope. Most studies use process-based LCA with ecoinvent as the LCI background database. The ReCiPe method (Huijbregts et al., 2016) is the most commonly applied LCIA approach, while SimaPro is the most frequently used LCA software, followed by openLCA and Brightway2.

Ultimately, the previous sections highlight the relevance of representative LCI information. Even though industry and research face different limitations regarding data collection and availability, the shortcomings intersect to a certain extent. In industry, aspects such as confidentiality, transparency and data gathering of highly complex production chains and maintenance services currently represent the biggest hindrance when conducting LCA within the sector.

As for research, for both aircraft production and maintenance, datasets for special alloys and composite materials are either present but with limited representativeness or not present at all. Even though the flight operations phase is the major focus of LCA studies, the inherent complexity of analysing both CO_2 and non-CO_2 effects and connecting meaningful results with other impact categories poses a challenge to LCA practitioners. At last, end-of-life is usually omitted from the scope of most LCA studies due to lack of realistic LCI data. Most scenarios consider complete disposal and dismantling of aircraft, which does not accurately depict its end stage.

Table 1

LCA studies in aviation, in which *SNB* and *LNB* stand for small narrow body and large narrow body, respectively.

Study	Chester (2008)	Lopes (2010)	Dallara et al. (2013)	Jordão (2012)	Lewis (2013)	Howe et al. (2013)	Cox (2018)	Fabre et al. (2022)
Aircraft type	B737	A330	A330	A330,B777	A320, A330,A380	A320	SNB,LNB	A320
Database	N.A.[a]	ecoinvent	ecoinvent	N.A.[b]	ecoinvent	ecoinvent	ecoinvent	ecoinvent
LCA Method	hybrid	P-LCA	S-LCA	S-LCA	hybrid	P-LCA	P-LCA	P-LCA
LCIA Method	N.A.[a]	ReCiPe	N.A.[c]	N.A.[c]	ReCiPe	ReCiPe	ReCiPe	ReCiPe
Software	N.A.[a]	SimaPro	N.A.[c]	N.A.[c]	SimaPro	SimaPro	Brightway2	openLCA
Manufacturing	●	●	●	●	●	●	●	●
Operations	●	●	●	●	●	●	●	●
Maintenance	●	◑	○	●	◑	○	◑	○
End-of-Life	○	●	◑	○	○	●	○	◑

●included; ◑ partially included; ○not included.

[a] Hybrid LCA: P-LCA and EIO-LCA.

[b] CO_2-eq emissions per PKM.

[c] Streamlined-LCA.

4. Improvements: MRO use-case

Maintenance is a pivotal aspect in reducing emissions. The vehicle degradation tendency due to operations is avoided by timely and correct maintenance. For instance, regular use of engine wash reduces the fuel consumption, which in turn reduces the environmental impact of flights. On the other hand, impacts can surface from different sources. Toxic materials from aircraft servicing and maintenance in different checks and MRO activities may be relevant for impact categories such as human toxicity and ecotoxicity (Halpern and Graham, 2018). In addition, energy-intensive activities during hangar operations are also present through the overall aircraft life cycle and must be addressed. Despite the relevance of maintenance when considering environmental impacts, there is a lack of MRO datasets in background LCI databases, such as ecoinvent, as the air transport datasets do not cover aircraft maintenance yet (Rupcic et al., 2023).

Based on the identified gaps and challenges, the following will demonstrate how an improved dataset can simplify the conduct of an LCA by using the example of MRO activities of a conventional passenger aircraft. Maintenance activities are a crucial component in an aircraft's life cycle, as they not only maintain the airworthiness of the aircraft but also have the potential to continuously reduce ecological impact over its entire life cycle through targeted measures. An example is the enhanced fuel efficiency of the engine following an engine wash, which pays off after just a few flights, both economically and environmentally (Rahn et al., 2021). The MRO dataset will be exemplarily generated based on calculations from Rahn et al. (2024) and examined from various perspectives, with the detailed LCI data available publicly in the same source. The aim of this analysis is twofold: Firstly, to establish the foundation of an MRO dataset for integration into LCI background databases, thereby making it accessible to other LCA practitioners. Concurrently, the aim is to expedite a guideline for generation of underrepresented LCI data, preparing them for implementation and use in various LCA applications.

To assess the ecological impact of aircraft MRO, a top-down methodology was utilized. The top-down approach focuses on various maintenance checks that aggregate maintenance activities into MRO packages. These packages vary in their level of detail, maintenance duration, and execution intervals, and can differ depending on the aircraft type or operational requirements. By employing the top-down approach, general maintenance parameters over the aircraft's entire life cycle are calculated. These parameters can, for example, entail the total duration an aircraft spends in maintenance during its service life or the service life of specific equipment. Maintenance intervals for aircraft components are determined by "whatever occurs first" principle (Hinsch, 2019), based on time in operation, Flight Hours (FHs), Flight Cycles (FCs), and the aircraft's operational environment (high or low outside temperatures, humidity, dust, and salt in the air). The overview of the maintenance types and intervals can be found in the supplementary material.

4.1. LCI dataset

The proposed LCI dataset is structured to encompass both airframe and engine maintenance activities. These maintenance processes involve various upstream activities, including energy consumption, material usage, and resource utilization (e.g., water). The MRO operations are interconnected with existing datasets concerning aircraft production, airport infrastructure, and kerosene production. In contrast, the detailed Maintenance Planning Document (MPD) analysis, which serves as a comprehensive guide for aircraft maintenance programs, including specific task descriptions, execution times, references to technical documentation, and required equipment, offers an insight into the ecological impact at the component level. This allows for more advanced analyses. The MPD provides granular data, enabling a more component-specific evaluation of the ecological footprint. Since UPRs in background databases represent individual processes of human activities and their respective exchanges with a higher level of data aggregation, the MPD in-depth analysis is not applied to this study.

Through the integration into the transport dataset, the MRO activities are incorporated alongside other life cycle phases. This approach provides calculations based on different FUs such as FC, FH, PKM as well as for the aircraft entire lifetime, which are then translated into impact categories during the LCIA phase. As illustrated in Fig. 3, the cumulative LCI methodology aggregates environmental inputs and outputs across the entire life cycle of a product or process. This cumulative approach provides a comprehensive understanding of the environmental impacts by considering all stages of the life cycle, i.e., in a cradle-to-gate approach. It is reasonable to also divide the maintenance dataset into different flight segments (from very short to very long haul). This segmentation reflects the varying maintenance needs and ecological impacts associated with different flight lengths and operational characteristics. For simulation purposes, the A320 class is chosen as the operating aircraft for all flight routes.

Generally, the maintenance efforts for commercial aircraft can be categorized into three main areas: engines, airframe, and components. These areas constitute the aircraft's maintenance demands during its operational life (Ackert, 2011). For the purpose of this analysis, airframe and components are merged into a single category. During its operational life, engines undergo wear, stress, and fatigue, leading to lower efficiency and reliability, and critical components such as the fan, compressor, and turbine (referred to as Life Limited Parts (LLPs)) have to be replaced at fixed intervals to ensure safety. Moreover, the aircraft and engine are not necessarily coupled for their entire life span. This means that an engine, after undergoing a detailed engine shop visit, can be reassigned to another aircraft. Particularly safety-critical components such as LLPs in the engine have defined life spans and must be replaced at fixed intervals, leading to a high demand for newly produced parts.

Hence, the maintenance activities are divided into two types: airframe (structure and components) maintenance and engine maintenance. This division was chosen since the aircraft and engine are two highly complex systems with different conditions that are challenging to represent in a single dataset. Separating the airframe and engines also allows for the representation of aircraft with varying numbers of engines. Airframe maintenance includes line maintenance (daily, weekly, and A-checks), base maintenance (C- and D-checks), and shop maintenance (Auxiliary Power Unit (APU) and landing gear), whereas engine maintenance is comprised of engine shop visit and LLPs exchanges. In addition, materials and resources used in each activity are distinct for airframe and engine MRO. For instance, composite materials are extensively used for maintaining the aircraft airframe through its life cycle, while engine parts and LLPs are generally comprised of special aviation alloys (e.g., titanium, nickel, and steel).

The approach is elaborated in greater detail in Rahn et al. (2024) and can be adapted to various operational scenarios. The LCA was conducted utilizing the ecoinvent version 3.9.1 database, employing the allocation, cut-off by classification system model (ecoinvent, 2023a). The Environmental Footprint (EF) 3.0 LCIA methodology (Fazio et al., 2018) was chosen as per recommendation provided by the European Commission, given its robustness and recognition as a reliable framework to quantify environmental performance (European Commission, 2024). The generated results are applied to various flight schedules in order to represent the different hauls. The aircraft's life cycle is simulated using DLR-internal framework called Life Cycle Cash Flow Environment (LYFE) for discrete-event simulation (Pohya et al., 2021). This tool allows for aircraft life cycle simulation based on flight schedules and maintenance needs and calculates the occurrence of individual maintenance activities throughout the aircraft life span. An average flight distance for each flight category is assumed. For example, for very long haul flights, the assumed distance is always set to 7000 km per flight event, equivalent to the great circle distance between Frankfurt (FRA) and Chicago (ORD). It is assumed that the flight schedule either starts or

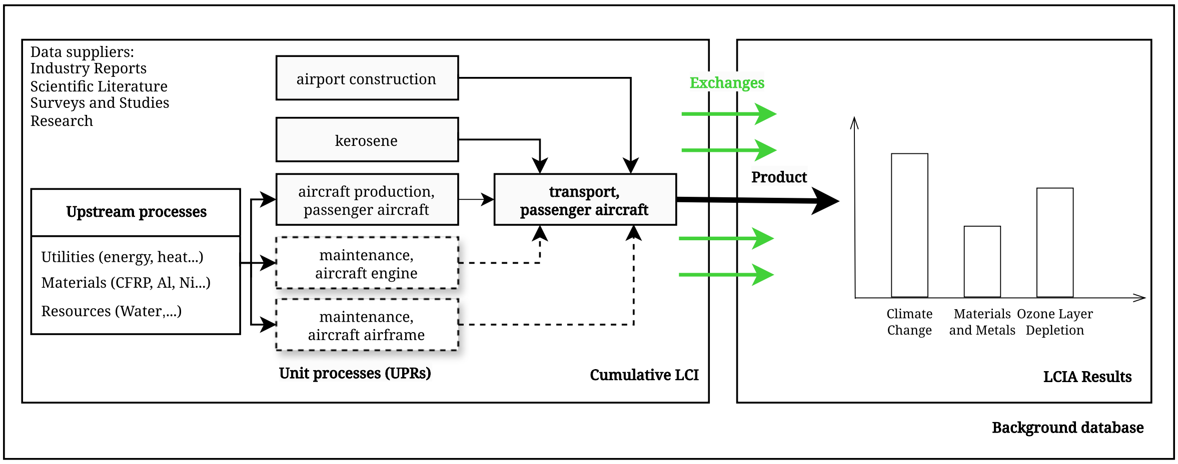

Fig. 3. The proposed MRO dataset is categorized into airframe and engine maintenance. The upstream processes comprise utilities, materials, and resources, which serve as inputs to the MRO activities. The MRO UPR is utilized downstream by the transport activity. The inventory represents a cumulative LCI, i.e., it spans over the product whole life cycle. Finally, the environmental impact results are calculated and translated into different impact scores based on existing LCIA methods. (adapted from ecoinvent (2023b)).

ends at one of these airports. In addition, the obtained LCA results for each maintenance check type (e.g., line, base, or shop) are then aggregated and distributed according to its occurrence for each flight haulage. The occurrence of maintenance activities for each flight distance changes, e.g., aircraft operating in very short- or short-range networks exhibit higher FCs due to shorter distances and more frequent flights, whereas long- and very long-range routes present higher FHs due to longer flights per cycle.

4.2. Results and Sensitivity Analysis (SA)

A summary of the results for each impact category can be found in the supplementary material to this article. The MRO simulation for all passenger-dedicated flights assumes a passenger capacity of 150, with an average load factor of 80% and no cargo load. Table 2 presents the climate change results [kgCO_2-eq] for flights of varying duration, ranging from very short to long hauls, considering a 25-year lifespan. The flight range influences factors such as FC, FH, and the lifetime distances of the aircraft. Here, a FC begins with the aircraft takeoff and ends after its landing and usually represents the interval unit for LLPs replacement, whereas FH comprises the actual hours flown by the aircraft and triggers activities such as engine and APU shops (Ackert, 2011).

Lifetime distances are obtained by the product of the average flight distances and the total number of flight cycles during the whole aircraft operation phase. A PKM is a unit of measurement that represents the transportation of one passenger over a distance of 1 km. It is calculated by multiplying the number of passengers by the vehicle's lifetime distance. Maintenance activities were assumed to predominantly occur in Germany or, in cases where additional data was unavailable, within Europe.

Fig. 4 illustrates the results for the climate change impact category per lifetime, PKM, FC, and FH for various flight distances. All maintenance checks are performed during an aircraft lifetime, but at different points in time. The frequency of such tasks is significantly influenced by the aircraft's utilization. The accumulated impact over the lifespan increases as the total lifetime distance rises. Despite having the smallest accumulated result, very short haul flights had the highest environmental impact per FH due to shorter duration. Conversely, very long range networks exhibited the highest environmental contribution per flight cycle.

Since LCA is a relative approach structured around a FU (ISO, 2006a), to which all in- and outputs in the LCI and consequently the LCIA profile are related, it is thus relevant to analyse the suitability of such unit in this study. FCs can represent diverse routes ranging from very short haul trips, e.g., Frankfurt to Munich, to very long haul flights, such as Frankfurt (DE) to Chicago (US). Since FUs are reference units and should represent the primary service provided by a product system, the variability associated to FCs makes it unsuitable as a FU.

A more spread trend is observed in the climate change results per PKM and FH, revealing distinctions between very short and short haul and medium to very long haul flights. For distances between 500 km and 1150 km, the environmental impact per flown hour and per passenger kilometre is exceptionally high when compared to longer distances (from medium to very long haul). That is due to the larger amount of flight cycles in shorter distance flights. For higher distances, the values do not vary significantly, demonstrating a similar tendency for ranges between 2750 km and 7000 km. In air transportation datasets and in aviation, PKM is the most commonly used FU and considered a good unit of comparison of the entire aircraft operation (Keiser et al., 2023). Since

Table 2
Overview of results for very short haul (500 km), short haul (1150 km), medium haul (2750 km), long haul (4500 km), and very long haul (7000 km).

Flight haulage	Lifetime distance [km]	Climate change			
		[tCO_2-eq./lifetime]	[kgCO_2-eq./PKM]	[kgCO_2-eq./FH]	[kgCO_2-eq./FC]
Very short haul	17.76×10^6	1531	0.57×10^{-3}	30.4	43.1
Short haul	39.93×10^6	1734	0.29×10^{-3}	24.0	49.9
Medium haul	69.92×10^6	2069	0.20×10^{-3}	19.1	81.4
Long haul	90.73×10^6	2298	0.17×10^{-3}	18.5	114.0
Very long haul	100.42×10^6	2601	0.17×10^{-3}	19.3	181.3

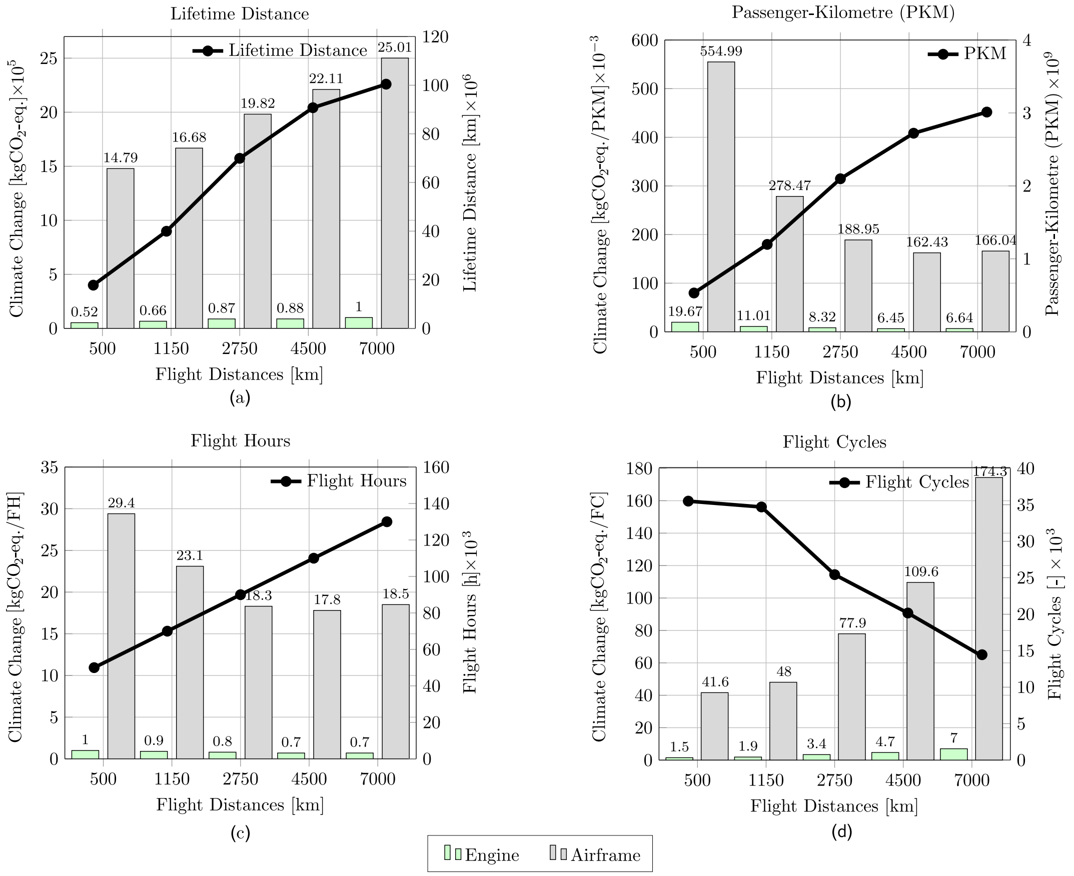

Fig. 4. Climate change results [kgCO$_2$-eq.] per (a) accumulated lifetime, (b) PKM, (c) FH, and (d) FC.

FHs are relevant for life cycle phases as flight operations and maintenance, but not so representative of production and end-of-life, PKM is the recommended FU. It also allows for the connection to other UPRs comprised in passenger transportation datasets, such as aircraft and kerosene production.

Depending on the intended use and target audience, the necessary level of data aggregation may change. For MRO and aviation-specific applications, the differentiation between different flight distances is relevant due to distinct frequency of maintenance checks. Modularity in LCI datasets is especially valuable for LCA applications within aviation (Rupcic et al., 2023). For sector-specific purposes, datasets for different flight distances enable in-depth calculations given the granularity of inventories. The distinction between different haulages becomes especially relevant due to the high climate change results per PKM in flight schedules for very short and short haul networks.

On the other hand, for general LCA purposes, practitioners might benefit from an aggregated dataset representing general maintenance activities for passenger aircraft, i.e., a gate-to-gate UPRs, typically average or representative models of product systems. Background LCI databases require a balance between providing sufficient detail and avoiding unnecessary complexity in data aggregation. Given that background databases typically represent an average technology description of activities of a given area, a dataset representative of aircraft maintenance in Germany for aircraft operating medium-range networks is proposed.

The main contributors are the energy consumption for hangars and equipment operation, accounting for approximately two-thirds of the overall results (Rahn et al., 2024). Consequently, these parameters are considered key drivers and require closer examination through a Sensitivity Analysis (SA). A local SA allows for assessing the behaviour of a model when some input parameters are varied around a nominal value. It takes a one-at-a-time approach, i.e., vary one input while keeping the others fixed (Pohya et al., 2022).

Input parameters such as electricity for hangar operation (EASA, 2015; Department for Business, Innovation & Skills, 2016) and diesel for Ground Power Unit (GPU) operation (Hydro Systems KG, 2024) are interchangeably varied and fixed. Fig. 5 shows the respective change in the output results in comparison to the baseline in a Δoutput vs. Δinput visualization. The following impact categories are presented: Climate Change (CC), Freshwater Ecotoxicity (FETP), Energy Carriers, Photochemical Ozone Creation Potential (POCP), Ionising Radiation (IRP), and Freshwater Eutrophication (FEP).

In terms of CC, changes in both input parameters reflect a slightly small deviation in the output results. For GPU operations powered by diesel, the greatest effect can be seen in the FETP, Energy Carriers, and POCP categories. FETP is strongly affected by chloride emission to surface water contributing to freshwater ecotoxicity (Müller et al., 2019). In addition, the extraction and use of diesel contributes to Energy Carriers, given the importance of crude oil extraction and the fact that diesel is a non-renewable energy source. Lastly, diesel fuels release volatile organic compounds (VOCs) and nitrogen oxides (NOx) during combustion. These substances are significant contributors to the photochemical ozone creation potential (POCP) impact category (Derwent et al., 2007). On the other hand, hangar operations are particularly based on the German electricity mix. IRP is particularly impacted by nuclear power in Germany, since the composition of the market dataset is valid for the year 2014 (Reinert et al., 2021). At last, fossil-fuel-based power generation (e.g., coal, natural gas) contributes to nutrient overload in water bodies, impacting freshwater systems, thus affecting the FEP category.

These findings illustrate how different energy sources and their associated emissions affect different environmental impact categories. In the context of aircraft maintenance, which is notably energy-

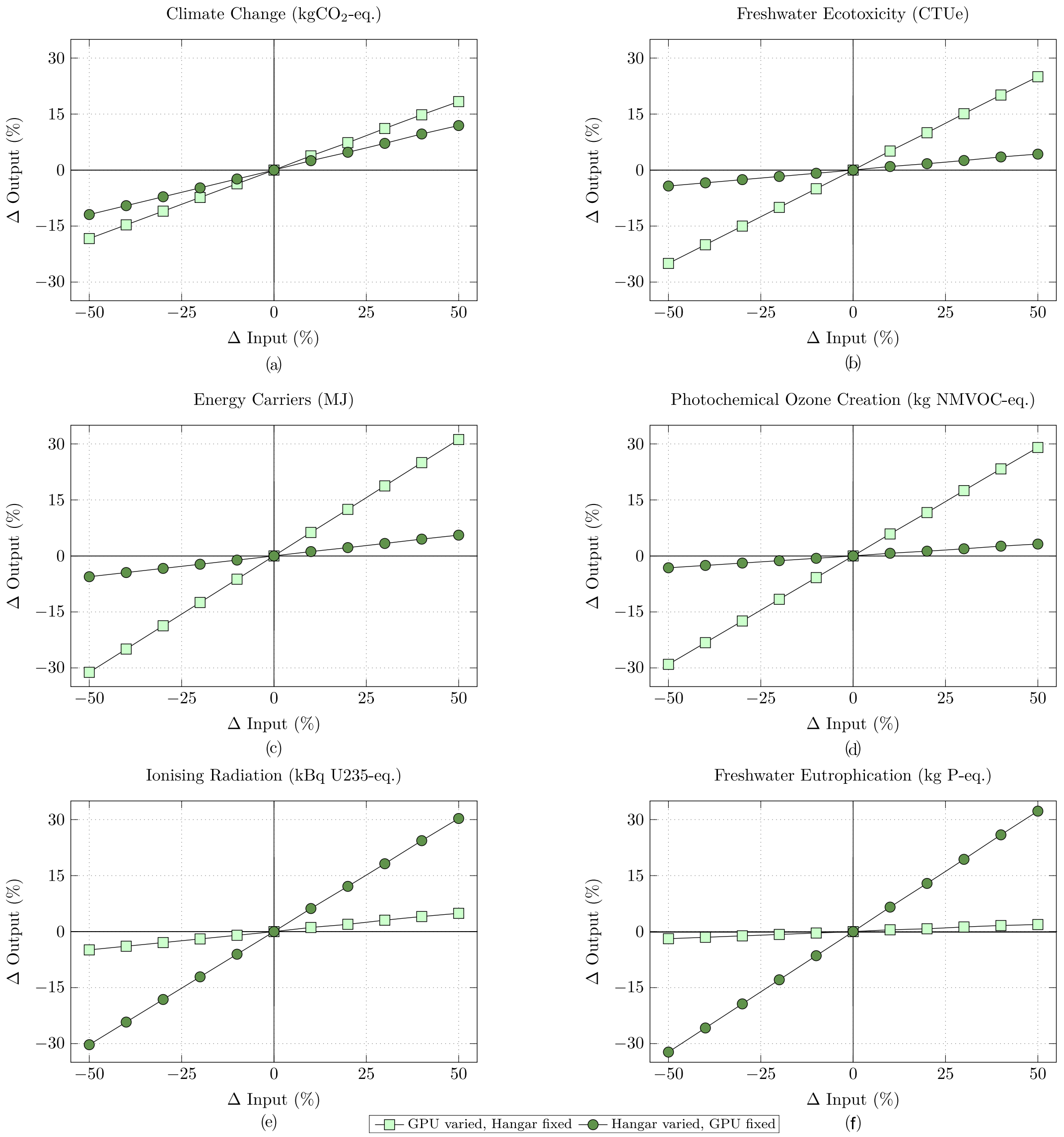

Fig. 5. Sensitivity analysis of environmental performance. Dark green circles represent scenarios where the GPU operation is fixed and the hangar operation is varied, while light green squares show results where the GPU operation is varied and the hangar operation is fixed, illustrating the effect of these parameters on the output values. Results are presented for the (a) CC, (b) FETP, (c) Energy Carriers, (d) POCP, (e) IRP, and (f) FEP impact categories. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

intensive, technological improvements that reduce the energy demand of maintenance activities hold significant potential for advancing sustainable aviation.

5. Discussion

Within aviation, the conduction of LCA is particularly hindered by sector-specific LCI data limitations, e.g., maintenance and materials. The results presented in the previous section indicate that the environmental impacts of aircraft maintenance activities vary depending on flight distances. Additionally, it is necessary to categorize MRO tasks into airframe and engine maintenance owing to their distinct complexities and characteristics. This dataset is derived from an in-depth analysis of scheduled maintenance activities throughout an aircraft's complete life cycle, with variations observed based on the chosen flight distance (Rahn et al., 2024). It holds potential advantages for end-users of background databases, as it facilitates more comprehensive comparison studies of different transportation modes or the environmental impact share of maintenance across the overall aircraft life cycle (e.g., production, flight operations, or end-of-life).

Translating extensive and detailed foreground data into background data requires comprehensive interpretation, assumptions, and hypotheses consistent with the system boundaries. The level of data aggregation is a crucial aspect, varying depending on the intended purpose of the study and the target audience. LCI background databases typically represent average models of product systems, requiring a balance between providing sufficient detail and avoiding unnecessary complexity in data aggregation. However, aviation experts and LCA practitioners in the sector may require more disaggregated, detailed LCI data (Thonemann et al., 2024). Particularly in the context of new aircraft concepts, components may exhibit different maintenance requirements, and potential burden shifting between different life cycle phases can occur (e.g., from climate change to minerals and metals categories). For that end, in-depth inventories are especially relevant when conducting comparative studies.

Regarding the presented MRO use-case, our findings suggest that airframe and engine maintenance should be separated due to differing system complexities and operational life characteristics throughout the life cycle. For the intended use of general LCA studies, the authors recommend the dataset aggregation representative of aircraft maintenance activities in Germany for aircraft operating medium-range networks. For LCA applications within aviation, the distinction between different haulages becomes especially relevant due to the high GWP results per PKM in flight schedules for very short and short haul. Additionally, the most suitable FU was found to be PKM, as it remains relatively consistent regardless of flight distance, unlike FC, which varies significantly depending on haulage. Moreover, PKM is the most commonly used FU in air transportation datasets, allowing for connection to other UPRs.

However, the study has limitations. Firstly, only routine and scheduled maintenance activities are within the scope of analysis, potentially underestimating MRO events and environmental impacts by excluding unscheduled maintenance events. Secondly, the disposal or recycling of components, such as LLPs, is not considered, despite their complex aviation alloys, making analysis of the end-of-life stage relevant for more comprehensive results. Additionally, to maintain simplicity and avoid infinite inventories or feedback loops, the system boundaries do not include the manufacturing and maintenance of tools and equipment, transportation within maintenance facilities, or impacts related to maintenance staff. Lastly, the geographical representativeness of the MRO dataset is limited to activities conducted in Germany, with a smaller extent within Europe.

6. Conclusion and outlooks

Conducting LCA is primarily based on meaningful and accurate LCI data. However, the aviation industry faces significant challenges regarding the sensitivity and confidentiality of such data. This difficulty arises from the complex nature of aviation operations and the proprietary information involved. However, overcoming this challenge is crucial for accurately assessing the environmental impacts of air transport activities. In the industry context, LCA is a relatively new discipline and most companies do not possess a deep level of expertise in the subject yet, meaning that process LCI is usually provided in a rather raw format, and LCA practitioners are required to extensively restructure and review data, which is highly resource-intensive. Due to data sensitivity and legal constraints, the data gathering process is especially difficult. An alternative to such issue is the inclusion of data extracted from patents, which are already used as indicators in fields such as technological forecasting. Since aviation is a highly evolving and changing field of application, future analysis with a prospective nature is relevant, and for that end, the use of patents-extracted to build LCI foreground data for LCA studies is thus applicable (Spreafico et al., 2023). This approach is particularly relevant for novel technologies, such as fuel cell and mild-hybrid aircraft, and could significantly enhance future research when considering technology forecasting (Thonemann et al., 2020).

In research, despite facing own issues with data collection and awareness on the relevance of environmental assessments, researches still most of the time underlie their own confidentiality regulations. Initiatives as the Supply Chain Act in Germany (Federal Ministry for Economic Cooperation and Development (BMZ), 2023) represent key drivers for the future and aim to prevent, reduce or end any violation of human rights and environmental obligations at any point in the supply chain, including contractual partners, direct, and indirect suppliers. Additionally, alternative strategies such as data aggregation can prove effective. Aggregation involves the combining of data, such as summing individual emissions into specific categories or merging processes into a simplified UPR where only input and output flows are disclosed (Edelen and Ingwersen, 2016).

Within this context, data enrichment plays a pivotal role in generating more meaningful and accurate LCA results. Special attention is given to data shortcomings for aircraft maintenance activities. This study delves into the process of generating aviation-specific LCI background data based on expert level primary data through an exemplary MRO use-case. The high flexibility of our aircraft life cycle simulation tool allows for calculations of maintenance efforts for different flight distances. Based on the study findings, dividing airframe and engine maintenance is also needed due to different maintenance characteristics and demands through the aircraft service life. For future, the inclusion of end-of-life scenarios is beneficial to ensure completeness. Additionally, enhancing the representation of special aviation alloys such as aluminium, titanium, and nickel alloys, as well as fibre reinforced polymers, and characterizing energy-intensive maintenance processes can improve results for LLPs. Linking the proposed MROs dataset to downstream air transport processes can benefit other LCA practitioners aiming for comprehensive studies.

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CRediT authorship contribution statement

Joana Albano: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Antonia Rahn:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Jens Bachmann:** Writing – review & editing, Conceptualization. **Gerko Wende:** Funding acquisition.

Declaration of competing interest

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

Data availability

Data is shared in supplementary material.

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Appendix A. Supplementary data

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References

Ackert, S., 2011. Engine maintenance concepts for financiers: elements of turbofan shop maintenance costs. URL: http://www.aircraftmonitor.com/uploads/1/5/9/9/15993320/engine_mx_concepts_for_financiers__v2.pdf.

Aerospace Technology Institute, 2021. Sustainability in aerospace. URL: https://www.ati.org.uk/wp-content/uploads/2021/08/insight_16-sustainability.pdf.

Aihara, N., Morimoto, F., Tsujimura, T., 2007. Inventory analysis of transport in Japan based on input-output tables. Quarterly Report of RTRI 48. https://doi.org/10.2219/rtriqr.48.221.

Airbus, 2008. Process for advanced management of end of life of aircraft (PAMELA). URL: https://trimis.ec.europa.eu/project/process-advanced-management-end-life-aircraft.

Atescan Yuksek, Y., Mills, A., Ayre, D., Koziol, K., Salonitis, K., 2024. Comparative life cycle assessment of aluminium and cfrp composites: the case of aerospace manufacturing. Int. J. Adv. Des. Manuf. Technol. https://doi.org/10.1007/s00170-024-13241-3.

Bachmann, J., Yi, X., 2020. The ECO-COMPASS EU-China project. In: I European Conference on Multifunctional Structures (EMuS 2019), pp. 96–101. URL: https://www.scipedia.com/public/Bachmann_Yi_2020a.

Bicer, Y., Dincer, I., 2017. Life cycle evaluation of hydrogen and other potential fuels for aircrafts. Int. J. Hydrogen Energy 42. https://doi.org/10.1016/j.ijhydene.2016.12.119.

BMWI, 2024. Foerderung von forschungs- und entwicklungsvorhaben im rahmen des siebten nationalen zivilen luftfahrtforschungsprogramms klima – erster programmaufruf (lufo klima vii-1). URL: https://www.bundesanzeiger.de/pub/publication/wo9HEtVGx58dt1xtkMV/content/wo9HEtVGx58dt1xtkMV/BAnz/20AT/2019.04.2024/20B1.pdf.

Boeing, 2023. Boeing 2023 sustainability report. URL: https://www.boeing.com/content/dam/boeing/boeingdotcom/principles/sustainability/sustainability-report/2023/assets/2023-Boeing-Sustainability-Report.pdf.

Bourgault, G., Lesage, P., Samson, R., 2012. Systematic disaggregation: a hybrid lci computation algorithm enhancing interpretation phase in lca. Int. J. Life Cycle Assess. 17, 774–786. https://doi.org/10.1007/s11367-012-0418-7. https://publications.polymtl.ca/15734/.

Calado, E.A., Leite, M., Silva, A., 2019. Integrating life cycle assessment (lca) and life cycle costing (lcc) in the early phases of aircraft structural design: an elevator case study. Int. J. Life Cycle Assess. 24. https://doi.org/10.1007/s11367-019-01632-8.

Chester, M., 2008. Life-Cycle Environmental Inventory of Passenger Transportation in the United States. University of California, Berkeley, CA, USA. PhD Thesis.

Chester, M.V., Horvath, A., 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. 4. https://doi.org/10.1088/1748-9326/4/2/024008.

Ciroth, A., Arvidsson, R., 2021. Life Cycle Inventory Analysis: Methods and Data. LCA Compendium – the Complete World of Life Cycle Assessment. Springer International Publishing. URL: https://books.google.de/books?id=FihAEAAAQBAJ.

Ciroth, A., Di Noi, C., Burhan, S., Srocka, M., 2019. Lca database creation: current challenges and the way forward. Indonesian J. Life Cycle Assess. Sustain. 3. https://doi.org/10.52394/ijolcas.v3i2.105.

Cox, B., 2018. Mobility and the Energy Transition: A Life Cycle Assessment of Swiss Passenger Transport Technologies Including Developments until 2050. ETH Zurich, Zurich. https://doi.org/10.3929/ethz-b-000276298. Phd thesis.

Curran, M., 2008. Life-cycle assessment. In: Jørgensen, S.E., Fath, B.D. (Eds.), Encyclopedia of Ecology. Academic Press, Oxford, pp. 2168–2174. https://doi.org/10.1016/B978-008045405-4.00629-7. URL: https://www.sciencedirect.com/science/article/pii/B9780080454054006297.

Dallara, E., Kusnitz, J., Bradley, M., 2013. Parametric life cycle assessment for the design of aircraft. SAE Int. J. Aerospace 6. https://doi.org/10.4271/2013-01-2277.

Department for Business, Innovation & Skills, 2016. UK mro labour market analysis. URL: https://assets.publishing.service.gov.uk/media/5a75b99fed915d506ee8105a/bis-16-132-uk-mrol-analysis.pdf.

Dér, A., Dilger, N., Kaluza, A., Creighton, C., Kara, S., Varley, R., Herrmann, C., Thiede, S., 2021. Modelling and analysis of the energy intensity in polyacrylonitrile (pan) precursor and carbon fibre manufacturing. J. Clean. Prod. 303, 127105. https://doi.org/10.1016/j.jclepro.2021.127105. URL: https://www.sciencedirect.com/science/article/pii/S095965262101324X.

Derwent, R., Jenkin, M., Passant, N., Pilling, M., 2007. Photochemical ozone creation potentials (pocps) for different emission sources of organic compounds under european conditions estimated with a master chemical mechanism. Atmos. Environ. 41, 2570–2579. https://doi.org/10.1016/j.atmosenv.2006.11.019. URL: https://www.sciencedirect.com/science/article/pii/S135223100601140X.

Dolganova, I., Bach, V., Rödl, A., Martin, K., Finkbeiner, M., 2022. Assessment of critical resource use in aircraft manufacturing. Circular Econ. Sustain. 2. https://doi.org/10.1007/s43615-022-00157-x.

Duflou, J., De Moor, J., Verpoest, I., Dewulf, W., 2009. Environmental impact analysis of composite use in car manufacturing. CIRP Annals 58, 9–12. https://doi.org/10.1016/j.cirp.2009.03.077. URL: https://www.sciencedirect.com/science/article/pii/S0007850609000304.

Dwulet, L., 2016. Afra – leading the way in safe and sustainable aircraft end-of-life management. URL: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2016/ENVReport2016_pg196-198.pdf.

EASA, 2015. Acceptable means of compliance (amc) and guidance material (gm) to annex ii (part-145) to regulation (eu) no 1321/2014. URL: https://www.easa.europa.eu/en/document-library/acceptable-means-of-compliance-and-guidance-materials/group/amc-gm-to-regulation-eu-no-13212014.

EASA, 2022. Environmental sustainability status in the aviation maintenance and production organisation (m&p) domain. URL: https://www.easa.europa.eu/en/downloads/138573/en.

ecoinvent, 2023a. Ecoinvent version 3.9.1. URL: https://support.ecoinvent.org/ecoinvent-version-3.9.1.

ecoinvent, 2023b. Upr, lci & lcia. URL: https://support.ecoinvent.org/upr-lci-lcia.

Edelen, A., Ingwersen, W.W., 2016. Guidance on Data Quality Assessment for Life Cycle Inventory Data. US Environmental Protection Agency. Technical Report EPA/600/R-16/096.

EEA, 2013. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2013 – Technical Guidance to Prepare National Emission Inventories. Publications Office. https://doi.org/10.2800/92722.

EU, 2020. Hydrogen-powered Aviation – A Fact-Based Study of Hydrogen Technology, Economics, and Climate Impact by 2050. Publications Office. https://doi.org/10.2843/471510.

European Commission, 2013. Commission recommendation of 9 april 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations text with eea relevance. URL. http://data.europa.eu/eli/reco/2013/179/oj.

European Commission, 2024. About environmental footprint methods. URL: https://green-business.ec.europa.eu/environmental-footprint-methods/about-environmental-footprint-methods_en.

Fabre, A., Planès, T., Delbecq, S., Budinger, V., Lafforgue, G., 2022. Life cycle assessment models for overall aircraft design. In: AIAA SCITECH 2022 Forum. American Institute of Aeronautics and Astronautics, Reston, Virginia, pp. 1–20. https://doi.org/10.2514/6.2022-1028.

Facanha, C., Horvath, A., 2006. Environmental assessment of freight transportation in the u.s. Int. J. Life Cycle Assess. 11. https://doi.org/10.1065/lca2006.02.244.

Fazio, S., Biganzoli, F., Laurentis, V.D., Zampori, L., Sala, S., Diaconu, E., 2018. Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Methods. Technical Report KJ-NA-29600-EN-N (online), KJ-NA-29600-EN-C (Print). European Commission's Joint Research Centre, Luxembourg (Luxembourg), 10.2760/002447(online),10.2760/090552(print).

Federal Ministry for Economic Cooperation and Development (BMZ), 2023. The German act on corporate due diligence obligations in supply chains. URL: https://www.bmz.de/resource/blob/154774/lieferkettengesetz-faktenpapier-partnerlaender-eng-bf.pdf.

Fernanda Rojas Michaga, M., Michailos, S., Akram, M., Cardozo, E., Hughes, K.J., Ingham, D., Pourkashanian, M., 2022. Bioenergy with carbon capture and storage (beccs) potential in jet fuel production from forestry residues: a combined techno-economic and life cycle assessment approach. Energy Convers. Manag. 255, 115346. https://doi.org/10.1016/j.enconman.2022.115346. URL: https://www.sciencedirect.com/science/article/pii/S019689042200142X.

Ferrari, A.M., Volpi, L., Settembre-Blundo, D., na, F.E.G.M., 2021. Dynamic life cycle assessment (lca) integrating life cycle inventory (lci) and enterprise resource planning (erp) in an industry 4.0 environment. J. Clean. Prod. 286, 125314. https://doi.org/10.1016/j.jclepro.2020.125314. URL: https://www.sciencedirect.com/science/article/pii/S0959652620353592.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manag. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018. URL: https://www.sciencedirect.com/science/article/pii/S0301479709002345.

Fricke, K., Bergs, T., Ganser, P., Gierlings, S., Albano, J., 2022. Life cycle inventories for engine blisk lca. IOP Conf. Ser. Mater. Sci. Eng. 1226, 012103. https://doi.org/10.1088/1757-899X/1226/1/012103. URL:

Gardiner, G., 2014. Recycling carbon fiber for structural applications. URL: https://www.compositesworld.com/articles/recycling-carbon-fiber-for-structural-applications.

Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E., 2016. Introduction to lca with simapro. URL: https://pre-sustainability.com/files/2014/05/SimaPro8IntroductionToLCA.pdf.

Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S., 2022. Digital Product Passport: the ticket to achieving a climate neutral and circular European economy? Technical Report EURO-TECH-REP-2022-001. European Commission, Brussels, Belgium. URL: https://epub.wupperinst.org/frontdoor/deliver/index/docId/8049/file/8049_Digital_Product_Passport.pdf.

Groetsch, T., Creighton, C., Varley, R., Kaluza, A., Dér, A., Cerdas, F., Herrmann, C., 2021a. A modular lca/lcc-modelling concept for evaluating material and process innovations in carbon fibre manufacturing. URL: https://publica.fraunhofer.de/handle/publica/266650.

Groetsch, T., Maghe, M., Rana, R., Hess, R., Nunna, S., Herron, J., Buckmaster, D., Creighton, C., Varley, R.J., 2021b. Gas emission study of the polyacrylonitrile-based continuous pilot-scale carbon fiber manufacturing process. Ind. Eng. Chem. Res. 60, 17379–17389. https://doi.org/10.1021/acs.iecr.1c02253. URL:

Halpern, N., Graham, A. (Eds.), 2018. The Routledge Companion to Air Transport Management, first ed. Routledge. https://doi.org/10.4324/9781315630540.

Haupt, J., Cerdas, F., Herrmann, C., 2024. Derivation of requirements for life cycle assessment-related information to be integrated in digital battery passports. Procedia CIRP 122, 300–305. https://www.sciencedirect.com/science/article/pii/S2212827124000659. . 31st CIRP Conference on Life Cycle Engineering.

Hauschild, M., Huijbregts, M., 2015. Life Cycle Impact Assessment. LCA Compendium – the Complete World of Life Cycle Assessment. Springer Netherlands. URL: https://books.google.de/books?id=kqOiBwAAQBAJ.

Hauschild, M., Rosenbaum, R., Olsen, S., 2017. Life Cycle Assessment: Theory and Practice. Springer International Publishing. URL: https://books.google.de/books?id=S7szDwAAQBAJ.

Hellweg, S., Milà i Canals, L., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science (New York, N.Y.) 344, 1109–1113. https://doi.org/10.1126/science.1248361.

Hendrickson, C., Horvath, A., Joshi, S., Juarez-Espinosa, O., Lave, L., Matthews, H., Mcmichael, F., Cobas-Flores, E., 1998. Economic Input-Output-Based Life-Cycle Assessment (Eio-lca).

Hermansson, F., Ekvall, T., Janssen, M., Svanström, M., 2022. Allocation in recycling of composites - the case of life cycle assessment of products from carbon fiber composites. Int. J. Life Cycle Assess. 27. https://doi.org/10.1007/s11367-022-02039-8.

Hermansson, F., Janssen, M., Svanström, M., 2019. Prospective study of lignin-based and recycled carbon fibers in composites through meta-analysis of life cycle assessments. J. Clean. Prod. 223, 946–956. https://doi.org/10.1016/j.jclepro.2019.03.022.

Hinsch, M., 2019. In: Industrielles Luftfahrtmanagement: Technik und Organisation luftfahrttechnischer Betriebe. 4., aktualisierte auflage ed. Springer Vieweg, Berlin and Heidelberg. https://doi.org/10.1007/978-3-662-58804-8.

Howe, S., 2011. Environmental Impact Assessment and Optimisation of Commercial Aircraft. Cranfield University, Cranfield. Master thesis.

Howe, S., Kolios, A., Brennan, F., 2013. Environmental life cycle assessment of commercial passenger jet airliners. Transport. Res. Transport Environ. 19, 34–41. https://doi.org/10.1016/j.trd.2012.12.004.

Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., Zelm, R., 2016. Recipe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22. https://doi.org/10.1007/s11367-016-1246-y.

Hydro Systems KG, 2024. Ground support equipment: precisely the professional choice. URL: https://www.hydro.aero/de/ground-support-equipment.html.

IATA, 2024. Helping aircraft decommissioning. URL: https://www.iata.org/en/programs/environment/aircraft-decommissioning/.

Islam, S., Ponnambalam, S., Lam, H.L., 2016. Review on life cycle inventory: methods, examples and applications. J. Clean. Prod. 136, 266–278. URL: https://www.sciencedirect.com/science/article/pii/S0959652616306163, 10.1016/j.jclepro.2016.05.144. pRES'15: Cleaner energy planning, management and technologies.

ISO, 2006a. In: Environmental Management — Life Cycle Assessment — Principles and Framework. ISO 14040:2006, second ed. International Organization for Standardization, Geneva, Switzerland. ISO 14040:2006.

ISO, 2006b. In: Environmental Management — Life Cycle Assessment — Requirements and Guidelines. ISO 14044:2006, first ed. International Organization for Standardization, Geneva, Switzerland. ISO 14044:2006.

Jemioło, W., 2015. Life Cycle Assessment of Current and Future Passenger Air Transport in Switzerland. University of Nordland, Bodø. Master thesis.

Johanning, A., Scholz, D., 2013. A first step towards the integration of life cycle assessment into conceptual aircraft design. In: Proceedings of the German Aerospace Congress, pp. 1–16.

Jordão, T.C., 2012. Life cycle assessment oriented to climate change mitigation by aviation. In: Proceedings of the 15th International Conference on Environmental Economy, Policy and International Environmental Relations, pp. 1–19.

Keiser, D., Schnoor, L.H., Pupkes, B., Freitag, M., 2023. Life cycle assessment in aviation: a systematic literature review of applications, methodological approaches and challenges. J. Air Transport. Manag. 110, 102418. https://doi.org/10.1016/j.jairtraman.2023.102418. URL: https://www.sciencedirect.com/science/article/pii/S0969699723000613.

Kjæ r, L., Host-Madsen, N., Schmidt, J., McAloone, T., 2015. Application of environmental input-output analysis for corporate and product environmental footprints—learnings from three cases. Sustainability 7, 11438–11461. https://doi.org/10.3390/su70911438.

Krieg, H., Ilg, R., Brethauer, L., 2012. Environmental impact assessment of aircraft operation: a key for greening the aviation sector. J. Aerospace Sci. Tech. Syst. 91, 73–78.

Laca, A., Herrero, M., Díaz, M., 2011. 2.60 - life cycle assessment in biotechnology. In: Moo-Young, M. (Ed.), Comprehensive Biotechnology, second ed.). second ed. ed. Academic Press, Burlington, pp. 839–851. https://doi.org/10.1016/B978-0-08-088504-9.00140-9. URL: https://www.sciencedirect.com/science/article/pii/B9780080885049001409.

Lengsfeld, H., Mainka, H., Altstädt, V., 2020. Carbon Fibers: Production, applications, processing. https://doi.org/10.3139/9781569908297.

Lewis, T., 2013. A Life Cycle Assessment of the Passenger Air Transport System Using Three Flight Scenarios. Norwegian University of Science and Technology, Trondheim. Master thesis.

Liu, Z., 2013. Life Cycle Assessment of Composites and Aluminium Use in Aircraft Systems. Master Thesis. Cranfield University, Cranfield.

Lopes, J., 2010. Life Cycle Assessment of the Airbus A330-200 Aircraft. Universidade Técnica de Lisboa, Lisbon. Master thesis.

Maaß, S., 2020. Aircraft Recycling – a Literature Review. https://doi.org/10.15488/11549.

Mayyas, A.T., Qattawi, A., Mayyas, A.R., Omar, M.A., 2012. Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy 39, 412–425. URL: https://www.sciencedirect.com/science/article/pii/S0360544211008589. sustainable Energy and Environmental Protection 2010.

Megill, L., Deck, K., Volker, G., 2024. Alternative climate metrics to the global warming potential are more suitable for assessing aviation non-co2 effects. Commun. Earth Environ. 5. https://doi.org/10.1038/s43247-024-01423-6.

Melby, E.G., Castro, J.M., 1989. Glass-reinforced thermosetting polyester molding: materials and processing. In: Allen, G., Bevington, J.C. (Eds.), Comprehensive Polymer Science and Supplements. Pergamon, Amsterdam, pp. 51–109. https://doi.org/10.1016/B978-0-08-096701-1.00206-8. URL: https://www.sciencedirect.com/science/article/pii/B9780080967011002068.

Melo, S.P., Barke, A., Cerdas, F., Thies, C., Mennenga, M., Spengler, T.S., Herrmann, C., 2020. Sustainability assessment and engineering of emerging aircraft technologies—challenges, methods and tools. Sustainability 12. https://doi.org/10.3390/su12145663. URL: https://www.mdpi.com/2071-1050/12/14/5663.

Müller, J.B., Melegari, S.P., Perreault, F., Matias, W.G., 2019. Comparative assessment of acute and chronic ecotoxicity of water soluble fractions of diesel and biodiesel on daphnia magna and aliivibrio fischeri. Chemosphere 221, 640–646. https://doi.org/10.1016/j.chemosphere.2019.01.069. URL: https://www.sciencedirect.com/science/article/pii/S0045653519300694.

Mussatto, S.I., Motta, I.L., Filho, R.M., van der Wielen, L., Capaz, R., Seabra, J., Osseweijer, P., Posada, J., de Freitas Gonçalves, M., Scorza, P.R., Dragone, G., 2022. Sustainable aviation fuels: production, use and impact on decarbonization. In: Comprehensive Renewable Energy. Elsevier, pp. 348–371. https://doi.org/10.1016/B978-0-12-819727-1.00057-1.

Notten, P., Althaus, H.J., Burke, M., 2018a. Carbon fibre reinforced plastic, injection moulded. glo, ecoinvent database version, 3.9.1.

Notten, P., Althaus, H.J., Burke, M., 2018b. Life cycle inventories of global air freight - global. URL: https://sri-lci.ecoinvent.org/files/sectorial_report_sri_glo_air_transport_v2.pdf.

Ogin, S., Brøndsted, P., Zangenberg, J., 2016. 1 - composite materials: constituents, architecture, and generic damage. In: Talreja, R., Varna, J. (Eds.), Modeling Damage, Fatigue and Failure of Composite Materials. Woodhead Publishing. Woodhead Publishing Series in Composites Science and Engineering, pp. 3–23. https://doi.org/10.1016/B978-1-78242-286-0.00001-7. URL: https://www.sciencedirect.com/science/article/pii/B9781782422860000017.

Ogugua, C.J., Anton, S.V., Tripathi, A.P., Larrabeiti, M.D., van Hees, S.O., Sinke, J., Dransfeld, C.A., 2023. Energy analysis of autoclave cfrp manufacturing using thermodynamics based models. Compos. Appl. Sci. Manuf. 166, 107365. https://doi.org/10.1016/j.compositesa.2022.107365. URL: https://www.sciencedirect.com/science/article/pii/S1359835X22005462.

Oliveux, G., Dandy, L.O., Leeke, G.A., 2015. Current status of recycling of fibre reinforced polymers: review of technologies, reuse and resulting properties. Prog. Mater. Sci. 72, 61–99. https://doi.org/10.1016/j.pmatsci.2015.01.004. URL: https://www.sciencedirect.com/science/article/pii/S0079642515000316.

Pigosso, D.C.A., Grandi, C.M., Rozenfeld, H., 2013. Strategic implementation of design for environment at embraer. URL: https://api.semanticscholar.org/CorpusID:227043057.

Pohya, A.A., Wehrspohn, J., Meissner, R., Wicke, K., 2021. A modular framework for the life cycle based evaluation of aircraft technologies, maintenance strategies, and operational decision making using discrete event simulation. Aerospace 8. https://doi.org/10.3390/aerospace8070187. URL: https://www.mdpi.com/2226-4310/8/7/187.

Pohya, A.A., Wicke, K., Kilian, T., 2022. Introducing variance-based global sensitivity analysis for uncertainty enabled operational and economic aircraft technology assessment. Aero. Sci. Technol. 122, 107441. https://doi.org/10.1016/j.ast.2022.107441. URL: https://www.sciencedirect.com/science/article/pii/S1270963822001158.

Protokol, 2024. Enhancing sustainability through the integration of dpps and lcas. URL: https://www.protokol.com/insights/enhancing-sustainability-through-the-integration-of-dpps-and-lcas/.

Prussi, M., Lee, U., Wang, M., Malina, R., Valin, H., Taheripour, F., Velarde, C., Staples, M.D., Lonza, L., Hileman, J.I., 2021. Corsia: the first internationally adopted approach to calculate life-cycle ghg emissions for aviation fuels. Renew. Sustain. Energy Rev. 150, 111398. https://doi.org/10.1016/j.rser.2021.111398. URL: https://www.sciencedirect.com/science/article/pii/S1364032121006833.

Rahn, A., Pohya, A.A., Wehrspohn, J., Wicke, K., 2021. A modular framework for life cycle assessment of aircraft maintenance. AIAA AVIATION 2021 FORUM. https://doi.org/10.2514/6.2021-2369.

Rahn, A., Schuch, M., Wicke, K., Sprecher, B., Dransfeld, C., Wende, G., 2024. Beyond flight operations: assessing the environmental impact of aircraft maintenance through life cycle assessment. J. Clean. Prod. 453, 142195. https://doi.org/10.1016/j.jclepro.2024.142195. URL: https://www.sciencedirect.com/science/article/pii/S0959652624016433.

Rahn, A., Wicke, K., Wende, G., 2022. Using discrete-event simulation for a holistic aircraft life cycle assessment. Sustainability 14, 10598. https://doi.org/10.3390/su141710598.

Reinert, C., Deutz, S., Minten, H., Dörpinghaus, L., von Pfingsten, S., Baumgärtner, N., Bardow, A., 2021. Environmental impacts of the future German energy system from integrated energy systems optimization and dynamic life cycle assessment. Comput. Chem. Eng. 153, 107406. https://doi.org/10.1016/j.compchemeng.2021.107406. URL: https://www.sciencedirect.com/science/article/pii/S0098135421001848.

Reinhard, J., Wernet, G., Zah, R., Heijungs, R., Hilty, L., 2019. Contribution-based prioritization of lci database improvements: the most important unit processes in ecoinvent. Int. J. Life Cycle Assess. 24. https://doi.org/10.1007/s11367-019-01602-0.

Rupcic, L., Pierrat, E., Saavedra-Rubio, K., Thonemann, N., Ogugua, C., Laurent, A., 2023. Environmental impacts in the Civil aviation sector: current state and guidance. Transport. Res. Transport Environ. 119, 103717. https://doi.org/10.1016/j.trd.2023.103717.

Scheelhaase, J.D., Dahlmann, K., Jung, M., Keimel, H., Nieße, H., Sausen, R., Schaefer, M., Wolters, F., 2016. How to best address aviation's full climate impact from an economic policy point of view? Transport. Res. Transport Environ. 45, 112–125. https://doi.org/10.1016/j.trd.2015.09.002.pII:S1361920915001261.

Shirinfar, M., Hosseini nasab, H., Sadegheih, A., Fakhrzad, M., 2022. Aircraft component spare parts logistics and operation planning: a case study in farsco aircraft mro center. Int. J. Supply Oper. Manag. 9, 461–472. https://doi.org/10.22034/ijsom.2021.109333.2328. URL: http://www.ijsom.com/article_2883.html.

Silva, D., Rocha, R., Ribeiro, F., Monteiro, H., 2024. Environmental impact of an innovative aeronautic carbon composite manufactured via heated vacuum-assisted resin transfer molding. Sustainability 16. https://doi.org/10.3390/su16083253. URL: https://www.mdpi.com/2071-1050/16/8/3253.

sphera, 2022. Process data set: carbon fiber reinforced plastic part. URL: https://sphera.com/2023/xml-data/processes/62a88e0b-175a-4743-bebe-f36addc3ca5d.xml.

Spreafico, C., Landi, D., Russo, D., 2023. A new method of patent analysis to support prospective life cycle assessment of eco-design solutions. Sustain. Prod. Consum. 38, 241–251. https://doi.org/10.1016/j.spc.2023.04.006. URL: https://www.sciencedirect.com/science/article/pii/S2352550923000787.

Su-Ungkavatin, P., Tiruta-Barna, L., Hamelin, L., 2023. Methodological framework for life cycle assessment of sustainable aviation (SA) systems. Sci. Total Environ. 885, 163881. https://doi.org/10.1016/j.scitotenv.2023.163881.

Suzuki, T., Takahashi, J., 2004. Lca of lightweight vehicles by using cfrp for mass-produced vehicles. In: Proceedings of the 15th International Conference on Composite Materials (ICCM-15), pp. 1–4.

Suzuki, T., Takahashi, J., 2005. Prediction of Energy Intensity of Carbon Fiber Reinforced Plastics for Mass-Produced Passenger Cars.

Tech Briefs, 2019. Lightweighting in aerospace component and system design. URL: https://www.techbriefs.com/component/content/article/33914-lightweighting-in-aerospace-component-and-system-design#::text=Critical/20requirements/20for/20aerospace/20structural,such/20as/20cost/2C/20servicing/2C/20and.

Thonemann, N., Saavedra-Rubio, K., Pierrat, E., Dudka, K., Bangoura, M., Baumann, N., Bentheimer, C., Caliandro, P., De Breuker, R., de Ruiter, C., Di Stasio, M., Elleby, J., Guiguemde, A., Lemoine, B., Maerz, M., Marciello, V., Meindl, M., Nicolosi, F., Ruocco, M., Sala, B., Scharling Tromer Dragsdahl, A.L., Vezzini, A., Wang, Z., Wannemacher, T., Zettelmeier, J., Laurent, A., 2024. Prospective life cycle inventory datasets for conventional and hybrid-electric aircraft technologies. J. Clean. Prod. 434, 140314. https://doi.org/10.1016/j.jclepro.2023.140314. URL: https://www.sciencedirect.com/science/article/pii/S0959652623044724.

Thonemann, N., Schulte, A., Maga, D., 2020. How to conduct prospective life cycle assessment for emerging technologies? a systematic review and methodological guidance. Sustainability 12. https://doi.org/10.3390/su12031192.

Verstraete, J., 2012. Creating a Life-Cycle Assessment of an Aircraft. Hamburg University of Applied Sciences, Hamburg. Project thesis.

Vinodh, S., Gurunathan, S., Nithish, S., Veeramanikandan, R., 2017. Life cycle assessment of an aircraft component: a case study. Int. J. Ind. Syst. Eng. 27. https://doi.org/10.1504/IJISE.2017.10008235.

Vivalda, P., Fioriti, M., 2024. Stream life cycle assessment model for aircraft preliminary design. Aerospace 11. https://doi.org/10.3390/aerospace11020113. URL: https://www.mdpi.com/2226-4310/11/2/113.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part i): overview and methodology. Int. J. Life Cycle Assess. 21, 1–13. https://doi.org/10.1007/s11367-016-1087-8.