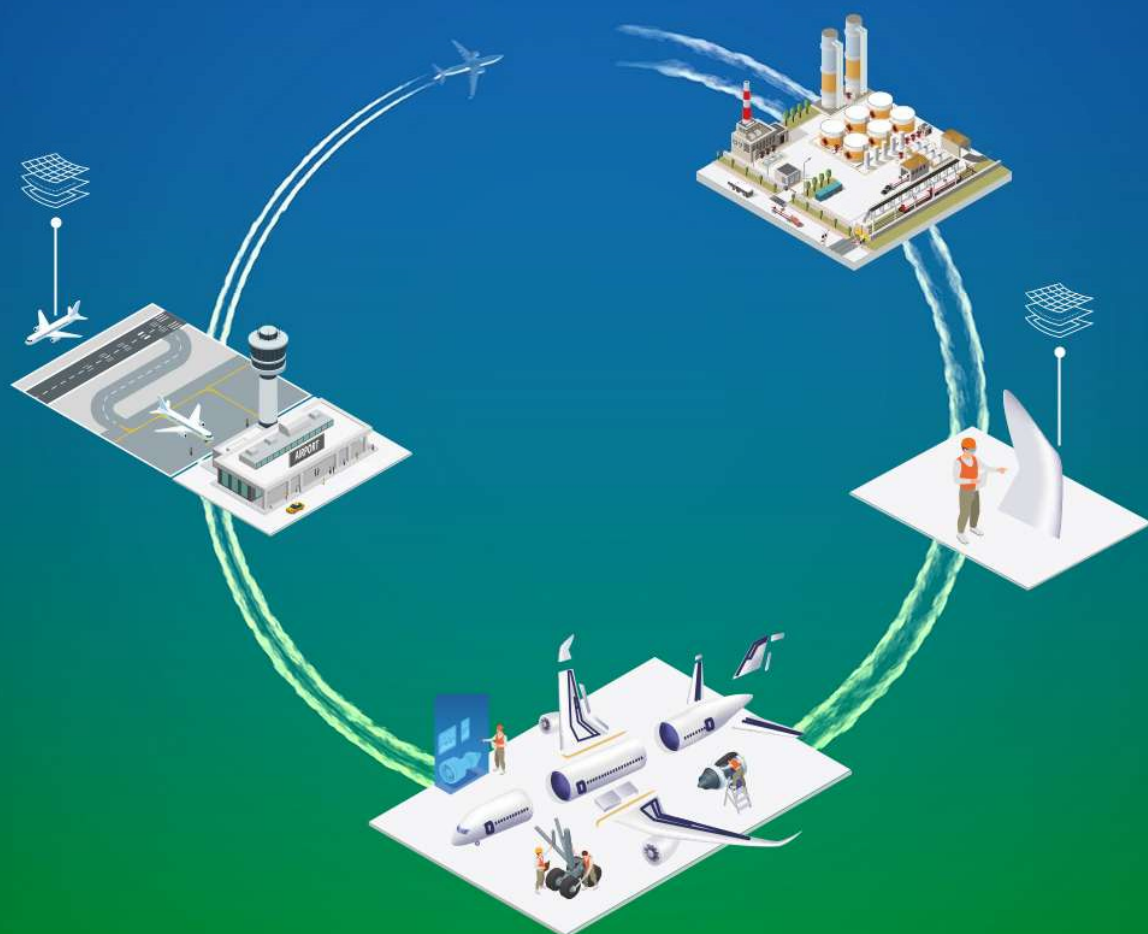
LIFE CYCLE ASSESSMENT IN THE AIR TRANSPORT SYSTEM



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Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

LIFE CYCLE ASSESSMENT IN THE AIR TRANSPORT SYSTEM

GUIDANCE DOCUMENT

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PREFACE

We are pleased to present this joint guidance document by the German Aerospace Center (DLR) and the Netherlands Aerospace Centre (NLR) on life cycle assessment (LCA) in the air transport sector. This document provides a comprehensive framework for assessing the environmental impacts of the air transport system, enabling informed decision-making and sustainable development.

As leaders in the aviation research ecosystem, DLR and NLR recognize the importance of providing guidelines and metrics for consistent and credible communication on the sustainability performance of the air transport system. This guidance document aims to facilitate the improved LCA practices, support stakeholders in making informed decisions that include environmental considerations, and enhance communication to interested stakeholders.

The purpose of this guidance is to support researchers, companies, and other stakeholders in evaluating the environmental impact of the air transport system, including fuel and aircraft production, airport infrastructure, and their operations. This document aims to ease the process of conducting life cycle assessments in the air transport system, building on the best available scientific knowledge and methods, and facilitating consistency with relevant international standards.

By adopting this guidance, stakeholders can contribute to a more sustainable air transport system, aligning with international standards and best practices. The following chapters provide a detailed overview of the guidance, including its scope, methodology, and applications, supporting stakeholders in their efforts to reduce environmental impacts and promote sustainable development.

"The publication of this guidance document on Life Cycle Assessment in the air transport system represents a significant milestone in our pursuit of a more sustainable future for aviation. By uniting the LCA expertise of NLR and DLR, we enable researchers, industry and policy makers to widen the scope from in-flight emissions to the full life cycle and from climate change to a comprehensive view of environmental impacts."

Dr Martin Nagelsmit

Chief Technology Officer, NLR

“The development of a climate-compatible air transport system requires innovative technologies and processes as well as assessment capabilities to determine their impact. Through our cooperation for a systemic LCA in aviation, DLR and NLR demonstrate that collaborative efforts can drive meaningful progress in providing such guidance.”

Dr Markus Fischer

Divisional Board Member for Aeronautics, DLR

“This guidance document is a crucial building block for achieving our goal of climate neutral aviation. Working together with our partners and stakeholders, we can use life cycle assessment to see where our impacts are and subsequently steer innovation to reduce emissions, ultimately creating a more sustainable industry.”

Mr Bram Peerlings

Programme Lead Climate Neutral Aviation, NLR

“Creating a sustainable air transport system is a shared challenge that crosses borders. Drawing on the joint research expertise of DLR and NLR, this guidance provides a clear framework and practical tools to assess the environmental impacts of aviation including its technical operations like MRO. It is designed to support the industry to uptake LCA and to shape international benchmarks and standards as well as to further enhance the well-established circularity of assembled materials.“

Prof. Gerko Wende

Head of Institute Maintenance, Repair and Overhaul, DLR

1. INTRODUCTION

Purpose of this guidance

This document serves as guidelines for Life Cycle Assessment (LCA) in the air transport system. This includes aircraft manufacturing, use, and end-of-life, the fuel or energy source supply chain, and airport infrastructure and operations, encompassing all components and processes involved in air transport. The content is based on joint DLR-NLR knowledge of air transport and LCA.

The objective of the guidance is to facilitate consistent and credible assessment and communication of the environmental life cycle impact of products, assets and part of the air transport system, providing state-of-the-art guidance for the people working in aviation. Specifically, this guidance is meant to:

- Ease the process of conducting LCA in the air transport system;
- Build on the best available scientific knowledge and methods;
- Facilitate consistency with the ISO 14040-14044 standards on LCA;
- Seek alignment with potential forthcoming Product Environmental Footprint Category Rules (PEFCR) guidance;
- Serve as reference work for LCA practitioners;
- Provide support for decision-making by leveraging LCAs of air transport systems.

Who is this guidance targeted at?

Researchers and companies seeking to evaluate the environmental impact of

- The entire air transport system, including electricity / fuel production, aircraft production; airport infrastructure, operations, maintenance and end-of-life;
- The life cycle of specific parts of the air transport system.

Specific target audiences are:

- Research institutes and academia in the aviation sector;
- LCA practitioners active in the aviation industry conducting product assessments and sharing results with value chain partners;
- Stakeholders utilizing LCA results to inform (business and policy) decisions;
- Value chain stakeholders requiring insight into the assumptions underlying environmental product claims, to prepare for upcoming legislation.

Relationship with existing standards and guidelines

This approach builds on the ISO 14040-14044 standards on LCA. A more detailed approach than the ISO standards is needed for two reasons. First, the ISO standards include steps, definitions and modelling choices, but leave a large degree of freedom to the LCA practitioner. To make results better comparable between studies, harmonisation in the approach is needed. Second, the aviation sector faces specific modelling challenges, for which methodological solutions are needed. The document offers aviation-specific guidance, building on existing standards.

The approach proposed in this document is the result of literature review of existing generic LCA standards (ISO 14040-14044, PEF, EN15804), existing LCA standards for aviation such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) Life Cycle Assessment Methodology, peer reviewed LCA studies, and internal discussions between LCA researchers in DLR and NLR. No formal stakeholder consultation process and no consensus building procedure has taken place. Rather, this document can serve as an input or starting point to create a formalised LCA standard for aviation. As the interest in, and knowledge of LCA in the air transport system is evolving, this guidance document should be updated or aid official standardisation activities.

Structure of the guidance document

The content of this document is structured around the four phases of Life Cycle Assessment (LCA) as defined in the relevant international standards.

> *Chapter 2: Goal and Scope of LCA in the air transport system* establishes the purpose of the study, product(s) to be studied, the function and functional unit, the system boundaries, and other methodological choices.
>
> *Chapter 3: Life Cycle Inventory Analysis* involves collecting data on all relevant inputs and outputs, such as energy use, emissions, and material flows across the system.
>
> *Chapter 4: Life Cycle Impact Assessment (LCIA)* translates these inventory data into potential environmental impacts, such as climate change, resource depletion, acidification, and fine particulate matter formation.
>
> *Chapter 5: Interpretation* integrates the findings, evaluates their significance, and provides recommendations to support informed decision-making.

In addition to the chapter on the four LCA phases, additional guidance is included in the chapters 6 and 7

> *Chapter 6: LCA Across Different Use-Cases* presents different use cases to illustrate the application of LCA in the air transport sector.
>
> *Chapter 7: References* provides the overview of references to literature, the list of abbreviations, and the lists of figures and tables

All seven chapters include definitions of the methodological choices, a literature review of LCA studies and international standards, and proposals for methodological choices for LCA in the air transport system.
The guidance can be used for LCA on the air transport system as a whole (including maintenance and flight operations, electricity and aviation fuels, aircraft materials, aircraft components, aircraft, airport infrastructure and operations).

CONTENTS

2. GOAL AND SCOPE OF LCA OF THE AIR TRANSPORT SYSTEM

The goal of LCA studies on (parts of) the air transport system is defined in accordance with the ISO 14040-14044 standard. Therefore, it contains the following elements:

- Intended application;
- Reasons for carrying out the study;
- Intended audience;
- Whether the results are intended to be used in comparative assertions or intended to be disclosed to the public.

2.1. Scope

In the literature of LCA on the air transport system, four main product systems are commonly analysed:

i. Air transport system as a whole (considering the complete life cycle impacts across all elements of the system);
ii. Production of aviation fuels (including upstream processes for conventional fuels and alternative fuels or other energy carriers);
iii. Production, use and maintenance of aircraft, materials and components (also covering their production, use phase, and maintenance activities of materials and components);
iv. Airport infrastructure and operations (encompassing construction, operation, and maintenance of airport facilities).

This document on LCA in the air transport system provides guidance on each topic. The aviation fuels, materials and components, airport infrastructure and operations, and their life cycles can be the object of analysis individually; at the same time, altogether they are part of the complete air transport system. The relationships among these four elements are further clarified in Figure 1 .

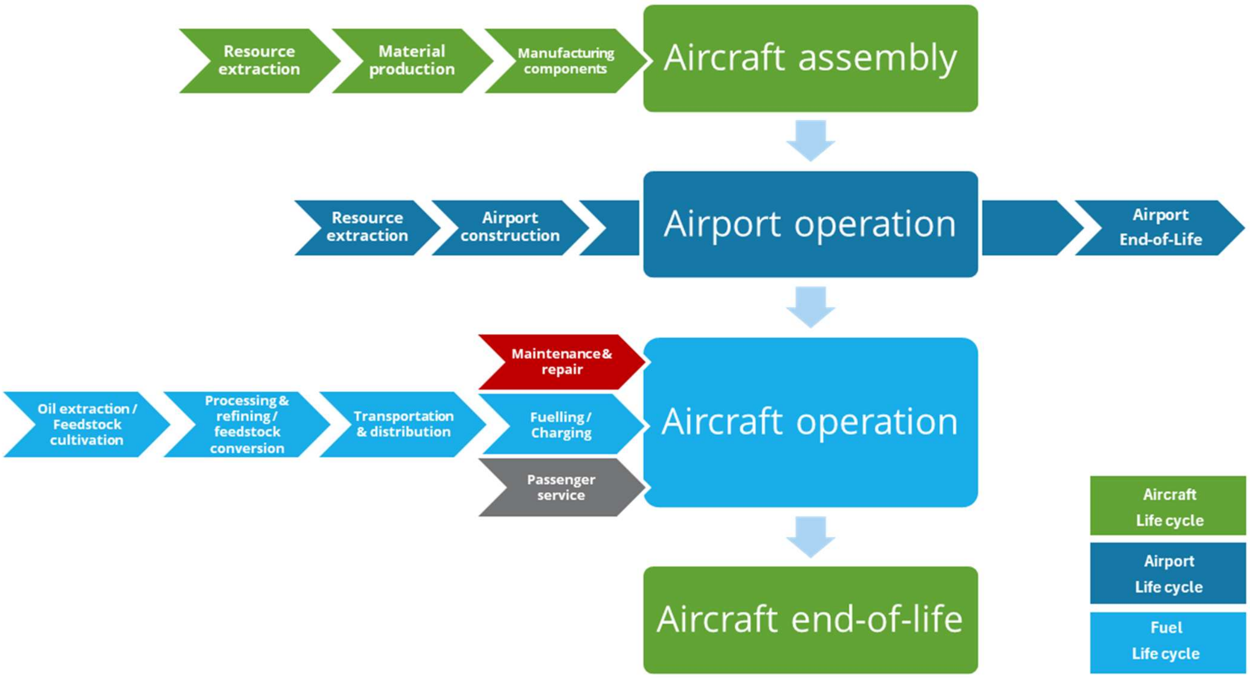

Figure 1: Relationship between the different elements of the air transport system.

The following topics are out of scope in this document:

- Life cycle phases such as direct impacts of research and development activities such as development of aircraft concepts, design studies, certification and approval of parts and aircraft;
- Air Traffic Management and Control, all activities on development and optimization of air traffic control systems, including future concepts (e.g., SESAR, NextGen), are excluded. The approach will be able to include the effects of more efficient routes since fuel production and consumption is in scope;
- Life Cycle Sustainability Assessment is not in scope. Social, economic, or financial analyses are not included as this guidance is focussing on environmental LCA;
- Activities Beyond the Air Transport System like downstream logistics, passenger behaviour, or multimodal transport interactions outside the defined system boundaries are also excluded.

2.1.1. The Air Transport System

The product system to be studied is depicted in Figure 1. It shows the relationship between the different elements of the air transport system consisting of aircraft assembly, airport operations, aircraft operations, maintenance, repair and overhaul (MRO) activities, and aircraft end-of-life (EoL).

2.1.1.1. Product System to be Studied

The following products systems are to be studied:

1. Air transport system as a whole;
2. Production of aviation fuels;
3. Production, use and maintenance of aircraft, materials and components;
4. Airport infrastructure and operations.

2.1.1.2. Function and Functional Unit

The Functional Unit (FU) of an LCA study is the "quantitative description of the function or service for which the assessment is performed, and the basis of determining the reference flow of product that scales the data collection" (Hauschild, 2018). In the ISO 14040-14044 standard on LCA, the importance of aligning the FU with the goal and scope of the study is emphasized. Furthermore, the FU has to be clearly defined and measurable.

The Environmental Footprint (EF) LCA framework from the European Commission includes four elements in the definition of the FU (EC, 2021). The FU for a Product Environmental Footprint (PEF) study is defined according to the following aspects (EC, 2021):

- The function(s)/service(s) provided: **'what';**
- The extent of the function or service: **'how much';**
- The expected level of quality: **'how well';**
- The duration/lifetime of the product: **'how long'.**

Linked to the functional unit is the reference flow. The reference flow is a "measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit" (ISO 14044). In this guidance, the definitions of the ISO standard 14040 (principles and framework of LCA) and ISO 14044 (detailed implementation of LCA) are used, together with the operationalization as described in the PEF method (EC, 2021).

In a literature review of LCA in aviation, Keiser et al. (2023) screened 1117 articles and analysed 45 contributions in detail. For aircraft operation, the most used FU is *person x km*. This unit of measurement quantifies the transportation of one passenger by a specific mode of transport (e.g. road, rail, air) over a distance of one kilometre. *Person x km* is also chosen FU by Keiser et al. themselves. Eurostat is using *passenger-kilometre*, as slightly different name for the same concept (EUROSTAT, 2025). Of the articles studied by Keiser et al. (2023), one article used *seat-kilometre*, which fits the object of analysis, but it excludes the load factor. Roberson (2016) uses *pax (person)* for a comparison between short haul flight and light rail. In a comparison between different modes of transport, there is a difference in distance between air, road, or rail transport to the same destination. The differences in trip distance are accounted for by using modality specific reference flows. This is reflected in the work of Roosien et al. (2024) using *journey per passenger*, *passenger-kilometres-travelled (PKT)* and *vehicle-kilometres-travelled (VKT)*. In some studies, (available) *seat x km* is used. Therefore, a comparison of a journey shall be made using different amounts of *person x km* for each modality. This guideline suggests to use great circle distance (GCD) in *person x km* as a functional unit. In those cases, the load factor of the aircraft is not included in the analysis and the results show the impact of the aircraft at full utilization, unless a default load factor is included in the modelling.

The draft Aircraft PEFCR contains the following description of the FU for aircraft: “transportation of one revenue-passenger in a safe way over one kilometre, meeting the minimum safety standards according to the European frameworks and regulations, during the reference lifetime of the aircraft” (EASA, 2022). The FU proposed by the PEFCR authors includes both *person or seat x km* and *freight x km* by merging them in the term *revenue-unit*. This approach avoids allocation as per the hierarchy proposed by the ISO 14040-14044 standard on LCA. In this guidance it is proposed to align with the draft Aircraft PEFCR definition. The proposed FU is summarized in Table 1.

Table 1: Functional Unit (FU) for LCA of the air transport system.

	FU of Air Transport
What?	Transportation of passengers and freight
How much?	One revenue-unit over 1 kilometre (1 revenue unit, representing 1 passenger or an equivalent 100 kg of freight)
How well?	In a safe manner, meeting the ICAO Standards And Recommended Practices (SARPs)*
How long?	During the reference lifetime of the aircraft
* Measures taken to comply with further regulations and policies on top of the ICAO SARPs are excluded as additional regional or national differences could affect comparability	

This FU can be based both on seat x km or *person x km*. *Seat x km* is typically used when comparing aircraft technologies, operations, or design concepts independent of passenger demand. It reflects the transport capacity offered by the aircraft and is useful for technology benchmarking.

Person x km includes the load factor (average percentage of seats occupied) and is appropriate when assessing real-world operations or comparing environmental performance at the system level. It reflects the actual transport work delivered to passengers and is often used in policy studies, airline sustainability reporting, and comparisons between different modes of transport (e.g., aviation vs. rail).

Load factors should be as specific as possible, based on company or route specific data that reflect the geographical and temporal scope of the study. The assumptions and data sources used must be reported transparently to ensure reproducibility and comparability of results.

2.1.1.3. System Boundaries

LCA studies require setting system boundaries, which demarcate the product system from the surrounding economy and environment. According to Bjørn et al. (2018a), system boundaries should include processes needed to deliver the reference flow with a completeness level aligned with the study's goal and scope.

The ISO 14040-14044 standards allow for excluding processes based on mass, energy, or environmental significance, without specifying a fixed percentage on the total mass, energy or environmental significance. In contrast, the Environmental Footprint LCA framework uses as cut-off criteria less than 3% material and energy flow as well as environmental impact per category. The key takeaway is that practitioners should justify that the excluded processes would not meaningfully influence the overall results or conclusions of the study

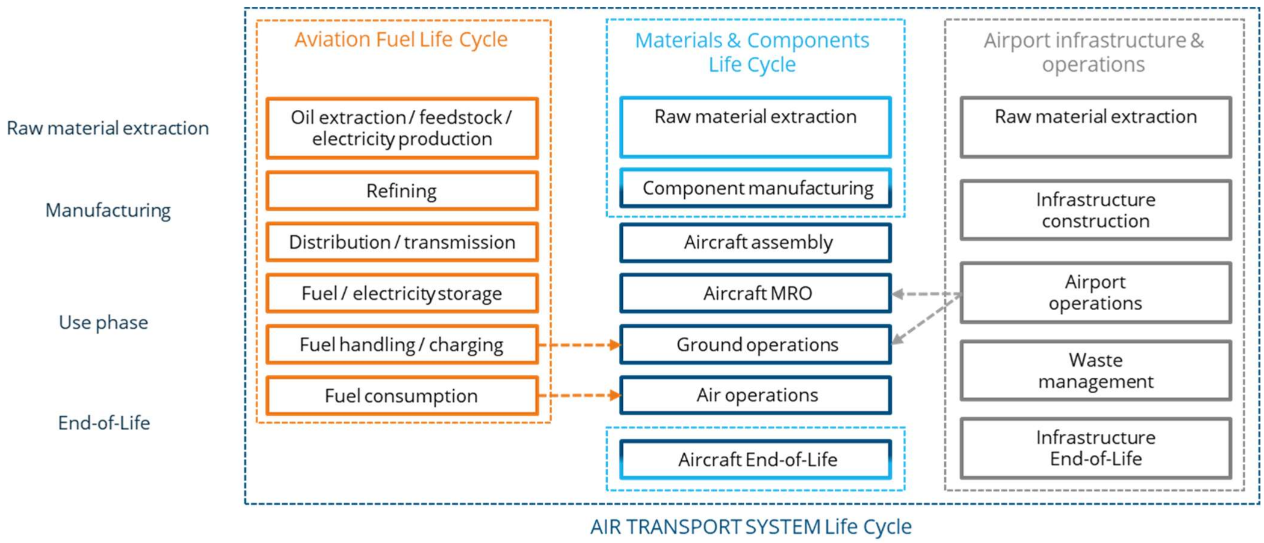

Figure 2: System boundaries of LCA in the air transport system (adapted from Melo et al., 2020 and Keiser et al., 2023). Transport and energy use between and within life cycle stages are included.

In the previous sections, the different parts of the air transport system were introduced. The fuel life cycle will be described in section 2.1.2. Materials and components (including EoL) will be discussed in section 2.1.3. Airport infrastructure and operations will be presented in section 2.1.4. The remainder of this section (2.1.1), will cover the MRO operations, ground operations, air operations and EoL. An overview of the four topics and their relationship is included in Figure 2.

Maintenance, Repair and Overhaul Operations

According to Rahn et al. (2024), the MRO tasks highlighted in red in Figure 3 fall within the scope of the LCA. MRO life cycle inventory data for the highlighted tasks are included in the supplementary material of the referenced article and in ecoinvent 3.11.

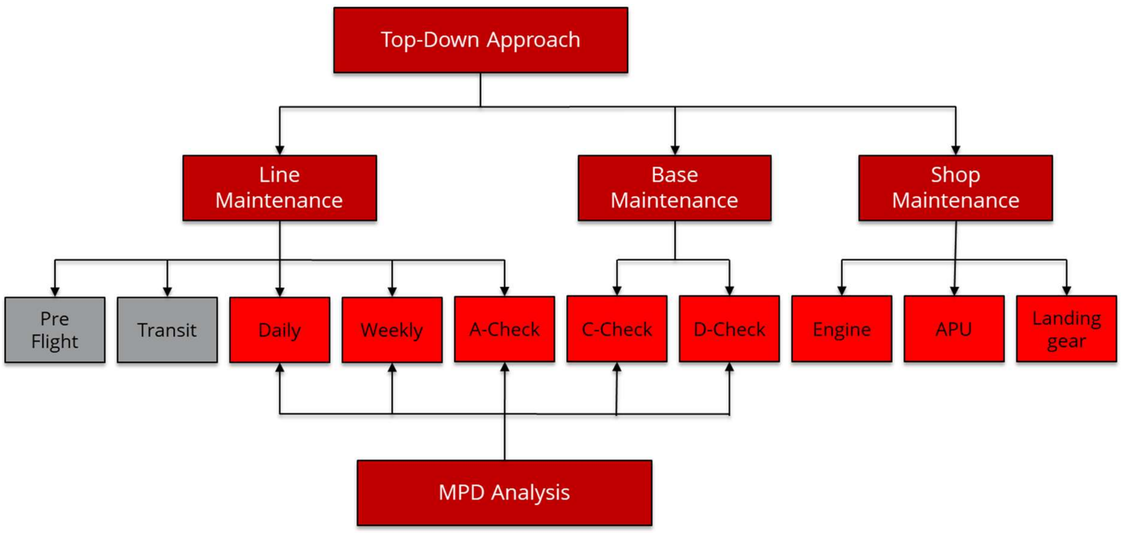

*Figure 3: Overview of the combined methodology for the assessment of aircraft maintenance (Rahn et al., 2024). *MPD = maintenance planning document.*

The MRO assessment excludes:

- Pre-flight and transit checks, as they have no direct environmental impact;
- The EoL phase and, therefore, waste treatment and recycling;
- The products and processes that have a secondary role in their use (for instance, the production of lamps, when assessing the energy consumption, or rags used for cleaning were not taken into account);
- The manufacturing and maintenance of tools and equipment;
- The transportation of products within the maintenance site;
- The impacts related to the maintenance staff, such as personal waste or commuting to the site.

Unplanned repairs are out of scope but they should be considered in future research

The range of activities included and considered within the maintenance assessment is diverse and may vary depending on the specific use case. A detailed breakdown of possible aspects incorporated in such LCA studies can be found, for example, in Rahn et al. (2024).

Ground Operations

Ground operations refer to the airport processes that take place on the ground. The following activities are included:

- Taxiing;
- De-icing (if applicable);
- Fuelling / charging;
- Baggage and catering handling;
- Passenger boarding (via finger or bus).

MRO is also considered a ground activity, but it is considered separately in the previous section.

Air operations

Air operations typically include all activities and processes related to the planning, execution, and management of flights. For the purpose of LCA, "air operations" refer to the in-flight phases of aircraft operations, as this is where the largest environmental impacts occur (Rupcic et al., 2023). Other aspects of air operations, such as flight planning and Air Traffic Management (ATM) activities are excluded.

Figure 4 shows the different phases of flight of an aircraft. The following emissions and resource use are included in air operations:

- Take-off;
- Departure and climb;
- Cruise;
- Descent and approach;
- Landing.

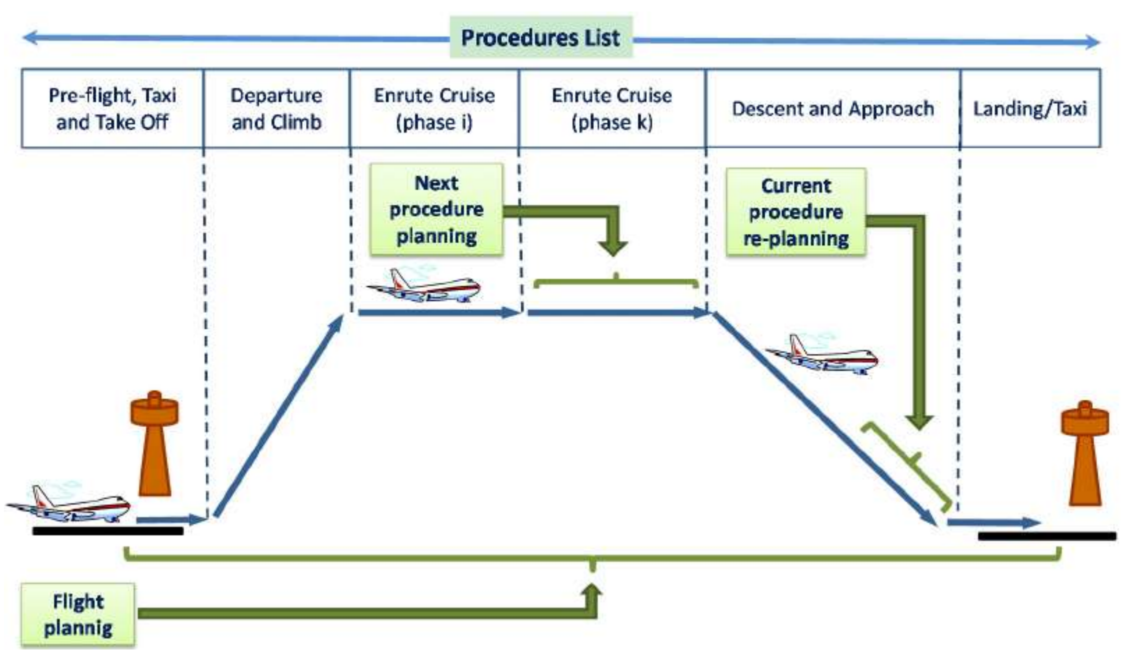

Figure 4: Phases of flight of an aircraft (Canino et al., 2015).

Taxiing is assigned to ground operations, since taxiing is arranged at the airport and it can be achieved by tugs, which is an airport asset. The emissions modelling should include the emission altitude and be aligned with the climate impact assessment modelling.

End-of-Life

The system boundaries of the EoL stage starts when the aircraft loses its airworthiness certificate. Airworthiness is the measure of an aircraft's suitability for safe flight (ICAO, 2018). Figure 5 shows the processes included in aircraft decommissioning, disassembly, dismantling and for returning parts into service by recertification. A component can return to airworthiness following FAA/EASA processes. Figure 5 shows that the aircraft EoL process consists of two phases:

- Phase 1: certified aircraft, parts removal for re-use, subject to aviation regulations;
- Phase 2: non-certified aircraft, final dismantling and recycling, no longer subject to aviation regulations.

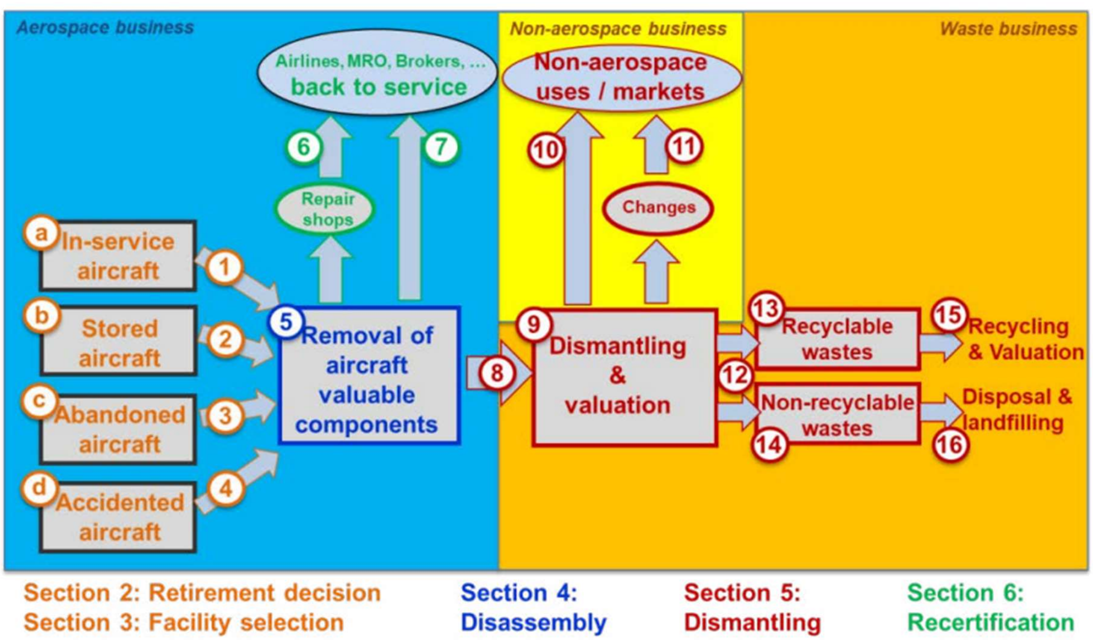

Figure 5: Process of aircraft decommissioning (ICAO, 2019).

More detail on end-of-life modelling is provided in section 2.1.3.4, which focuses on aircraft components and materials and addresses multifunctional processes. Many waste treatment processes serve multiple functions. For example, a recycling plant not only treats waste but also produces a recycled material.

2.1.1.4. Dealing with Multifunctional Processes

Many industrial processes or services have more than one function. For example, an aircraft can transport both passengers and freight within the same flight. In the context of LCA, this creates the challenge of determining how to allocate the total environmental impact of the flight between the passenger transport function and the freight transport function. This allocation can be based on several criteria, such as the share of payload weight, volume, or economic value that is attributable to passengers versus freight. The chosen allocation method can significantly influence the results of the LCA.

Similar allocation issues arise in other sectors. In mining, for instance, some ores are largely or exclusively mined as by-products of other ores (Nasser et al., 2015). Another example is the production of chlorine using the chloralkaline process (Alvarez-Gaitan et al., 2014). From a perspective of LCA system boundaries, it is difficult to determine which part of the process belongs to the main product or to the by-products.

In the ISO 14040-14044 standards on LCA, the following hierarchy of dealing with multifunctional processes is presented:

1. Subdivision, separating the process into sub-processes so that each deliver only one function;
2. System boundary expansion, including additional processes or systems to cover all functions jointly;
3. Allocation based on underlying physical relationship, distributing environmental impacts according to a physical parameter (e.g., mass, energy content, volume);
4. Allocation based on other relationships, using alternative criteria, such as economic value, to distribute impacts.

Our proposed functional unit for air transport follows this hierarchy by choosing subdivision as the primary approach.

> *"Transportation of passengers and freight, one revenue unit over one kilometre (1 revenue unit representing 1 passenger or an equivalent 100 kg of freight), in a safe manner, meeting the ICAO Standards and Recommended Practices (SARPs), during the reference lifetime of the aircraft."*

By expressing the functional unit in terms of revenue units per kilometre, the LCA is able to separate and attribute environmental impacts proportionally to passenger transport and freight transport, avoiding the need for more arbitrary allocation approaches based on economics or other surrogate measures.

There is no single correct way of dealing with multifunctional processes. It is however crucial to make sure the approach is consistently applied, in line with the background databases, and properly documented and reported.

2.1.2. Aviation Fuels

The main fuel used in global aviation is kerosene-based jet fuel, most commonly jet A-1. Regional variants such as Jet-A (used in the US) and TS-1 (used in Russia) have similar chemical properties, but different freezing points and volatility. Military grades such as JP-5, JP-8 and Jet B are used for very cold climates (Shell, 2024), are outside the primary scope of this guidance but may be considered in specific use cases where relevant.

As alternatives, the fuel types identified by the European Alternative Fuels Observatory from the European Commission are listed in Table 2.

Table 2: Fuels used for aviation (EC, 2024).

Fuel type	Description
Petroleum jet fuels	The main fuels used in global aviation are Jet-A1, Jet-A, and TS-1
Bio-jet fuels	Similarly, low blending of bio-jet fuels with conventional jet fuel reduces exhaust toxicity. The energy content (by weight) and other fuel properties of bio-jet fuels are rather like those of petroleum jet fuel, which aids adoption in existing engines.
Electro-jet fuels	Electro fuels are primarily produced from electricity via electrolysis of water with the use of captured carbon (or nitrogen), forming, for example, Fischer-Tropsch kerosene, methane, methanol, hydrogen, ammonia, and n-octane.
Liquefied methane	The studies and experimental tests have shown that Liquefied Natural Gas (LNG) is a viable option as an alternative aviation fuel; however, it is not used in normal service and operations. The main energy carrier in LNG is methane, which can also be produced from biomass pathways (e.g., liquefied biogas) and electro fuels pathways. However, several challenges remain in operating LCH_4 aircraft, where design and construction of the LCH_4 storage tanks and supply chain infrastructure are the biggest challenges. Cryogenic fuel tanks are required to operate LCH_4 in an aircraft; these are larger and heavier than other fuel tanks.
Hydrogen	H_2 is perceived as an attractive alternative aviation fuel both in recent and past research as it has a great supply potential, contains three times the energy content per weight of petroleum jet fuel (43.2 MJ/kg vs 120 MJ/kg respectively) and does not produce CO_2 from combustion. It is flammable, has a very short ignition time in comparison to conventional jet fuel, and provides a wider stability range. It has the highest thermal conductivity among all fuels, and high heat capacity and low dynamic viscosity, which provide superior cooling properties for operation at high speeds and high combustor temperatures.
Ammonia	Ammonia (NH_3) is perceived as a potential fuel for gas turbines as it has a high H_2 content but not any carbon atoms. Ammonia, mixed with H_2 or LCH_4, can be used as aviation fuel in low blending or as a dual fuel solution in modified aircraft engines and fuel cells.
Electricity	Electricity is used in fully electric or hybrid aircraft configurations

2.1.2.1. Product System to be studied

In this guideline, four types of fuel are considered:

1. Petroleum jet fuels;
2. Sustainable Aviation Fuels (SAF);
3. Electricity[1];
4. Hydrogen.

2.1.2.2. Function and Functional Unit

Most studies on fuels use *Vehicle km (or mile) travelled* (49% of all articles in the literature review by Liu et al. (2023)), followed by an energy-based FU (24% of the articles). Mass based FU are only used for studies using a single fuel production method, or various ways to produce a single fuel type. In those cases, the energy content per kg fuel is the same for all alternatives.

The literature review by Kolosz et al. (2020) shows that studies specifically focussing on aviation fuel tend to use the energy content of the fuel (37 of the considered articles used MJ or GJ). More recent examples with the FU of 1 MJ bio-jet fuel by Moretti et al. (2022), 1 MJ aviation fuel by Oehmichen et al. (2022), correspond with this finding. The proposal for the FU for aviation fuels is summarized in Table 3.

Table 3: Functional Unit (FU) for LCA of aviation fuels.

	FU of aviation fuel life cycle
What?	Provide energy for aircraft propulsion systems
How much?	1 MJ energy content
How well?	In accordance with the standards and specifications established by IATA (International Air Transport Association)
How long?	During the lifetime of the fuel

2.1.2.3. System Boundaries

Since each of the fuels listed in section 2.1.2.1 has its own production route, specific system boundaries are needed for each fuel. In order to ensure consistency in scope and comparability of the results, each source is analysed from well to wake (WtW). Figure 6 shows a schematic overview of the system boundaries of the petroleum jet fuel life cycle.

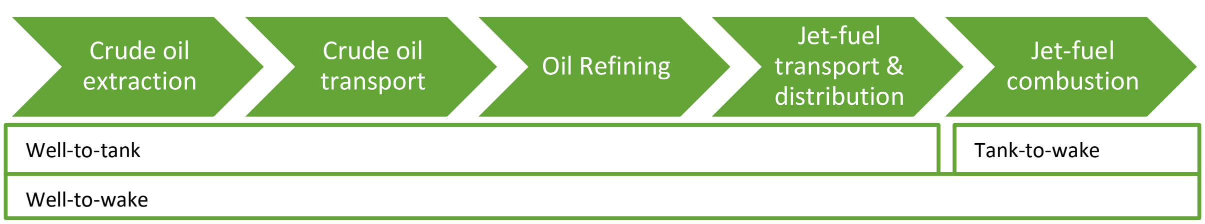

Figure 6: System boundaries of petroleum jet fuel (adapted from Ling et al., 2022).

[1] Although electricity is technically not a fuel, it is included in this chapter and table because (hybrid) battery-electric aircraft are among the industry's proposed solutions for decarbonizing the air transport system.

For Power to Liquid (PtL), synthetic and bio SAF, the production process includes additional steps compared to petroleum jet fuel. The steps shown in Figure 7 are included in the supporting documentation of the CORSIA Eligible Fuels - Life Cycle Assessment Methodology (2022) documents. This methodology is developed by ICAO and in line with the International Sustainability and Carbon Certification (ISCC), and the Roundtable on Sustainable Biomaterials (RSB). Aligning the scope with these established and international initiatives is important to ensure the latest consensus on calculating emissions from sustainable aviation fuel production and use.

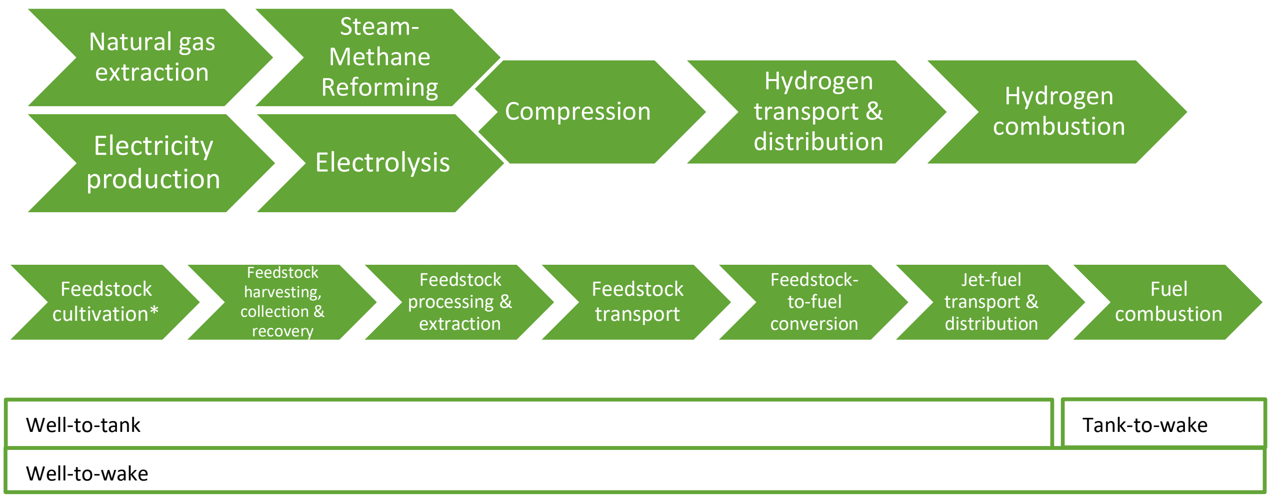

Figure 7: System boundaries of PtL, synthetic, and Bio SAF (adapted from CORSIA 2024).
**Feedstock cultivation is included for SAF from non-waste, non-residue, and non-by-product feedstock.*

For aircraft with an electric propulsion system, it is assumed that the electrical energy is stored in an on-aircraft battery. The electricity supply chain starts at production facilities, which can range from coal-fired powerplants to solar panels and wind turbines. The produced electricity is transmitted through the grid to the aircraft, when the aircraft is charging its batteries. This electricity is stored in the batteries until the operation phase of the aircraft, when the electricity is consumed by the propulsion system. Approaches such as the exchange of complete battery packs between flights and external charging are being explored to address the need for efficient battery management. However, this would drastically increase the demand for batteries and their infrastructure, resulting in greater consumption of scarce materials and potential burden shifting across different impact categories. Whether the production and replacement of batteries is then attributed to maintenance or flight operations in environmental (or economic) assessments varies widely in the literature, which makes comparability with other studies difficult (Rahn, 2025).

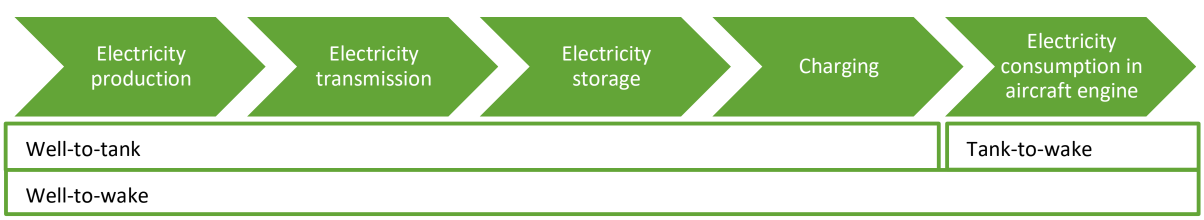

Figure 8: System boundaries of electricity production and use in electric aircraft.

Hydrogen powered aircraft use hydrogen as fuel for fuel cells. Alternatively, the hydrogen can be combusted in a jet engine (so-called direct combustion). Hybrid configurations are also possible. Furthermore, there are several ways to produce hydrogen. Green hydrogen can be produced using electrolysis of water with renewable electricity. Grey hydrogen is made by steam methane reforming. These two routes are shown in Figure 9.

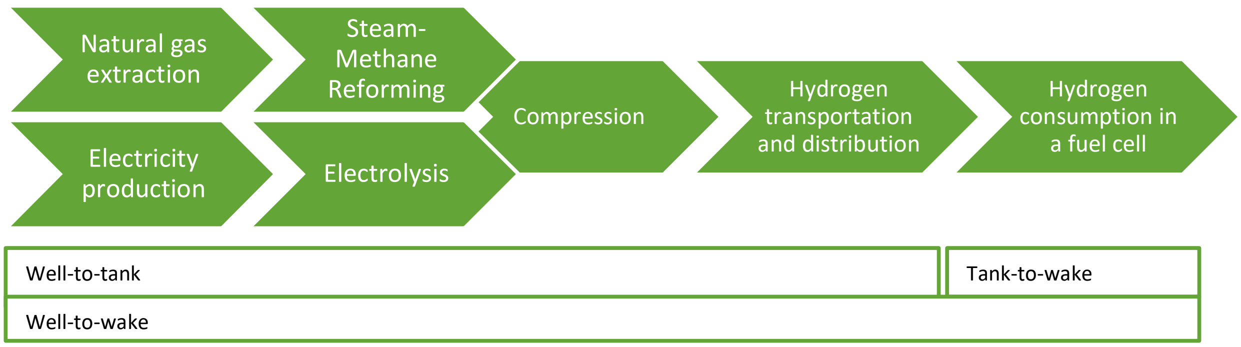

Figure 9: System boundaries of fuel production and use for a hydrogen aircraft.

Figure 9 shows two of the most common hydrogen production pathways. Table 4 shows a more elaborate overview from Hydrogen Europe (HE, 2025). The system boundaries should include the energy source, production pathway, compression / liquefaction, distribution, storage and use.

Table 4: Hydrogen production pathways (HE, 2025).

Colour	Production pathway
Green	Electrolysis using green electricity
Grey	From fossil fuel by steam methane reforming
Blue	Grey + CCS
Turquoise	Grey with solid carbon instead of CO_2 gas
White	Naturally occurring hydrogen
Red	High-temperature catalytic splitting of water using nuclear power thermal
Pink	Electrolysis using nuclear electricity
Purple	Combination of pink and red
Black / Brown	Produced from bituminous (black) and lignite (brown) coal

2.1.2.4. Dealing with Multifunctional Processes in the fuel supply chain

The supply chain of aviation fuels involves several multifunctional processes. The following approach is recommended for allocating environmental impacts in LCA of oil refineries and SAF production. Given the complexity and diversity of outputs in these systems, energy-based allocation—particularly using Lower Heating Value (LHV)—is proposed as a practical and consistent method in line with international guidelines, such as the CORSIA LCA methodology (ICAO, 2024).

Allocation in Oil Refineries:

- Complex co-product outputs make system boundary expansion impractical.
- Emissions are allocated based on energy content (LHV), reflecting real-world fuel use.
- This approach is consistent with the CORSIA LCA Methodology.

Application to SAF:

- LHV-based allocation applies to SAF co-products like steam, hydrogen, and other fuels.
- Emissions are proportionally distributed according to energy contribution of each output.

Feedstock Classification:

When applying allocation rules, it is essential to classify feedstocks correctly. In the CORSIA LCA methodology the following classification is used (ICAO, 2024):

- Residues: Unintended outputs from a production process (e.g., straw, bark, husks).
- Wastes: No economic value, inelastic supply (e.g., used cooking oil, MSW).
- By-products: Secondary outputs with economic value (e.g., tallow, technical corn oil).
- Co-products: Main products with high economic value (e.g., molasses).

The distinction between waste and co-products is critical, because it determines whether environmental burdens are attributed to the fuel or excluded. No emissions are allocated to feedstocks classified as waste, residues, or by-products with inelastic supply. Emissions are allocated only to primary and co-products with economic value and elastic supply.

2.1.3. Materials and Components

Aircraft are typically made of a combination of various materials. Figure 10 provides examples for material classes and their percentage share of the total weight of a modern commercial aircraft. While aluminium, steel and titanium alloys still have an important position, over the last decades, the proportion of fibre-reinforced polymers (FRP) composites has risen steadily and currently accounts for up to 50% of the overall structure in aircrafts such as an Airbus A350 or Boeing 787.

This section outlines the challenges of conducting an LCA of aircraft materials, using fibre reinforced composites as an example. High-level guidance is offered for materials and components, while fibre-reinforced composites are addressed in greater detail.

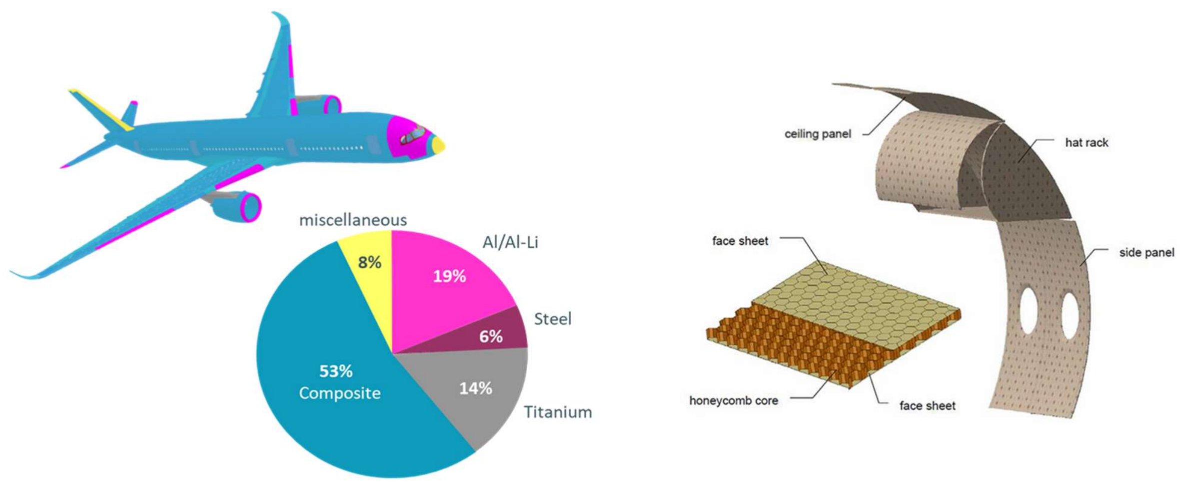

Figure 10: An overview of material classes and their percentage share of the total weight of a modern commercial aircraft (left) and a more detailed example of composite sandwich interior structures (right) (Bachmann., 2019).

Fibre-reinforced polymers (FRP) offer great potential for lightweight construction and have been established in the aviation industry for years. In their simplest form, they consist of a polymer matrix and reinforcing fibres. Due to the high variability in terms of structure and production, it is sometimes challenging to carry out detailed LCA studies.

2.1.3.1. Product System to be studied

The following materials are commonly used in aircraft production.

- Aluminium alloys
- Titanium alloys
- Steel alloys
- Fibre-reinforced polymers (FRP)
- Hybrid materials, combining different materials to achieve optimal properties

Usually, FRP are counted as a group, despite being composed of different fibres and matrix materials and design (e.g. monolithic laminates with stiffeners or sandwich panels). Fibres can be distinguished in glass (GF), aramid (AF) and carbon (CF) of different grades and semi-finished products (e.g. UD or woven fabric). Polymers are thermoset (e.g. epoxy, phenolic), thermoplastic (e.g. PAEK family) or elastomer variants.

2.1.3.2. Function and Functional Unit

In the case of materials or components, a Functional Unit (FU) such as 1 kg, 1 m², or 1 m³ can be used for the LCA of a single material or component. These simplified FUs are often referred to as Declared Units (DU). For example, comparisons may be made between 1 kg of carbon fibre and 1 kg of glass fibre, 1 kg of epoxy resin and 1 kg of phenolic resin, or 1 m^2 of unidirectional fabric and 1 m^2 of woven fabric. DUs are also typically used in Environmental Product Declarations (EPD), which calculate environmental impacts for a defined amount of product.

While a DU can be used for preliminary comparisons or to identify the environmental hotspots of one component, their meaningfulness for decision support is limited. Material properties that directly affect the final function and weight of a component are usually neglected. For comparisons of different materials or component designs, a more detailed FU is needed to ensure a fair comparison. Such an FU should take into account the quality of the material, its performance, the lifetime of the component, and the potential impact on energy consumption during the use phase, as well as additional requirements (e.g. FST properties) and possible recycling pathways.

Higher quality materials can have a higher environmental impact in a cradle-to-gate LCA, but this can be outweighed by using less material for the same function, achieving longer lifetimes, or reducing energy consumption during use. At component level, the FU should therefore be defined based on the specific function of the component. The proposed options for the FU for aircraft materials and components are summarized in Table 5.

Table 5: Functional Unit (FU) for LCA of aircraft materials and components

	FU of aircraft material/component (single product LCA & EPD)	FU of aircraft material/component (comparison)
What?	Function is based on the type of material or component	
How much?	A declared unit such as 1 kg, m^2 or m^3 can be used for materials. 1 piece can be used for components.	The weight should be defined based on the functional unit of the component.
How well?	Certified, developed or designed to be airworthy. Example for interior: Flammability, Smoke, and Toxicity (FST) requirements	
How long?	During the reference lifetime of the material or component	During the reference lifetime of the aircraft

2.1.3.3. System Boundaries

Due to the large number of compositions, modelling the life cycle inventory of polymers often involves a great deal of effort. The background here is formed by the reactive matrix systems, which require a hardener component in addition to the resin in order to become a permanently solid material. These systems can be divided into one and two-component systems. While the hardener component is already present in a one-component system, in two-component systems the resin and hardener are only mixed for further processing. For the life cycle inventory, this means that considering the pure resin alone is not sufficient for a holistic life cycle assessment. Furthermore, these matrix systems often contain other additives, such as reactive diluents, which must also be included in the analysis.

Additional to the materials, their processing into the final component can have an important impact on LCA results and should be included in the system boundary in a correct way. An example is the curing of thermoset carbon fibre reinforced polymers (CFRP) for wings covers. Auxiliary materials such as peel plies, release foil and tubes need to be included. The curing in an autoclave consumes high amounts of energy and must be linked to a reasonable level of utilisation of the autoclave, e.g. by filling the available space in the autoclave with two components instead of just one. If prepregs are used, their cooled storage has to be considered. In addition, the environmental conditions for some processes, such as the processing of prepregs, are subject to strict limits, which leads to the need for air conditioning in factory buildings, which should also be taken into consideration.

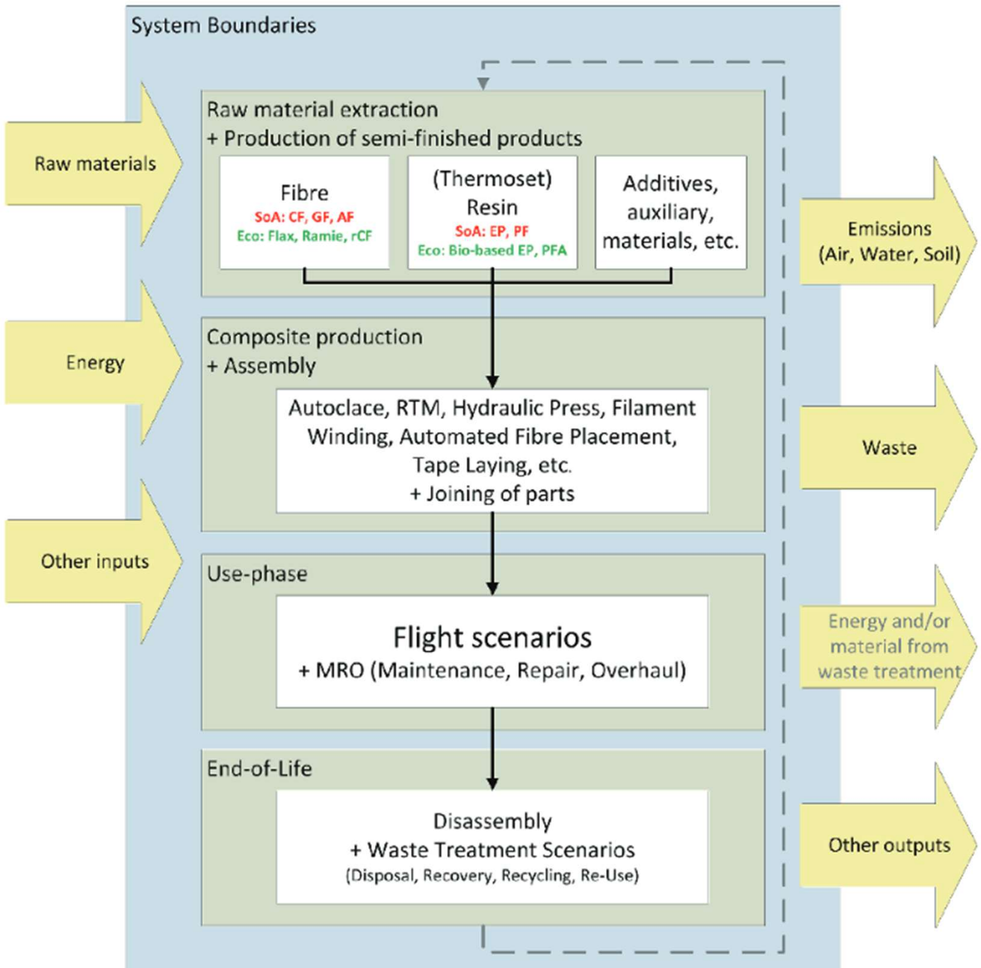

Figure 11: LCI of a simplified composite life cycle with inputs and outputs (Bachmann, 2017).

Figure 11 illustrates an exemplary life cycle of a composite material, beginning with the production of pre-products from raw materials which is usually crude oil for both, carbon fibres and matrix systems. Next steps are composite manufacturing, assembly, the use phase, and finally waste treatment respectively recycling at the end of life (Bachmann, 2017). Other material types and components can use the same structure as the composite case. This structure is generalized in Figure 12. While it is particularly necessary to consider all phases of life in aviation (Cradle-to-Grave), in certain cases a simplified approach is initially taken. Such simplified considerations are often used for material alternatives, which only include resource extraction up to the preliminary product. In addition, the end of life and options for recycling are also considered.

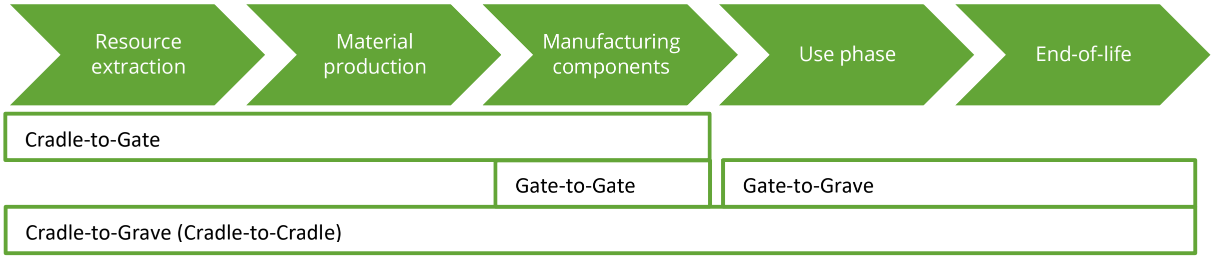

Figure 12: Typical material and components flow chart and life cycle phases.

In comparative LCA of different materials (e.g. CFRP vs. aluminium alloy) or processes (e.g. Autoclave, Out of Autoclave) it is crucial to model all competing materials and processes under comparable system boundaries to avoid misleading results. A poor example of the choice of system boundaries is, on the one hand, a very detailed model that also includes the means of production and, on the other hand, a simple aggregated data set from an LCA database. For example, the manufacture of an autoclave and the AFP unit in a fibre composite process compared to the pure manufacture of a metal without tools. Using the example of an autoclave process, consideration of the degree of filling is also crucial for the result of an LCA. Laboratory processes in particular, in which a small component is typically cured in a large autoclave, cannot be scaled up 1:1 to an industrial component such as a wing shell. Here, parameterized datasets as exemplarily shown for three sizes of autoclaves in Figure 13 can be useful to fill existing data gaps.

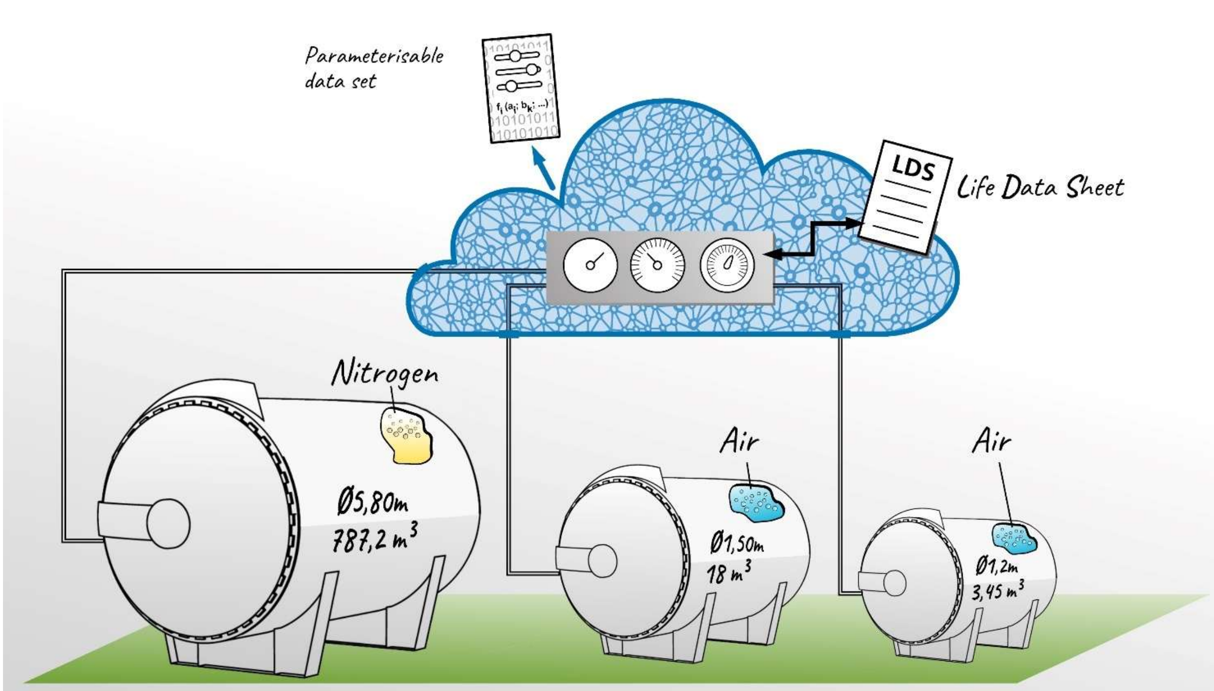

Figure 13: Different sizes and configurations of autoclaves at DLR Institute of Lightweight Structures (Bachmann & Kroos, 2025).

2.1.3.4. Dealing with Multifunctional Processes

For materials and components, the most critical multifunctionality issue concerns end-of-life allocation. End-of-life treatment not only fulfils the function of waste management (e.g., landfilling) but may also enable the production of a refurbished component, the recovery of secondary raw materials through recycling, or the generation of energy via incineration with energy recovery.

For the modelling of the impact of End-of-Life (EoL) scenarios for assets in the air transport sector, three modelling steps are needed:

1. Determine the EoL scenario of a component or material;
2. Choose the EoL inventory modelling approach;
3. Create the LCI dataset(s) (described in section 3.3.3 End-of-Life LCI datasets)

EoL scenarios for a component or material:

The first step is the determination of which EoL scenario is considered for the specific component or material:

- Back into service (reuse, refurbishment);
- Use in another sector (repurposing);
- Recycling (mechanical, chemical, thermal);
- Incineration (with or without energy recovery);
- Landfill.

The following choices are available regarding the EoL scenario for a specific component or material:

1. Modelling based on actual practices;
2. Modelling based on expected practices;
3. Modelling based on different scenarios.

The scenario must be based on actual industrial practices and in line with any relevant local or national waste management practises or legislation, EU directives, and/or international conventions. An exception can be made when the scenarios themselves (or aspects thereof) are part of the assessment. In case of sensitivity analysis for different EoL options, the baseline should reflect actual practices and the expected practices or scenarios should be realistic and feasible within the temporal scope of the study.

LCA end-of-life modelling approach

EoL modelling in LCA requires deciding which life cycle bears the burdens, such as emissions during collection and recycling, and which one receives the benefits, such as the reduced need for virgin materials. This can be the life cycle sending waste for recycling or the life cycle using recycled material as an input.

In general, five allocation approaches have been identified to include EoL aspects and processes within an LCA:

1. Cut-off approach (default approach in ecoinvent):
   Full environmental impacts of the primary material supply chain, while secondary materials come free of burdens (encouraging the use of more recycled content if adopted).

2. Avoided burden approach (commonly known as EoL approach):
   Credit to the system that produces any recycled material that can “substitute” primary material in a downstream system.

3. 50:50 approach:
   50% of the secondary material is modelled as a burden-free input (assuming closed-loop recycling) and 50% is for substituting primary material downstream (assuming displacement of primary material downstream).

4. Allocation at the Point of Substitution approach (APOS):
   Economic allocation between the primary and secondary usage of materials; it is one of the system models offered by ecoinvent.

5. Circular Footprint Formula (required approach for the EF method):
   Hybrid approach that takes into account the market status and the quality of secondary material in order to divide the burdens and the credits between the producer of secondary material/energy and the user of these flows in the following system.

The chosen approach plays a critical role in determining how the environmental burdens and benefits are distributed across the different life cycle phases. It determines how the environmental impacts and benefits of recycling are attributed, ultimately shaping the sustainability decisions made for the product. The choice should be in line with the goal and scope of the study, correspond with the modelling in the background database, and it should be documented clearly.

2.1.4. Airport Infrastructure and Operations

Airports are part of the air transport system's infrastructure, similar to the role of infrastructure in other modes, like rail or road transport. Investigating their emissions and resource use, both independently and in comparison to other modes, is necessary to evaluate the complete impact of aviation. This guidance document includes airports because they can be the sole focus of an LCA, but also because infrastructure should be included in comparisons between aviation and other modes of transport. Even if its expected impact might be limited, including aviation infrastructure in LCA studies ensures consistency.

2.1.4.1. Product System to be studied

The product system includes the airport infrastructure and operations.

2.1.4.2. Function and Functional Unit

In the FAA report on "Life-Cycle Assessment of Airfield Pavements and Other Airside Features" (2019), a number of functions and FUs for different elements of airport infrastructure are indicated. In literature, the following elements are included:

- Runways;
- Taxiways;
- Aprons;
- Drainage;
- Fences;
- Parking areas (inside fence area);
- Airside airport land vehicles;
- Aircraft;
- Land use;
- Signs and pavement markings;
- Pavement lighting.

There is, however, no function or FU defined for the entire airport. The proposal for the FU for airports is summarized in Table 6.

Table 6: Functional Unit for LCA of airports

	FU of Airport infrastructure and operation life cycle
What?	Allow passengers and cargo to safely board and disembark an aircraft
How much?	1 aircraft served
How well?	In a safe manner, meeting the ICAO Annex 14 Standards and Aerodrome Certification
How long?	From airport door to lift-off and from touch down to airport door

2.1.4.3. System Boundaries

The airport life cycle emissions are grouped in the following life cycle phases: resource extraction, airport construction, airport use phase, and airport EoL. Figure *14* provides more details on the elements that should be included in each life cycle phase. It should be noted that, in addition to the direct impacts of the use phase, the raw materials, construction and end of life of the activities in the use phase should also be included. This can be done by using background databases. These life cycle stages are excluded from the figure for simplicity.

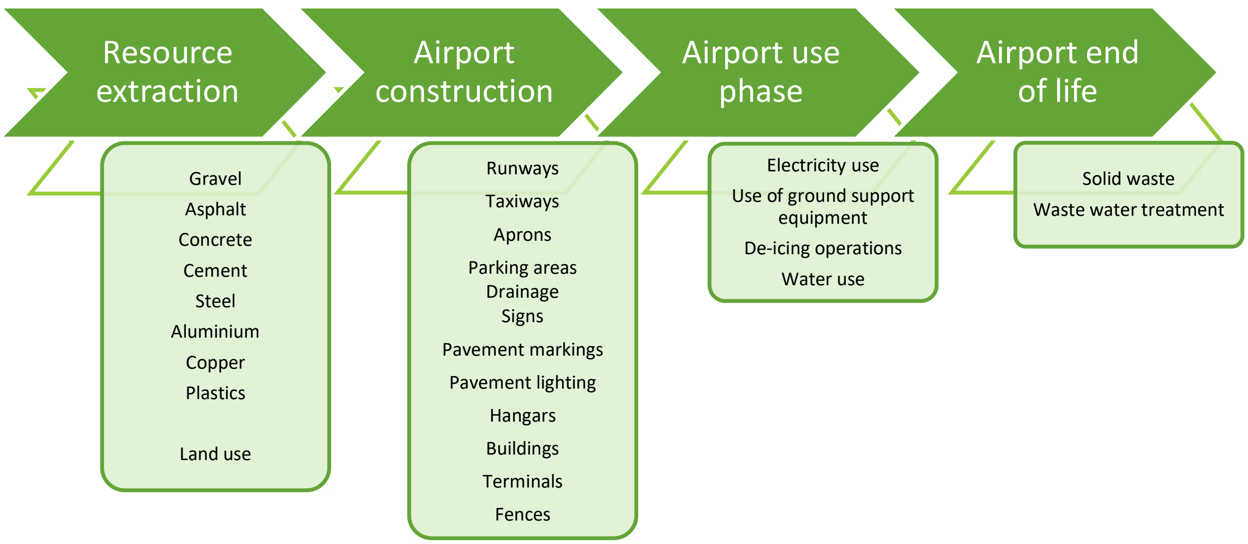

Figure 14: System boundaries of airports

2.1.4.4. Dealing with Multifunctional Processes

Terminal buildings often have multiple functions. On the one hand, the terminal buildings are used for leisure activities, such as shopping and hospitality in bars and restaurants. Terminal buildings also provide a space for the boarding processes such as check-in, baggage check-in, security, immigration and boarding the aircraft itself.

In order to avoid allocation between leisure activities and the processes that are legally linked and required to board the aircraft, the landside buildings are linked to the leisure function and the airside terminal buildings are linked to the boarding function. This distinction does not fully match the actual activities performed in the building as associated with leisure and boarding. The check-in desks are located in the landside part of the airport, and the airside buildings also contain stores and restaurants. The benefits of subdividing the terminal into landside and airside buildings is that the division is clear and well known in the industry. This is a benefit for the data collection. Furthermore, the division between landside and airside largely overlaps the functions and any overlap in functions is expected to cancel out. Check-in desks and baggage handling should be included, as well as security, as this in required to safely board the aircraft.

3. LIFE CYCLE INVENTORY ANALYSIS (LCI)

After defining the goal and scope of the study, the next phase of an LCA is the inventory phase. This is the most time-consuming phase of the assessment. Hauschild et al. (2018) have identified the following steps:

1. Identifying processes for the LCI model of the product system;
2. Planning and collecting data;
3. Constructing and quality checking unit processes;
4. Constructing LCI model and calculating LCI results;
5. Preparing the basis for uncertainty management and sensitivity analysis;
6. Reporting.

This chapter provides an overview of the processes per product system, guidance on the intermediate steps. The results of this step are a complete model of all material, energy and waste inputs and outputs and emissions into air, water and soil for the product supply chain (EC, 2021).

3.1. Primary Data Collection

Aviation-specific data collection presents unique challenges, such as the need for accurate fuel consumption data during different flight phases, information on the manufacturing processes of aircraft parts, and details on aircraft maintenance and EoL scenarios. Due to the high level of complexity in the aviation industry, thorough data collection techniques are required to ensure the reliability and completeness of LCI datasets. Overcoming the hurdles of data sensitivity and legal restrictions is essential for accurately evaluating the environmental impact of air transport activities. Due to data sensitivity and legal constraints, gathering data is especially challenging (Albano et al., 2024). The following general recommendations apply to the data collection phase.

1. Use a data collection template

- Develop easy-to-use forms or spreadsheets that clearly specify required data (e.g., material amounts, energy use, transport distances).
- Include units, timeframes, and reference flow per row to avoid inconsistencies.
- Log who provided the data, what system it came from, and how it was calculated, include details on data ownership.

2. Engage with your stakeholders

- Identify key people in production, energy management, logistics, etc.
- Explain what LCA is, what the goal of the LCI is and why their input matters.
- Establish a point of contact at each site or department.

3. Use existing documentation and records

- Production logs and batch records.
- Energy bills and metering systems.
- Procurement and inventory reports.
- Emissions reports or permits.

4. Focus on high-impact processes first

- Prioritize collecting data from core processes or hotspots identified in the system boundary or screening phase.
- For low-impact or generic processes, secondary data may be sufficient.

5. Validate data at the source

- Perform checks of the values during collection—e.g., do totals match facility output?
- If possible, compare with past data, industry averages, or mass/energy balances.

3.2. Background Data Sources

Many individual decisions have to be made while conducting an LCA. This applies in particular to the first two phases (Goal and Scope and Life Cycle Inventory), in which the foundation of the analysis is laid. Figure 15**Error! Reference source not found.** presents how the choice of selected databases affects the result of a fictitious glass fibre reinforced polymer composite (GFRP) within the same goal and scope, declared unit and system boundaries. Using these results e.g. for EPD, shows the importance to look into the potential impacts of using different databases. Therefore, a mix of different databases is currently not advised and should be avoided especially for comparative LCA.

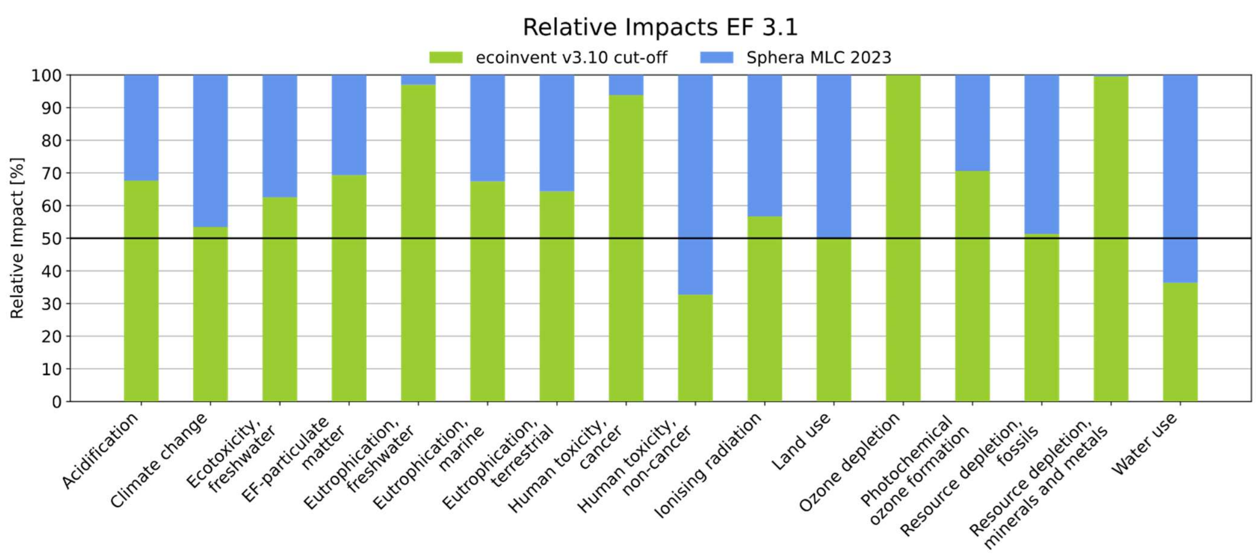

Figure 15: Relative Impacts of a fictitious generic GFRP modelled using Sphera LCA for Experts (blue) and Ecoinvent 3.10 Cut-off by classification (green) database in the 16 categories of the Environmental Footprint (EF) 3.1 whereas 100 % is defined as the sum of the individual results of both models (Kroos et al., 2024).

The following background databases are relevant for LCA in the air transport system:

ecoinvent
ecoinvent is one of the most comprehensive and widely used life cycle inventory (LCI) databases globally. It provides high-quality, transparent data on fuels, materials, transport, and energy systems—making it highly relevant for modelling aircraft components, jet fuel production, and airport infrastructure in LCAs. Most materials are modelled as industry averages, while the air transport sector is using very high-grade materials. This leads to potential mismatch between the background datasets and the topic of the study. Additional modelling is needed in those cases.

Sphera (GaBi Database)
The Sphera (formerly GaBi) LCI database is a commercial database known for its industry-specific and regionally detailed datasets. It supports advanced modelling of complex systems, including aviation and aerospace supply chains, and is commonly used in commercial and regulatory LCA work. Similar to ecoinvent, this is not an aviation-specific database

ESA LCA Database
Developed by the European Space Agency, this database provides specialized LCA data for space technologies, which can be relevant for aerospace manufacturing, high-performance materials, and electronics also used in aviation systems. It supports LCA in the context of innovation and extreme-performance applications.

GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies)
GREET, developed by Argonne National Laboratory for the U.S. Department of Energy, offers detailed LCA models for transportation fuels, including conventional jet fuel and a wide range of SAF production pathways. It is especially valuable for evaluating well-to-wake emissions and is widely used in North America, the data coverage is global.

openLCA Nexus
The openLCA Nexus is an online repository for LCA data. It combines data offered by world-leading LCA data providers.

LCI datasets can also be found in, or derived from (supplementary) documentation in scientific journals, such as:

- The International Journal of Life Cycle Assessment
- The Journal of Industrial Ecology
- The Journal of Cleaner Production

3.3. Modelling

This section includes guidance on inventory data modelling for specific parts of the air transport system.

3.3.1. Aircraft Emissions

Several direct emissions are relevant for LCA in the air transport system. CO_2 is the primary focus in most LCA studies due to the large share in the climate change impact. NO_X, SO_X, CO, PM, and unburned hydrocarbons (UHCs) should be included, because of their effect on climate change, but also for their effect in other impact categories. Water vapor and contrails are often excluded from due to methodological complexity, but it is important to include these as well due to their short-term climate impact. Advanced climate modelling (e.g., radiative forcing index adjustments) is needed to properly account for the impact. Emission quantities should be grouped per altitude to account for the difference between higher and lower altitude emissions. Emissions with indirect global warming potential are often excluded; in some cases, it can be important to include these emissions as well. For new technologies, such as hydrogen propulsion, the unburned or unconsumed hydrogen emissions from the aircraft should be included.

3.3.2. Maintenance, Repair and Overhaul

MRO plays a critical role in ensuring the functionality and airworthiness of aircraft. Maintenance activities are inevitable throughout an aircraft's life cycle and are performed through scheduled and unscheduled maintenance. Scheduled maintenance follows predefined intervals, usually based on flight hours, flight cycles or calendar times, while unscheduled maintenance addresses unexpected problems. The frequency and complexity of maintenance tasks evolve over time, with certain intensive checks occurring at specific intervals and an overall increase in maintenance needs as the aircraft ages due to wear and degradation.

The most critical step in assessing the environmental impact of aircraft maintenance is the preparation of a comprehensive LCI. This requires the definition of maintenance activities and the establishment of system boundaries, distinguishing between planned and unplanned maintenance tasks. Existing commercial databases contain limited data on aircraft maintenance. Since ecoinvent 3.11, an aggregated maintenance dataset is available for the A320 aircraft under different operating scenarios. However, in most cases background data from other sectors has to be adjusted to approximate the maintenance related impacts.

In literature there are only a few examples of environmental studies on aircraft maintenance. Maintenance is often excluded from LCA due to the perception that its environmental impact is relatively low, making the extensive data collection and modelling effort difficult to justify (Krieg et al., 2012). However, some more detailed studies, such as those by Rahn et al., 2024, Oestreicher et al., 2024 and Barke et al., 2023, have addressed this aspect. These studies identify the main contributors to the environmental impact of maintenance inventories, including:

- Energy consumption (e.g., hangar operations, ground support equipment);
- Material consumption (e.g., lubricants, filters, spare parts);
- Transport (e.g., transportation of aircraft components to workshops).

Relevant data sources include manufacturers' Maintenance Planning Documents (MPDs), airline training material, or operational data from maintenance providers. These sources contain detailed task descriptions, maintenance intervals and estimated labour times. Interviews with experts may help to refine these estimates, as actual task descriptions often vary considerably (e.g., the duration of tasks in the MPD are usually underestimated and can be higher by a factor of 3). Where detailed information is unavailable or unnecessary, maintenance activities can be clustered to provide an approximate estimate of total maintenance requirements. However, it is important to recognise the dynamic nature of maintenance requirements as workload varies throughout the life of the aircraft. In certain years more extensive checks take place, while older aircraft require increased maintenance due to progressive component wear.

Maintenance and flight operations are closely linked, as the timing, frequency and duration of maintenance activities have a direct impact on fleet availability and scheduling. Extensive maintenance increases aircraft downtime, which affects operational efficiency and may require adjustments to flight schedules. At the same time, maintenance can improve aircraft performance through modifications and overhauls, particularly of engines, leading to improved fuel efficiency and reduced emissions. These interactions need to be considered when assessing the overall environmental impact of MRO activities, as both the environmental impacts through maintenance and the operational benefits it provides contribute to the life cycle footprint of the aircraft.

3.3.3. End-of-Life LCI datasets

The emissions and resource use of recycling can be modelled using LCI background datasets. While specific EoL datasets for aircraft are often lacking, other industries have developed more comprehensive datasets (including for recycling processes). These can provide useful proxies for LCA studies. Furthermore, recycling processes in aviation are not always industrialized. Today, bio-composites are not used in aircraft yet. Also, for regular aircraft grade composites, recycling processes are not often industrialized. Pyrolysis is applied on small scale, and Solvolysis is under development. LCA studies focusing on future aircraft technologies have to deal with a lack of data on future EoL options and infrastructure. The following hierarchy is made for the choice of LCI data for recycling activities.

1. Use case specific recycling dataset (this should be done in collaboration with waste treatment experts in the field to make sure that the data reflects industry practice);
2. Use realistic assumptions on future EoL options and inventory data;
3. Use EoL datasets from existing LCI databases as proxy for current and future aircraft recycling inventory data.

The recommendations on Aircraft EoL in LCA can be summarized in the following points:

1. Use realistic recycling rates based on relevant industry practices for the year for which the analysis is conducted, supported by credible sources;
2. Choose a modelling approach which treats benefits and burdens as a package deal;
3. Take into account potential degradation effects (downcycling)
4. Be clear on the approach and report it transparently;
5. Use representative industry datasets.

3.4. Data Quality Assessment

Data quality plays a crucial role in LCA as it directly affects the accuracy and reliability of the results, which in turn inform decision-making processes related to environmental sustainability. High-quality data is essential in LCA to ensure that the assessments provide a realistic representation of the environmental impacts of products or systems, thereby supporting effective strategies for reduction and mitigation. The ISO 14044 standard defines data quality as "the characteristics of data that relate to their ability to satisfy stated requirements."

The aspects of data quality listed in Table 7 should be reported (ISO 14044). This can be done in a qualitative way, or quantitatively using a scoring between 1-5 for instance.

Table 7: Descriptions of Data Quality Requirements (DQR).

Criterion	Description
Time-related coverage	Age of data and minimum period of time for data collection
Geographical coverage	Geographical area for unit process data collection
Technology coverage	Specific technology or technology mix
Precision	Variability of data values (e.g., variance)
Completeness	Percentage of measured or estimated flow
Representativeness	Degree to which data reflects the true population of interest
Consistency	Uniform application of study methodology
Reproducibility	Ability to reproduce results based on methodology and data
Sources of data	Origin of the data used
Uncertainty	Uncertainty of data, models, and assumptions (e.g., data, models)

In a PEF study, the following aspects are required:

- Two minimum requirements:
    1. Completeness (All 16 EF impact categories shall be covered in the data set)
    2. Methodological appropriateness and consistency (in line with EF requirements)

- Four quality criteria (with a score of 1-5):
    1. Technological representativeness (TeR)
    2. Geographical representativeness (GR)
    3. Time-related representativeness (TiR)
    4. Precision (P)

- Three quality aspects:
    1. Documentation
    2. Nomenclature
    3. Review

Table 8: Quality rating for the data quality criteria (copied from Fazio 2020).

Quality rating	P_{EF} and P_{AD}	TiR_{EF} & TiR_{AD}	TiR_{SD}	TeR_{EF} & TeR_{SD}	GR_{EF} & GR_{SD}
1	Measured / calculated and verified	The data collection date) can be maximum 2 years old with respect to the "reference year" of the data set.	The "reference year" of the data set falls within the time validity of the secondary data set	Technology aspects have been modelled exactly as described in the title and metadata, without any significant need for improvement	The processes included in the data set are fully representative for the geography stated in the "location" indicated in the metadata
2	Measured / calculated / literature and plausibility checked by reviewer	The "reference year" of the data set is maximum 2 years beyond the time validity of the secondary data set.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the data set.	Technology aspects are very similar to what described in the title and metadata with need for limited improvements. For example: use of generic technologies' data instead of modelling all the single plants.	The processes included in the data set are well representative for the geography stated in the "location" indicated in the metadata.
3	Measured / calculated / literature and plausibility not checked by reviewer OR Qualified estimate based on calculations plausibility checked by reviewer.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the data set.	The "reference year" of the data set is maximum 3 years beyond the time validity of the secondary data set.	Technology aspects are similar to what described in the title and metadata but merits improvements. Some of the relevant processes are not modelled with specific data but using proxies.	The processes included in the data set are sufficiently representative for the geography stated in the ""location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.
4	Qualified estimate based on calculations, plausibility not checked by reviewer.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the data set.	The "reference year" of the data set is maximum 4 years beyond the time validity of the secondary data set.	Technology aspects are different from what described in the title and metadata. Requires major improvements.	The processes included in the data set are only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different electricity grid mix profile.
5	Rough estimate with known deficits	The data (collection date) is older than 8 years with respect to the "reference year" of the data set.	The "reference year" of the data set is more than 4 years beyond the time validity of the secondary data set	Technology aspects are completely different from what described in the title and metadata. Substantial improvement is necessary	The processes included in the data set are not representative for the geography stated in the "location" indicated in the metadata.
TiR-EF: time representativeness for the elementary flow TiR-AD: time representativeness for the activity data TiR-SD: time representativeness for the secondary data set					

The EF method also prescribes a certain level of data quality depending on the type of process. More detail can be found in the EF method documentation (EC, 2021) and the Guide for EF compliant data sets (Fazio et al., 2020).

The quality of the LCI data should at least be described qualitatively. Preferably a data quality score is calculated for the most relevant processes, as prescribed by the PEF data quality formula:

$$\mathrm{DQR} = \frac{\mathrm{TeR} + \mathrm{GR} + \mathrm{TiR} + \mathrm{P}}{4}$$

4. LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The third phase of LCA is the Life Cycle Impact Assessment (LCIA). In this phase, the effect of all emissions and resource use throughout all stages of the life cycle are translated to environmental impact on a range of topics called impact categories. The ISO 14040-14044 standards outline mandatory and optional steps for the LCIA phase (Hauschild, 2018).

The mandatory steps are:

1. Selection of impact categories and an LCIA method to determine which impacts to assess;
2. Classification of LCI result. In this step, each emission or resource used is linked to impact categories based on their potential effects. This is typically done automatically by LCI databases and LCA software or code;
3. Characterization of impacts. In this step the category indicator results are calculated by quantifying the contributions of inventory flows to various impact categories. There are two types of characterized results:
    a. Midpoint results, address specific environmental issues, such as climate change or acidification;
    b. Endpoint results assess the broader areas of protection or concern, usually impact on human health, biodiversity, and resource scarcity.

   Converting midpoint indicators to endpoint indicators facilitates easier interpretation of LCIA results, but each aggregation step introduces greater uncertainty (Huijbregts et al., 2017). The characterization calculations are typically done automatically by LCA software or code.

The optional steps are:

4. Normalization of results: Express LCIA results relative to a reference system to provide context;
5. Weighting of impacts: Prioritize or assign weights to each impact category to reflect their relative importance. This step can be used to derive a single score adding all impact categories. It is often debated as it is a subjective and not a scientific step. In the ISO standard on LCA this step in forbidden if the results are used for comparative assertions to be disclosed to the public. In the EF method from the European Commission, this step is mandatory in the reporting stage (EC, 2021).

4.1. Impact Assessment Methods

A broad range of impact assessment methods is available for use in LCA. The LCA practitioner should select an impact assessment method that aligns with the goal and scope of the study. The most used application of LCA in aviation is the evaluation of climate change impact. The most used single issue impact assessment method, meaning one that focusses on a single environmental issue such as climate change, is the IPCC method. This method is required for the major carbon accounting frameworks such as the GHG protocol (WBCFS & WRI, 2004), the EF method (EC, 2021), the international EPD system (EPD, 2025) and many other carbon accounting initiatives. This guideline describes several versions, alternative climate metrics, and adaptations to make the IPCC method better suitable to include the emissions at altitude and hydrogen emissions. As LCA aims to evaluate a broader range of environmental issues, this chapter also includes three suggestions for state-of-the-art multicriteria impact assessment methods.

4.1.1. Climate Change Impact

The Intergovernmental Panel on Climate Change (IPCC) is a United Nations entity that periodically publishes Assessment Reports (ARs), which include emissions metrics for Global Warming Potential (GWP) and Global Temperature Change Potential (GTP). Table 9 shows the different time horizons used in the assessment report.

These metrics form the basis of the IPCC method, which is the most widely used approach for calculating climate change impact (carbon footprint) in LCA. The IPCC method covers a range of greenhouse gases (GHGs) and includes multiple indicators. For this guideline, the 2021 IPCC Sixth Assessment Report (AR6) is referenced to ensure the use of the most up-to-date data and metrics.

Table 9: Climate metrics and their time horizon in the IPCC method.

Time horizon	Global Warming Potential	Global Temperature Potential
20 years	GWP20	
50 years		GTP50
100 years	GWP100	GTP100
500 years	GWP500	

The indicator that is most often used is GWP over 100 years (GWP100). The Life Cycle Initiative (UN Environment) recommends:

- Using GWP 100 for short-term climate change impacts;
- Using GTP 100 as a proxy for long-term impacts.

These recommendations are based on AR5/IPCC 2013 (Frischknecht & Jolliet, 2016). This guidance document suggests to include a sensitivity analysis for at least GTP100, and short-lived climate forcers. Additionally, other time horizons can be used if this is in line with the goal and scope of the study. The time horizon is very relevant for the relative contribution of short-lived species (contrails, cloud cirrus, aerosols and chemically reactive gases such as NO_x, CO, volatile organic compounds, SO_2 and ammonia). The contribution of short-lived species to the overall climate impact will be higher when choosing a shorter time horizon and lower for a 500-year time horizon where the long-lived greenhouse gasses such as CO_2 will dominate.

These recommendations are common practise in the LCA community, but for aircraft emissions, additional modelling can be desired, as these simple metrics with a fixed multiplier per GHG species do not take into account the time, longitude, latitude and altitude of the emissions.

In the Clean Aviation Support for Impact Monitoring (CLAIM[2]) project, specific recommendations are made for aviation impact assessment methodologies. The authors explain the difference between existing climate metrics (Dahlmann et al., 2025):

- Radiative Forcing (RF);
- Global Warming Potential (GWP);
- Efficacy-weighted Global Warming Potential (EGWP);
- Global Temperature Change Potential (GTP);
- Average Temperature Response (ATR);
- GWP* and extended GWP*.

The authors provide the following recommendations for the choice of climate metric(s) (Dahlmann et al., 2025):

- Use advanced climate metric methods that consider the location of emissions, rather than relying on simplified multipliers.
- Break down climate metrics into individual effect contributions to enable deeper analysis and understanding.
- Keep climate metrics up to date with the latest, well-established research.
- Validate metrics by cross-checking them against effect time series and occasionally testing with higher-fidelity models.
- Incorporate an uncertainty framework that enables risk analysis.

For this guidance we propose to at least include a sensitivity analysis in the simple approach, by using the following metrics:

- GWP 100 for short-term climate change impacts,
- GTP 100 as a proxy for long-term impacts.

Furthermore, it is advised to conduct an advanced climate impact assessment that includes:

- Spatial and temporal distributions of emissions;
- The recommendations from the CLAIM project, listed above

4.1.2. EF IA method (Environmental Footprint Impact Assessment)

The EF IA method is developed for the PEF and OEF (Organizational Environmental Footprint) initiative from the European Commission (DG Environment). The method covers a wide range of environmental issues in 16 impact categories. An overview is shown in Figure 16. The EF method includes four steps: classification, characterisation, normalisation, and weighting. The results of the EF impact assessment are reported in two ways: as characterised, normalised, and weighted results for each impact category, and as a single overall score based on weighting factors. The method also prescribes a way to determine and report the most

[2] https://www.claim-project.eu/

relevant impact categories based on a cumulative contribution of 80% of the total single score result. More detail on the method and the approach can be found in the EF method documentation (EC, 2021).

This method is mandatory for PEF studies, but it can also be used for any LCA that requires midpoint and single score results.

Figure 16: Overview of 16 impact categories covered by the EF method (DG ENV, 2025).

4.1.3. IMPACT WORLD+

The IMPACT World+ method, developed by the International Reference Center for Life Cycle Assessment and Sustainable Transition (CIRAIG) and the Technical University of Denmark (DTU), is an updated version of the IMPACT 2002+, EDIP, and LUCAS LCIA methods. It is a globally regionalized method for LCIA, incorporating state-of-the-art developments within a consistent framework. The method characterizes thousands of substances with spatially and temporally differentiated impacts when relevant (Bulle et al., 2019).

IMPACT World+ follows a midpoint-damage framework, featuring:

- 24 Midpoint indicators (e.g., Climate change, short term) at an intermediate position of the impact pathways
- 46 Damage indicators contributing to the ultimate societal concern (e.g., Ecosystem quality)
- 2 areas of protection
- Covering a total of 15 environmental issues.

The method can be used for any LCA that requires midpoint results and/or damage categories.

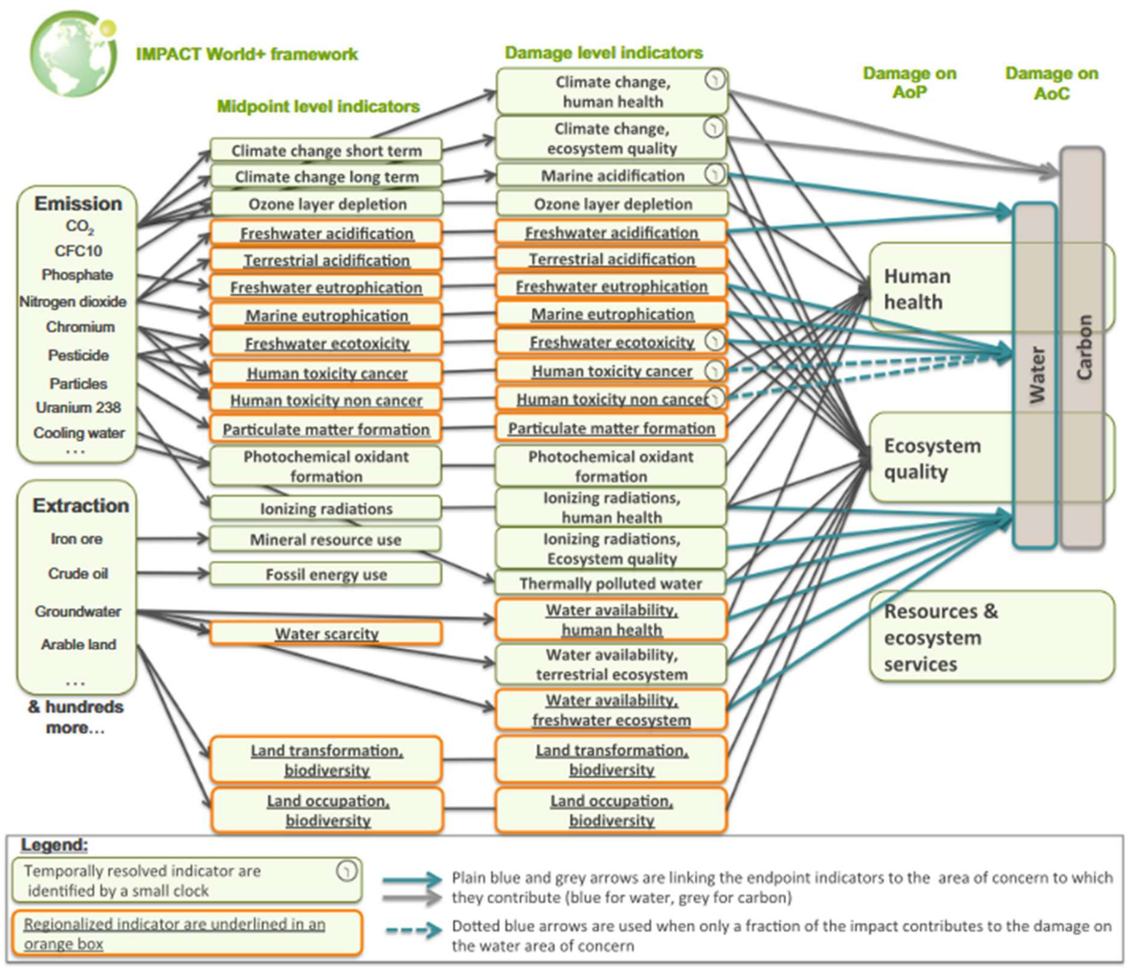

Figure 17: IMPACT World+ LCIA framework. Impact categories are represented by the corresponding indicators at midpoint and/or at damage level (Bulle et al., 2019).

4.1.4. GLAM (Global Life cycle impact Assessment Method)

Building on the Life Cycle Initiative's work since 2002, the GLAM project was launched in 2013, co-led by the University of Michigan, Norwegian University of Science and Technology (NTNU), and Denmark's Technical University (DTU). The goal of GLAM is to develop a comprehensive, consistent, and Global environmental Life cycle impact Assessment Method covering classification, characterization, normalization, weighting. The method includes midpoint impacts and endpoint modelling for human health, ecosystem quality and socio-economic assets (natural resources, ecosystem services). More information can be found on the GLAM website[3] of the UNEP Life Cycle Initiative.

4.2. Biogenic Carbon emissions modelling

Biogenic carbon emissions are part of the short carbon cycle or the natural exchange of carbon between the atmosphere, plants, and soil over a relatively short time scale. Therefore, its climate effect is considered to be limited. This can be modelled in two ways:

1. Neutral Accounting (0/0 approach)

- Uptake (when carbon is absorbed, e.g., during plant growth): 0 kg CO_2
- Emission (when carbon is released, e.g., burning wood): 0 kg CO_2

2. Balanced Accounting (-1/+1 approach)

- Uptake: -1 kg CO_2
- Emission: +1 kg CO_2

Here, the carbon absorption during biomass growth is recorded as a negative emission (a removal of CO_2), and the release is recorded as a positive emission. The two cancel out over time, but the flow is explicitly documented.

Furthermore, adaptations to the IPCC method can be made to increase the coverage of climate effects in aviation. This is further discussed in the following sections.

4.3. Emission Modelling at Altitude

Modelling emissions in the atmosphere and at different flight altitudes is a big challenge in LCA of flight operations. One major problem is that traditional LCA methods often lack precise data on the exact emission locations and conditions during flight (Rahn et al., 2015). This is particularly critical for considering non-CO_2 effects. The formation of contrails or the release of nitrogen oxides (NO_X) can significantly influence the radiative effect of aviation (Niklaß et al., 2019). These effects are highly altitude-dependent, as chemical reactions such as the formation of ozone or cirrus clouds occur primarily in the upper layers of the

[3] https://www.lifecycleinitiative.org/activities/life-cycle-assessment-data-and-methods/global-guidance-for-life-cycle-impact-assessment-indicators-and-methods-glam/

atmosphere between 8 and 12 km altitude (Jungbluth and Meili, 2019). The challenge in incorporating these effects into LCA methods lies in their spatial and temporal variability and their non-linear nature, which makes accurate quantification difficult (Scheelhaase et al., 2016). The existing literature shows that these effects, which can account for up to two-thirds of climate change caused by aviation, are often insufficiently considered, even though they have a significant impact on the overall assessment (Dahlmann et al., 2023).

One approach to solving this problem is to expand traditional LCA methods to model the altitude-dependent climatic effects of NO_X emissions and contrails. Studies such as those by Cox (2018) and Johanning and Scholz (2013) have, for example, adapted the ReCiPe LCIA method to integrate the specific effects at different flight altitudes. They used alternative climate indicators such as Global Temperature Potential (GTP), which takes into account the long-term temperature effects of emissions and allows for a differentiated consideration of altitude and distance variabilities (Johanning and Scholz, 2013). This approach could serve as a basis for a more comprehensive and reliable LCA of flight operations in the future.

Additionally, future LCA methods should integrate improved emission factors for different fuel types and aircraft technologies, as SAF or hydrogen in particular could exhibit different emission dynamics (Yang and Yao, 2025). The development of more accurate datasets for these new technologies and more detailed modelling of the climatic impacts at different flight altitudes are crucial for reducing and correctly assess the climate impact of the air transport system.

4.4. Climate Impact of Hydrogen Emissions

One of the proposed solutions to reduce the climate impact of the air transport system is the use of hydrogen propulsion. Hydrogen can be used in fuel cells to generate electricity for electric motors or it can be combusted in gas turbine engines. Since hydrogen is a small molecule, leakages can occur during production, distribution, storage and use of hydrogen.

Although hydrogen itself is not a direct greenhouse gas, its chemical reactions influence the concentrations of other gasses and particles. The following effects are quantified by Sand et al. (2023):

- Increase in methane levels and lifetime in the troposphere;
- Increase in ozone in the troposphere;
- Increase and decrease in ozone in the stratosphere;
- Increase in production of water vapour in the stratosphere.

The following characterisation factors are developed (Sand et al., 2023) for H_2 emissions based on global atmospheric chemistry models: GFDL; OsloCTM; INCA; WACCM; and UKCA.:

GWP 20	37.3 ± 15.1 kg CO2-eq
GWP 100	11.6 ± 2.8 kg CO2-eq
GWP 500	3.31 ± 0.98 kg CO2-eq

For GWP100, the largest contribution is from changes in methane (44%), followed by ozone (38%) and stratospheric water vapor (18%). Aerosol effects are excluded.

4.5. Additional Environmental Information

Not all impacts of the air transport system are included in current LCIA models. For example, the impact of noise and of local air quality are not included in the impact assessment models described in the previous sections. In the case of noise, current work is exploring how to translate its impact into impact categories (Meyer et al., 2019). For local air quality, the challenge is that all indicators related to air quality are summed over the life cycle.

These additional effects can be included in a separate section on additional environmental information.

5. INTERPRETATION

In the ISO 14040-14044 standards on LCA, the fourth phase of an LCA is the life cycle interpretation phase. The interpretation phase includes the following steps:

1. **Considering the study's goal and scope**, including the appropriateness of system functions, FUs, and system boundaries, as well as limitations identified by data quality assessments and sensitivity analyses.
2. **Identifying significant issues**, such as environmental hotspots in inventory data, impact categories, and significant contributions from life cycle phases, by structuring results from the LCI and LCIA phases.
3. **Evaluating the results**, including completeness of inventory data and impact categories, sensitivity, and consistency checks, to establish confidence in the results and identify any limitations.
4. **Drawing conclusions and making recommendations**, based on the evaluation, for the intended audience, including decision-makers, and ensuring that they are consistent with the study's goal and scope.

This phase is iterative, with each step informing and refining the others, to ensure that the conclusions and recommendations are robust, reliable, and relevant to the study's intended application (ISO 14040-14044).

5.1. Sensitivity Analysis

According to best practices and as recommended by the ISO 14044 standard, a sensitivity analysis should be an integral part of LCA. The ISO standard defines sensitivity analysis as ‘procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study’.

In essence, sensitivity analysis examines the impact of changes in assumptions, methods and data on the results, often done by introducing variations within a specified range and comparing the outcomes. The goal of the analysis is to identify significant changes in results, which can inform decisions about excluding for example non-essential life cycle stages, inputs, and outputs. On the other hand, it can inform on incorporating new ones. It is thereby streamlining data handling to focus on the most significant factors. Sensitivity analysis can be applied to various aspects such as: boundary settings, allocation procedures, impact assessment methods, weighting methods, etc. It is useful to perform sensitivity checks for each phase of the study including the goal and scope definition, the life cycle inventory and impact assessment.

As an example, related to the airport transport system, sensitivity analysis can be used to investigate the impact of different fuel scenarios on the overall environmental footprint of an aircraft’s life cycle. When considering future aircraft that utilize alternative fuels such as hydrogen, SAF or batteries, it is particularly important to perform sensitivity analysis on aspects such as the electricity grid mix.

5.2. Uncertainty Analysis

To use LCA as a tool for decision-making and to draw meaningful conclusions, it is necessary to be aware of the trustworthiness and potential limitations of the analysis. Therefore, uncertainty analysis should always be carried out. Finnveden at al (2009) describe uncertainty as “the discrepancy between a measured or calculated quantity and that quantity’s true value”.

As a first step, uncertainties within the LCA can be characterised based on the following classification scheme proposed by Walker et al. (2003):

- **Nature:** The goal is to describe the uncertainty’s relation to reality. While epistemic uncertainties stem from a lack of knowledge and are therefore beyond full quantification, aleatory or stochastic uncertainties refer to the inherent variability and the non-deterministic behaviour of nature. They can therefore be fully quantified and described. The distinction between the two is not mutually exclusive.

  Examples: The ambient air temperature varies every day and is therefore subject to aleatory or stochastic uncertainty. Energy demands for the production of a component could vary by factory and machinery. From the perspective of an LCA practitioner, this energy demand often needs to be estimated based on a limited number of measurements or on literature. It is therefore underlying epistemic uncertainty.

- **Location:** Depending on where it is located within the LCA framework, an uncertainty’s effect and treatment may significantly differ. Uncertainties in the goal and scope definition mainly concern the system boundaries and FU. They can best be treated by scenario analysis, for example by comparing multiple FUs. Within the LCI and LCIA, quantity uncertainties in the input data play a significant rule. The ISO standard 14044 suggests using value ranges or probability distributions to describe them.

  Examples: To address uncertainty in the FU, a practitioner might perform the same LCA for two options, e.g., for one passenger kilometre and for one ASK. The results can then be compared. For uncertainty within a product flow within the LCI, a deterministic maintenance duration of 1h may be supplemented with an assumed probability distribution, e.g. a lognormal distribution with a mean of 1h and a standard deviation of 10min.

- **Level:** The level or degree of uncertainty refers to the knowledge that is present about the uncertainty. At the lowest level, accurate and representative statistical data is available. This enables the definition of probability distributions and a detailed description of the uncertainty. With a higher level of uncertainty, data becomes scarce and the uncertainty is significantly harder to quantify. In the extreme case, there is no information on the uncertainty at all and more research needs to be done.

  Examples: For the electricity consumption of an aircraft, plenty of historical data may be present, allowing for statistical treatment. Consequently, the level of uncertainty is low. In contrast, the quantity of material for a new component may be still unknown, since it has not been produced yet. Further research and estimations will therefore be necessary.

Uncertainty quantification within the input data of the LCI and LCIA may use the following steps:

1. Listing the uncertain parameters.
2. Characterising the uncertainties that are present for each parameter (see above).
3. Defining a value range or probability distribution for each parameter. Ideally, this can be based on statistical information from measurements or extensive literature research. If there is no reliable statistical information available, a probability distribution can be deducted from qualitative expert judgement, e.g. by employing the Pedigree approach by Ciroth et al. (2016) that is described below.
4. Propagating the uncertainties to the overall LCA result, i.e., examining how the uncertainties within the LCI and LCIA data are reflected in the end result. This can be achieved in various ways, with the random sampling method called Monte Carlo Simulation being commonly used. Other approaches include analytical propagation and min-max range inquiry, i.e., sampling parameters at the extremes of their distribution.

The Pedigree approach can be used to translate expert judgement into log-normal probability distributions. Ciroth et al. (2016) provide the following five categories, on each of which each parameter is ranked between 1 and 5.

- **Reliability:** The reliability captures how the data has been collected. Verified data that is based on measurements would get the highest score of 1, whereas mere estimates would result in the lowest score of 5.
- **Completeness:** The completeness refers to the representativeness of the data that arises from the relationship between the product system under study and the production sites as well as time periods that are used in obtaining the data. The highest score would be attributed to representative data captured at all relevant production sites over an adequate time period.
- **Temporal correlation:** For all of the three correlation-based categories, the central question is whether the context of the product system fits the context of the data. Regarding the temporal correlation, it should be asked how quick the data will be outdated in the specific context and how this timeframe compares to the data's age. As a fall-back, data that is less than three years old may be regarded as up-to-date and data of fifteen or more years age as outdated
- **Geographical correlation:** With data from the precise location of the study the best case, an unknown origin or distinctive different origin would get the lowest score.
- **Further technological correlation:** Ideally, the study should be able to capture the precise processes and materials used within the product system. However, this is typically not the case. If data on different technologies or Technology Readiness Levels (TRLs) is used, this considered by the further technological correlation.

After a parameter has been ranked in each category, the results are transformed into a log-normal probability distribution using the conversion table shown in Table 10.

Table 10: Log-normal probability distribution conversion table.

Characteristic	Symbol	1	2	3	4	5
Reliability	$(\sigma_g)_1$	1.00	1.54	1.61	1.69	1.69
Completeness	$(\sigma_g)_2$	1.00	1.03	1.04	1.08	1.08
Temporal correlation	$(\sigma_g)_3$	1.00	1.03	1.10	1.19	1.29
Geographical correlation	$(\sigma_g)_4$	1.00	1.04	1.08	1.11	1.11
Further technological correlation	$(\sigma_g)_5$	1.00	1.18	1.65	2.08	2.80

The resulting log-normal distribution uses the deterministic amount of the parameter as the mean μ and calculates the standard deviation of the underlying normal distribution σ_N using the formula

$$\sigma_N = \frac{\sqrt{\sum_i^5 \ln(\sigma_g)_i^2}}{2}.$$

6. LCA ACROSS DIFFERENT USE-CASES

Table 11 provides examples of LCA studies for the different of use cases, including aircraft components, entire aircraft, and transportation mode comparisons. It provides an overview of the choices in the four phases of the LCA methodology: Goal & Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.

Table 11: LCA guidance for different use cases, organized by the four phases: Goal & Scope, LCI, LCIA, and Interpretation.

Use case	Goal & Scope	LCI	LCIA	Interpretation
Aircraft component (Bachmann et al., 2017)	- **Objective**: Assess the environmental impact of the specific component throughout its life cycle. Compare different materials, designs and production processes. - **Functional Unit**: Define based on the component's function (mechanical properties, FST requirements, etc.) (e.g., per unit produced or per flight hour). - **System Boundaries**: Include resource extraction, main equipment, component manufacturing, transport, maintenance, and EoL disposal.	- **Data Collection**: Gather data on materials used including auxiliaries, energy consumption during manufacturing (electricity, heat), direct emissions (e.g. VOC) and maintenance activities. - **Data Sources**: Supplier and OEM primary data, industry databases, laboratory and literature.	- **Impact Categories**: Analyse all categories in order to avoid burden-shifting. - Analyse trade-offs and break-even points from production to the flight operations phase (e.g., aluminium in comparison to composite materials).	- **Analysis**: Identify key processes contributing to environmental impacts. - **Recommendations**: Suggest design or material changes to reduce impacts.
Entire aircraft (Rahn et al., 2022)	- **Objective**: Evaluate the environmental impacts of the aircraft from production to EoL. - **Functional Unit**: Per passenger-kilometre or per aircraft over its operational life. - **System Boundaries**: Cover resource extraction, manufacturing, operation (fuel use and emissions at altitude),	- **Data Collection:** Compile data on material composition, fuel consumption during operation, maintenance schedules, and disposal methods. - **Data Sources**: Literature, OEM data, operational databases (e.g., Cirium database), and LCA background databases (e.g., ecoinvent)	- **Impact Categories**: Analyse each life cycle phase and impact categories, and identify hotspots and key drivers, for instance: ✓ <u>Production</u>: GWP, Resource Depletion, FETP, Energy Carriers, POCP ✓ <u>Maintenance</u>: GWP, and energy-intensive hangar operations (FETP, Energy Carriers, POCP, and IRP),	- **Analysis**: Determine life cycle phases with the highest environmental burdens. - **Recommendations**: Propose improvements in design, materials, or operations to mitigate

	maintenance, and disposal.		HTP (hazardous substances during MRO checks), ✓ Flight Operations: GWP, PMFP, POCP, HTP and consideration of non-CO_2 effects (ICAO, 2013) ✓ End-of-life: inclusion of relevant EoL scenarios and avoided burdens	
Transportation mode comparison (Roosien et al., 2023)	**Objective**: Compare the environmental impacts of different transportation modes for a specific journey. - **Functional Unit**: Per passenger-kilometre or ton-kilometre. - **System Boundaries**: Encompass vehicle production, fuel production, operation, maintenance, and EoL processes for each mode.	**Data Collection**: Collect data on vehicle manufacturing, fuel production, operational energy use, and maintenance for each transportation mode considering cargo and passenger load factors. - **Data Sources**: Transportation agencies, industry reports, and LCA studies	**Impact Categories**: Compare GWP, energy carriers, emissions, energy consumption, and other relevant impacts between modes.	- Analysis: Identify the transportation mode with the lowest environmental impact for the given journey. - Recommendations: provide data-driven insights to guide policy development and consumer decisions toward transport alternatives.

GET IN TOUCH

This guidance is meant as a living resource. Therefore, we welcome your feedback, questions, and ideas for collaboration. If you would like to know more about the guidance, discuss applications, or share experiences, please feel free to reach out:

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We look forward to continuing the conversation together.

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7.2. Abbreviations

ACRONYM	DESCRIPTION
AF	Aramid Fibre
APOS	Allocation at the Point of Substitution
APU	Auxiliary Power Unit
AR	Assessment Report
ASK	Available Seat Kilometre
ATA	Air Transport Association
ATM	Air Traffic Management
CH_4	Methane
CIRAIG	Centre for Life Cycle Assessment and Sustainable Transition
CF	Carbon Fibre
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DG	Directorate-General
DLR	German Aerospace Centre
DTU	Technical University of Denmark
DQR	Data Quality Requirements
DU	Declared Units
EASA	European Union Aviation Safety Agency
EC	European Commission
EDIP	Environmental Design of Industrial Products
EF	Environmental Footprint
EoL	End of Life
EPD	Environmental Product Declaration
FAA	Federal Aviation Administration
FETP	Freshwater Ecotoxicity Potential
FU	Functional Unit
FST	Flammability, Smoke, and Toxicity
GCD	Great Circle distance
GF	Glass Fibre
GHG	Greenhouse Gas
GPU	Ground Power Unit
GTP	Global Temperature change Potential
GWP	Global Warming Potential
H_2	Hydrogen
HTP	Human Toxicity Potential

IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
IRP	Ionizing Radiation Potential
ISCC	International Sustainability and Carbon Certification
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LUCAS	LCIA method Used for a Canadian Specific context
MPD	Maintenance Planning Document
MRO	Maintenance, Repair and Overhaul
NH_3	Ammonia
NLR	Royal Netherlands Aerospace Centre
NO_x	Nitrogen Oxides
NTNU	Norwegian University of Science and Technology
OEF	Organizational Environmental Footprint
OEM	Original Equipment Manufacturer
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PKT	Passenger-kilometres-travelled
PM	Particle Matter
POCP	Photochemical Ozone Creation Potential
RSB	Roundtable on Sustainable Biomaterials

7.3. List of figures

7.4. List of tables