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Life Cycle Assessment Methodologies and Life Cycle Inventories for Aviation

Literature Research

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Abbreviations

ALCA Attributional Life Cycle Assessment

ATR Average Temperature Response

BTF Buy-to-Fly Ratio

CC Climate change

CFRP Carbon Fibre Reinforced Polymer

CLCA Consequential Life Cycle Assessment

CPACS Common Parametric Aircraft Configuration Schema

CTUe Comparative Toxic Unit for ecosystems

CTUh Comparative Toxic Unit for humans

EIO-LCA Economic Input-Output Life Cycle Assessment

EU European Union

GFRP Glass Fibre Reinforced Polymer

GHG Greenhouse Gas

GSA Global Sensitivity Analysis

IA Impact Assessment

LCA Life Cycle Assessment

LCC Life Cycle Costing

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LSA Local Sensitivity Analysis

MEW Manufacturer Empty Weight

NMVOC Non-Methane Volatile Organic Compound

OEW Operational Empty Weight

PKM Passenger-Kilometre

pLCA Process-based Life Cycle Assessment

RF Radiative Forcing

SA Sensitivity analysis

UA Uncertainty analysis

VOC Volatile Organic Compound

WBM Weight and Balance Manual

WoS Web of Science

1 Introduction

After the Covid-19 crisis, the aviation sector is expected to recover significantly and reach a steady growth pace, with air passenger number increasing at an average annual rate of 3.3 % [1]. It is considered to be one of the fastest-growing sources of Greenhouse Gas (GHG) emissions. In 2017, in the European Union (EU), direct emissions from aviation represented 3.8 % of total CO_2 emissions [2]. When non-CO_2 emissions are taken into account, aviation contributes to around 3.5 % of the impacts on climate. [3]

In this scenario, the European Commission's Green Deal has been launched, in 2019, being a great effort to reduce the emissions in transport sector by 90% by 2050, when compared to 1990 figures. Hence, there is a need to reduce the environmental impact of aviation in the long term.

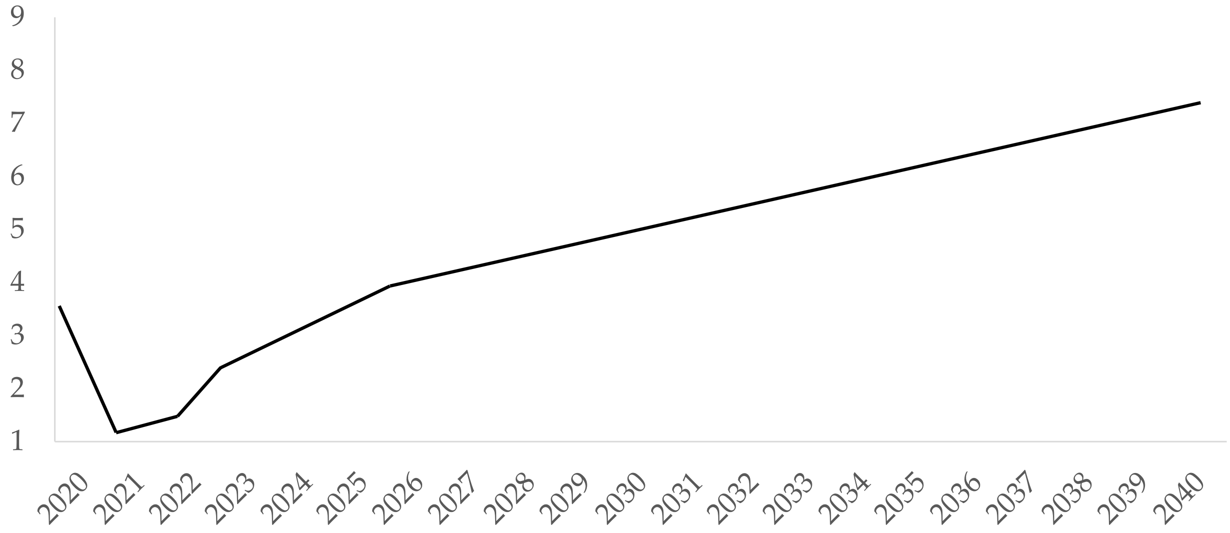

Figure 1.1: Global air passengers, past and forecast, billions [1]

In addition, the ecological impact associated to novel technologies and innovative propulsion concepts needs to be analysed in order to avoid shifting burdens from one impact category to another when developing new products. In this context, the Life Cycle Assessment (LCA) method is a powerful tool to draw recommendations and help identifying potential improvements.

This literature research focus specially on the application of the LCA method to address and analyse the environmental impacts within the aviation sector, as well as the use of the adequate Life Cycle Inventory (LCI) and respective databases within this industry. At last, Life Cycle Impact Assessment Life Cycle Impact Assessment (LCIA) methods and other aviation-specific metrics will be investigated on their strengths and limitations within aviation.

In the transport sector, aviation accounts for 13.9 %, making it the second biggest source of transport GHG emissions after road transport. Within this scenario, in 2019, the European Commission's

Green Deal was presented and aims to reduce transport sector emissions by 90 % by 2050 compared 1990 levels.

The objective of this literature research is to outline relevant fundamental concepts regarding sustainable aviation in the context of existing and novel technologies as well as alternative propulsion concepts. In order to accurately assess the environmental impact of a product or a system, a widely spread method called LCA is used to analyse the burdens caused to the environment over a product's entire life cycle. Such method will be investigated in the present text, and some relevant aspects will be addressed.

In addition, since such method is highly data-intensive, the so-called LCI will also be the focus of this literature research. The limitations and shortcomings of LCA and LCI in aviation will be analysed. Also, databases (such as ecoinvent and GaBi) with focus on transportation and aviation will be investigated, as well as an overview of LCIA methods with a potential relevance in aviation will be examined.

This literature research is hence divided into three parts. The first part is comprised of fundamental concepts for a comprehensive overview of the present text, with a brief introduction to LCA and its phases, with focus on LCI data, as well as the life cycle approach applied to aviation, and the limitations of such method. In addition, a few concepts on aviation complex systems and its interconnections including its energy supply will be presented.

In the second part, the literature review in the current methods for environmental assessment in aviation are outlined and investigated. The definition of relevant research terms and keywords is done, and the obtained statistics will be further discussed and analysed, as well as the publications that seem most fitting to this review's scope will be described and summarized.

In the third part, the information gathered will be used to a research gap analysis, in which the current boundaries are analysed.

2 Fundamental Concepts

2.1 Enviromental Impacts in Aviation

The main environmental impacts associated to aviation are: the emission of greenhouse gases (GHG), noise pollution and land use. The burning of aviation fuel releases carbon dioxide (CO_2) and other GHG such as nitrous oxide (N_2O) as well as water vapor. In addition, the aircraft engines release pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter, which can cause adverse effects on both human health and the environment.

Noise pollution impacts both the communities near airports and wildlife in adjacent areas, causing disturbance in sleep, increased stress levels and overall impacts on human health. Such impacts are usually assessed by the so-called social Life Cycle Assessment. At last, airports and associated infrastructure can lead to deforestation, habitat destruction and disruption of ecosystems. The land use for aviation can displace communities and impact local biodiversity.

Most of aircraft emissions occur at higher altitudes (around 90% of total), whereas the minority is produced during airport ground level operations or takeoff and landing. Emissions caused by the combustion of aircraft engine are a great source of environmental impacts, being roughly composed of 70% of CO_2, around 30% of H_2O and less than 1% of NO_x, CO, SO_x, particulates, among others. Depending on the altitude, the emissions can be considered local air quality pollutant (if they occur near the ground) or greenhouse gases (at altitude). The main emissions for combustion processes are shown in table 2.1. [4]

The emissions, however, are not caused only by the aircraft. They are also originated from vehicles that provide access to airports, shuttle services offered between terminals and to the aircrafts, ground equipment that provide services to aircrafts, auxiliary power units providing electricity and air conditioning to aircraft parked at airport terminal gates, among others. [5]

In addition, the aircraft emissions with an impact on air quality are essentially comprised of nitrogen oxides (NO_x), which contribute to ozone formation at ground level, and increase system exposure to acidification and eutrophication. The impacts of gases emitted by civil aviation are shown in table 2.2. [5]

Table 2.1: Emissions from combustion processes of aircraft engines [4]

Gas	**Source**
CO_2	Carbon dioxide is the product of complete combustion of hydrocarbon fuels like gasoline, jet fuel, and diesel. Carbon in fuel combines with oxygen in the air to produce CO_2.
NO_x	Nitrogen oxides are produced when air passes through high temperature/high pressure combustion and nitrogen and oxygen present in the air combine to form NO_x.
HC	Hydrocarbons are emitted due to incomplete fuel combustion. They are also referred to as volatile organic compounds (VOCs). Many VOCs are also hazardous air pollutants.
H_2O	Water vapor is the other product of complete combustion as hydrogen in the fuel combines with oxygen in the air to produced H_2O.
CO	Carbon monoxide is formed due to the incomplete combustion of the carbon in the fuel.
SO_x	Sulfur oxides are produced when small quantities of sulfur, present in essentially all hydrocarbon fuels, combine with oxygen from the air during combustion.
Particulates	Small particles that form as a result of incomplete combustion, and are small enough to be inhaled, are referred to as particulates, which can be solid or liquid.
O_3	O_3 is not emitted directly into the air, but is formed by the reaction of VOCs and NO_x in the presence of heat and sunlight.

For a given flight, the engine used, load factor and design of the vehicle, weather in route, atmospheric conditions and elevations may affect the emission dispersion and production. The combustion of fuel (jet kerosene and jet gasoline) vary according to the performance of the engine. Figure **??** depicts an overview of the associated environmental impacts of jet engine combustion. The complete combustion would yield a cleaner profile of emissions; however, it is not the case with the current engine technologies. The main GHG emissions are CO_2 and H_2O. [6]

Table 2.2: Impacts on atmosphere caused by gas emissions from aviation [5]

Gas	Source
CO_2	Long-lived GHG. Contributes to global warming.
CH_4	Lifetime of 10 years. Aircraft NO_x destroys ambient CH_4.
H_2O	Due to its small addition to natural hydrological cycle, the contribution is small.
O_3	Lifetime of weeks to months. Product of NO_x emissions plus photochemistry. Its effect is high at subsonic cruise levels and causes radioactive reactions at such levels.
Sulphate	Scatters solar radiation to space. Impact is one of cooling.
Soot	Absorbs solar radiation from space. Impact is oe of warming.
Contrails	Reflect solar radiation and have a cooling effect. However, they reflect some infrared radiation down to earth, which has a warming effect. Net effect is warming.
Cirrus	Contrails can grow to larger cirrus clouds (contrail cirrus). Generally have warming effects.

As shown in figure **??**, the uncertainties rise as one moves from quantifying aviation emissions and radiative forcing to quantifying temperature and precipitation changes or socioeconomic impacts. Since the Global Warming Potential (GWP) concept is not as adequate for aviation, IPCC proposed a different metric called Radiative Forcing (RF), which can be defined as the global, annual mean radiative imbalance caused to Earth's climate system due to anthropogenic activity, measured in watts per square meter $[W/m^2]$. [6]

RF, however, is an instantaneous measure (snapshot) that does not capture the integrated effects of a new unit of aviation emissions. Dallara [7] proposes a new metric called *Average Temperature Response (ATR)* in order to take into account the time horizon. It is defined as the temperature changes integrated over a time period H. The determined effect on climate is dependent on actual emissions progress. ATR is a climate metric specifically tailored for aircraft design rather than for policy decision-making. The following equation describes the metric: [7, 8, 9]

$$ATR_H = \frac{1}{H}\int_0^{\infty} \Delta T_{sust,H}(t)w(t)dt \tag{2.1}$$

in which $\Delta T_{sust,H}$ is the time-varying global mean-temperature change, H is the aircraft lifetime (usual values are 20, 50 and 100 years) and $w(t)$ is the weighting function.

In order to holistically assess the environmental impacts in different stages in an aircraft's life cycle, the following framework is proposed (figure 2.1). For aircraft production, maintenance and end-of-life, the method used is Life Cycle Assessment, whereas during the operation phase, the Impact Assessment (IA) is applied. This is done by expanding existing standards to include aviation-relevant aspects, such as the Average Temperature Response (ATR) metric.

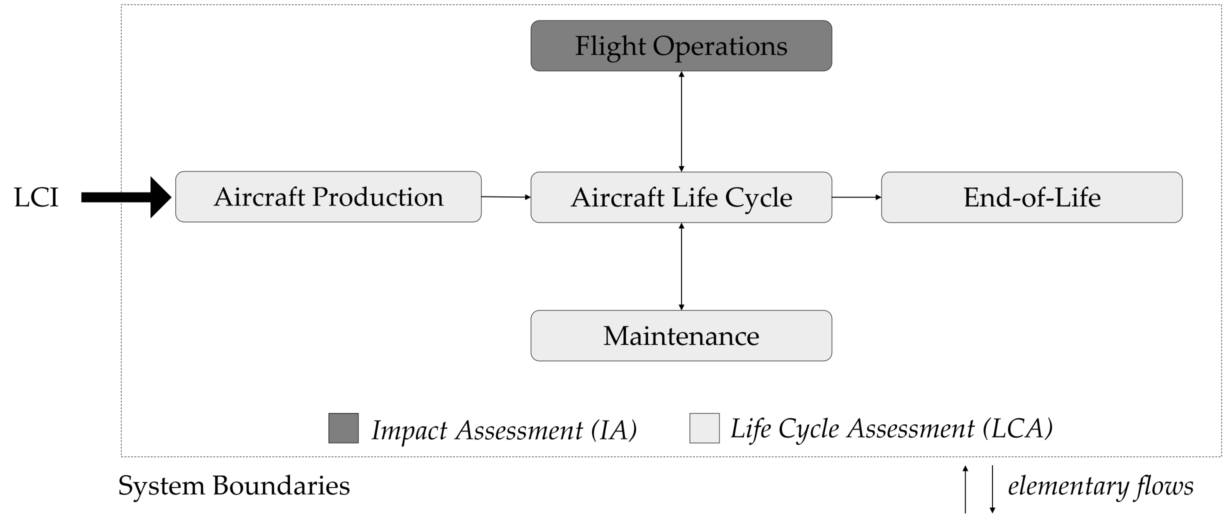

Figure 2.1: System boundaries.

2.2 Life Cycle Assessment

In this section, the Life Cycle Assessment methodology is briefly presented. At first, the definition of the framework is given, followed by the relevant phases (Goal and Definition, Life Cycle Inventory, Life Cycle Impact Analysis and Interpretation), which are described in detail. At last, the strengths and weaknesses of LCA are shown.

2.2.1 Definition and Elements

The Life Cycle Assessment (LCA) is a technique developed for better understanding and addressing the associated environmental impacts of products, both manufactured and consumed. This framework outlines the environmental aspects and potential environmental impacts throughout a product's life cycle, from raw material acquisition through production, use, end-of-life, recycling and final disposal [10].

The DIN ISO 14040 defines four different phases for the conduction of an LCA study, as shown in figure 2.2. Different databases can be used during the Life Cycle Inventory phase, and the most widely used are ecoinvent and GaBi (sphera). The main LCA softwares are SimaPro, openLCA, umberto and Brightway2.

LCA can help identifying opportunities to improve the environmental performance of products throughout many points of the life cycle, selecting relevant indicators of environmental performance, and for industry-driven purposes such as strategic planning, priority setting, product or process design and redesign.

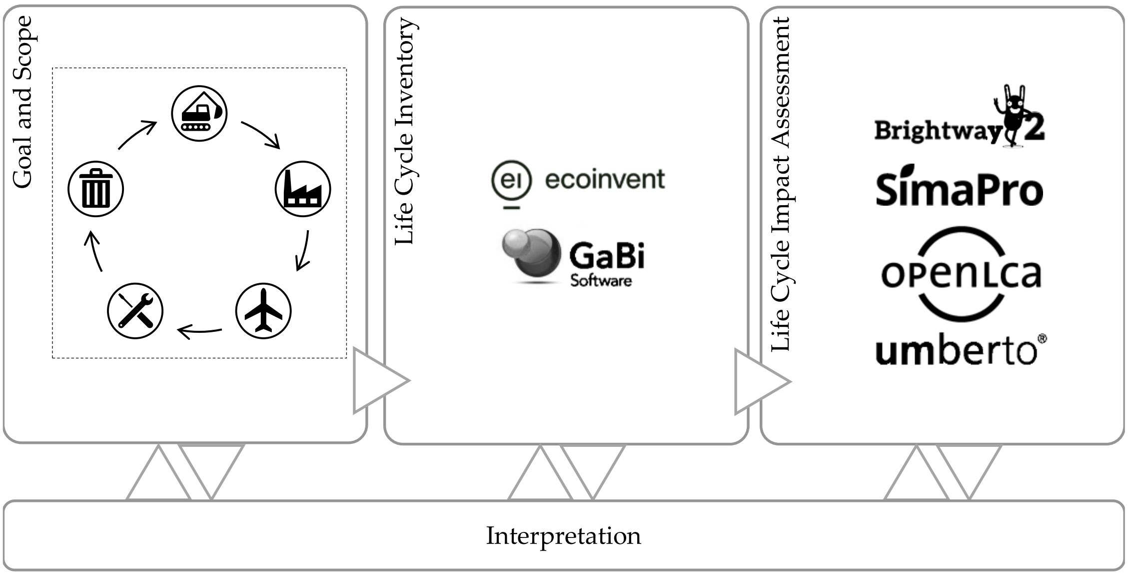

Figure 2.2: Life Cycle Assessment phases [10]

The scope, the system boundary and the level of detail of an LCA depends on the aimed goal of the study. The LCI analysis is an inventory of input/output data regarding the system in scope, and involves the compilation of data necessary to meet the goals of the study. The LCIA phase aims to provide additional information to help assess the LCI's results as to comprehend the environmental significance. The interpretation is the final phase, in which the results of LCI and/or LCIA are summarized and analysed for conclusions, recommendations and decision-making in line with the goal and scope definition.

Finally, since data quality and sources may affect the obtained results from an LCA, an uncertainty analysis (UA) should always be part of the study. The main aspects of uncertainty and sensitivity analysis (SA) will be outlined.

The two main LCA types are namely attributional LCA (Attributional Life Cycle Assessment (ALCA)) and consequential (Consequential Life Cycle Assessment (CLCA)). While ALCA outlines an estimate of what part of the global environmental burdens belongs to the study object, CLCA addresses an estimate of how the production and use of the object in scope affect the global environmental burdens. [11]

ALCA examines a snapshot of the current or past state of affairs to adress the environmental impacts that can be *attributed* to the product in scope, i.e., assuming a static system. CLCA examines future scenarios to determine the impacts that may occur as a *consequence* of a change in the use, method of production, production level of a product. ALCA is defined as a 'retrospective' study for hotspot identification, whereas CLCA is 'prospective' study to evaluate the consequences of future changes. [12]

Goal and Scope

Life cycle assessment enables holistic comparisons among possible systems or optimizing an existing system. For achieving a successful result from an LCA study, it is necessary to define an clear and unambiguous purpose (goal definition) from the start. This will help define the scope and boundaries of the study. In turn, the scope should be sufficiently defined so that the depth and level of detail of the study are compatible and enough to achieve the intended goal. [13]

The goal of an LCA must state the intended application, the reasons to perform the study, and the intended audience. The scope, on the other hand, includes the product system to be analysed, the functions of such system or systems, the functional unit, the system boundary, the selected impact categories as well as the methodology of IA, data requirements, limitations, data and initial data quality requirements. [10]

The functional unit defines the product or process being studied properly. It aims to provide a reference to which the inputs and outputs are related. The reference is necessary to ensure comparability between LCA results. This is specially critical when different systems are being assessed. The functional unit ensures that the comparisons are made on a common basis. [10]

The system boundary defines where the analysis of the specific life cycle begins and where it ends, and outlines the activities included within the technical system. There should be spatial and temporal boundaries. Data collection for each process and sub-process should be representative of the defined goal, within the time and geographic boundaries. [13]

Depending on which phase the system boundaries are set to start and to end, the LCA can be either a *cradle-to-gate*, *cradle-to-grave*, *gate-to-gate* or *cradle-to-cradle* study, as shown in figure 2.3. The cradle-to-gate approach is comprised of the raw material extraction phase until the factory gate, i.e., until the product is ready to be used in the operation phase, while a cradle-to-grave LCA study goes from the raw material extraction through the product use/operation phase and disposal. The gate-to-gate system boundary starts at one defined point along the life cycle to a second defined point further along the life cycle. At last, the cradle-to-cradle is usually referred to as a cradle-to-grave approach in which the product is recycled at end of life phase. [14]

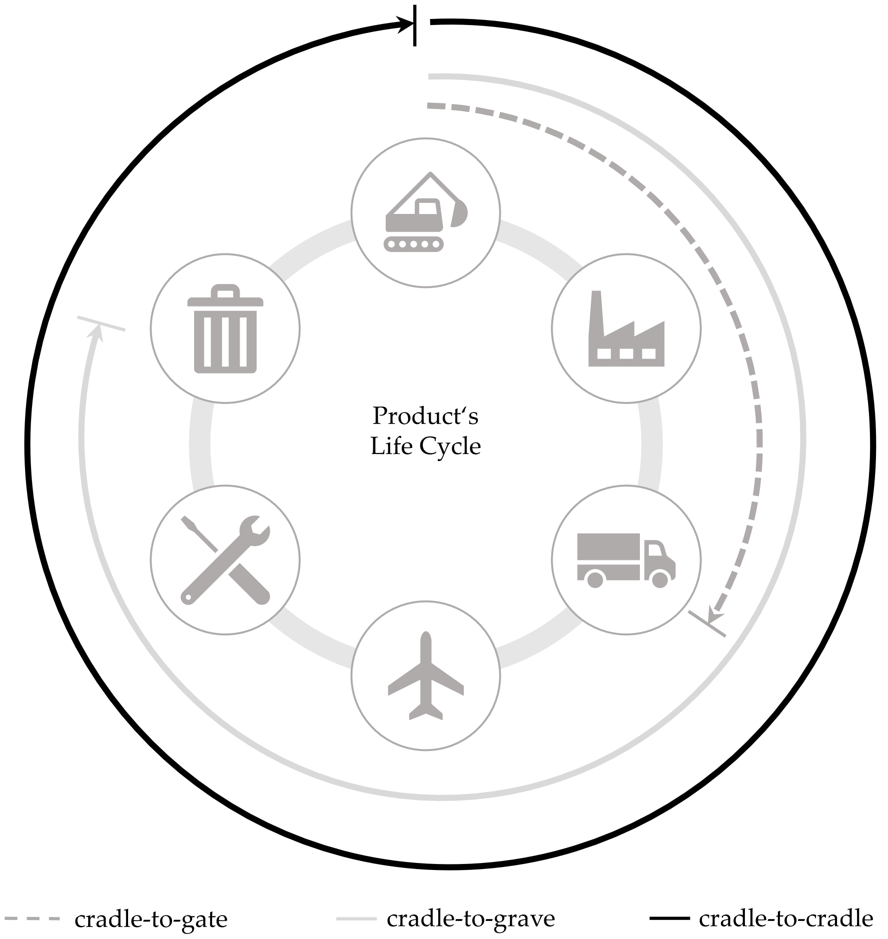

Figure 2.3: Cradle-to-gate vs. cradle-to-grave vs. cradle-to-cradle [14]

The data quality requirements define in general terms the characteristics of the data needed for the LCA conduction. The reliability of the study results as well as the correct interpretation of the study outcomes depend on the descriptions of data quality. [10]

Life Cycle Inventory Analysis

The Life Cycle Inventory Analysis is usually the most time-consuming phase of an LCA. The analysis is guided by the goal and scope definition. The main objective is to collect and compile the data on elementary flows from all processes on a combination of different sources. The results of the LCI analysis phase is a compiled inventory of elementary flows, which are used subsequently in the Life Cycle Impact Assessment phase. [15]

The LCI analysis process is iterative, since as data are collected and more is known about the system, new data requirements or limitations may appear. This requires that the data collection procedures be updated in accordance with goal of the study. [10]

The object of study in an LCI analysis is the *product system*, which is a set of processes which are connected by energy or material flows and should perform the functions defined during the goal and scope definition phase. The *functional unit* is the quantified performance of the product system, and is the reference unit to which all flows are scaled in the LCI analysis. The *system boundary* is the border between a product system, the natural environment, and other product systems, i.e., it delimits the product system to be studied. [16]

In addition, the *unit process* is the smallest element in a LCI model for which input and output data are quantified. The input and output data are organized into six categories of physical flows. The input flows are divided into materials, energy and resources. The output flows are divided into products, waste to treatment and emissions. Usually, unit processes do not gain or lose mass through time and the sum of all input flows should be equal to the sum of all outputs flows. [15]

An output flow such as product or waste to treatment from a previous unit process can be the input flow to the categories materials and energy for a different unit process. Resources and emissions are not exchanged between unit processes, and are denominated as *elementary flows*. Figure 2.4 shows a unit process of steel sheet rolling and the respective examples of flows for each of the six categories (input and output flows). [15]

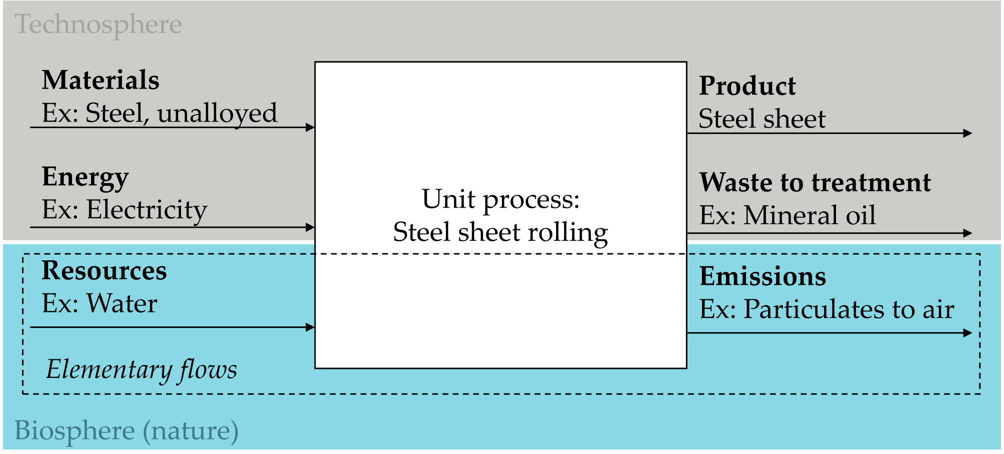

Figure 2.4: Unit process of steel sheet rolling [15], [17]

Life Cycle Impact Assessment

The impact assessment phase of LCA focus on the evaluation of the significance of environmental impacts using the LCI results, associating inventory data with determined impact categories and category indicators. This phase also provides information for the life cycle interpretation phase, as well as revises the goal and scope definition phase, to check whether the objectives of the study have been met. If not, the goal and scope would then be reviewed. [10]

The LCIA phase provides a holistic interpretation of the elementary flows provided in the LCI phase and translation into relevant impact scores, representing the product‘s system impact on global warming, acidification, among others. This can support decision-making as well as answer the questions stated in the goal and scope definition phase. [18]

The mandatory elements for the LCIA phase are:

1. Selection of impact categories, category indicators and characterization models;
2. Assignment of LCI results (classification);
3. Calculation of category indicator results (characterization)

At last, the output is the category indicator results and the LCIA results (LCIA profile). The optional elements are normalization, grouping and weighting. [10]

The selection phase is where the impacts to be analysed are selected according to the chosen goal and a method chosen for each impact category. In the classification phase, the elementary flows of the inventory (resource consumption and energy to air or water) are designated to the relevant impact categories previously selected in step 1. In the characterization phase, for each elementary flows, previously assigned to an impact category, the value is multiplied with a characterization factor, which gives a quantitative representation of its importance for a specific impact category. [18]

The main aspects as well as the units of the impact categories are shown in table 2.3.

Table 2.3: Environmental impact categories [19]

Impact category	**Unit**	**Description**
Climate change (CC)	kg CO_2-eq	Indicator of potential global warming due to emissions of GHG to the air: (1) fossil resources, (2) bio-based resources and (3) land use change.
Ozone depletion	kg CFC-11-eq	Inidicator of emissions to ar that causes the destruction of the stratospheric ozone layer
Acidification	kg mol $H+$	Indicator of the potential acidification of soils and water due to the release of NO_x and SO_x
Eutrophication - freshwater	kg PO_4-eq	Indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to nitrogen and phosphorus compounds emission
Eutrophication - marine	kg N-eq	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen compounds
Eutrophication - terrestrial	mol N-eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen compounds
Photochemical ozone formation	kg $NMVOC$-eq	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight
Depletion of abiotic resources - minerals and metals	kg Sb-eq	Indicator of the depletion of natural non-fossil resources
Depletion of abiotic resources - fossil fuels	MJ, net calorific value	Indicator of the depletion of natural fossil fuel resources
Human toxicity - cancer, non-cancer	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer-related
Eco-toxicity (freshwater)	CTUe	Impact on freshwater organisms of toxic substances emitted to the environment
Water use	m^3 world eq. deprived	¨Indicator of the relative amount of water used, based on regionalized water scarcity factors
Land use	-	Measure of the changes in soil quality (biotic production, erosion resistance, mechanical filtration)
Ionising radiation, human health	kBq U-235	Damage to human health and ecosystems linked to the emissions of radionuclides
Particulate matter emissions	Disease incidence	Indicator of the potential incidence of disease due to particulate matter emissions

Interpretation

The interpretation is the final phase on an LCA study, in which the results of the previous phases are reviewed and analysed, considering the assumptions made throughout the study as well as the data uncertainties. [15]

The interpretation phase should follow three steps. The first is the identification of significant issues (for instance, main processes and assumptions and most relevant elementary flows) from the other LCA phases are identified. The second is the evaluation of such issues, regarding their influence on the general results of the study, as well as to the completeness, sensitivity and consistency with which they have been regarded throughout the LCA study. The last step is drawing conclusions, limitations and recommendations based on the evaluation of the results.

Uncertainty and Sensitivity Analysis

The uncertainty analysis in LCA aims to evaluate the uncertainty of LCA output results (LCIA) considering the uncertain input parameters (LCI). Significant uncertainties can results from data sources from measurements or from models, missing data and deficient model assumptions. [20]

The term "uncertainty" which is widely used in LCA can be divided into uncertainty and variability. Uncertainty can be reduced or eliminated via more reliable and more accurate data acquisition, while variability cannot be reduced but better characterized by improved sampling (it refers to the inherent heterogeneity or diversity of data in an assessment). [20, 21]

The sources of uncertainty in LCA are split into three main categories: model, scenario and parameter uncertainty. The first, *parameter uncertainty* (stochastic or data uncertainty) is defined as uncertainty in observed or measured values deriving from inherent variability in the sampled population as well as related to data quality. *Scenario uncertainty* relates to uncertainty associated to normative choices such as choice of functional unit, time horizon, geographical scale, among others. *Model uncertainty* arise from the structure of and the mathematical relationships defining models themselves (such as models for deriving emissions and characterization factors in impact assessment models). [12]

Sensitivity analysis can be used along with uncertainty analysis in order to assess the robustness of the results and their sensitivity to data, assumptions and models. The two main types of the method are local sensitivity analysis (LSA) and global sensitivity analysis (GSA). LSA investigates how a small perturbation around a reference input value affects the output value, while GSA analyses the effects of uncertain factors when such factors vary over a significant range of uncertainty. [20]

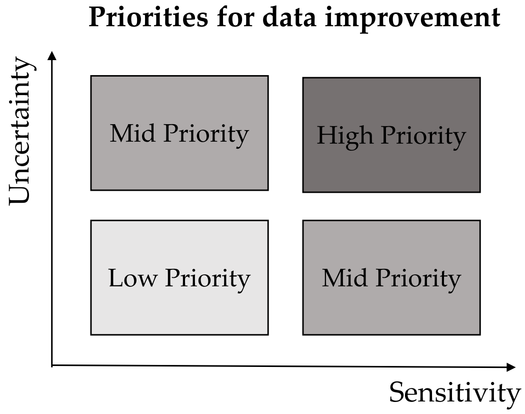

Figure 2.5: Priorities for data improvement [22]

Figure 2.6 illustrates the procedure of a global sensitivity analysis with a schematic LCA model which contains four input parameters. First, the input parameters and the respective uncertainties are represented by density functions (step 1). Second, uncertainty propagation is performed (e.g. Monte Carlo simulation), which propagates uncertainty through the LCA model (step 2) to obtain a distribution function of the output. Third, the variance of the output is calculated (step 3). Then, once the uncertainty propagation is done, a method for GSA is chosen (step 4). This step determines how much each input parameters contributes to the output variance (step 5). The example in figure 2.6 shows that parameters 1 and 2 are the ones which contribute the most to the output variance. [23]

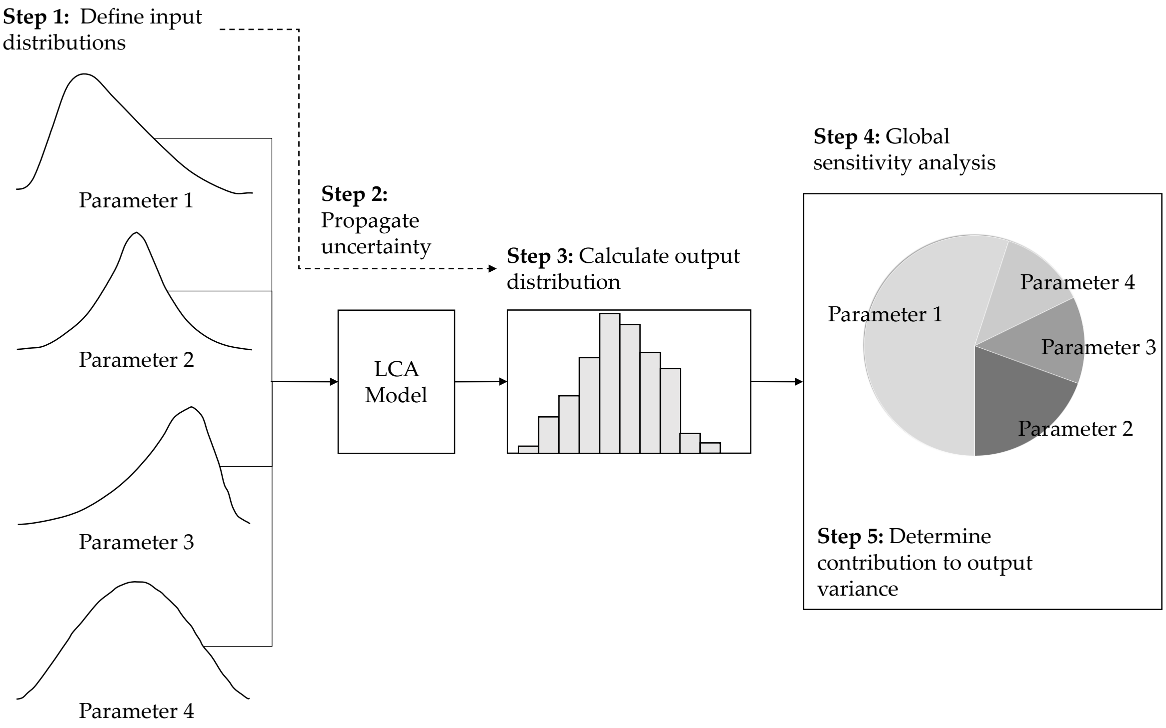

Figure 2.6: Global sensitivity analysis in LCA [23]

2.2.2 Strengths and Limitations

The comprehensiveness of LCA in terms of its life cycle perspective and coverage of environmental issues can be seen as a strength and a limitation. It allows the comparison of environmental impacts of different product systems - which are comprised of hundreds of processes and thousands of resource uses and emissions, in different places and times.

On the other hand, the comprehensiveness can be a limitation, since it requires simplifications and generalisations in the modelling of a product system and the environmental impacts. Since the necessary amount of data required to conduct an LCA study is great and it is not feasible to gather such high quantity of data, it is thus needed to consider simplifications and generalisations. This, on the other hand, prevents LCA from calculating the actual environmental impacts. Since there are considerable uncertainties associated to an LCA study, while mapping of resource use and emissions, it is more precise to say LCA calculates impact *potentials*. [15]

In addition, while LCA can compare and tell which product system is better for the environment, it cannot tell if better is "good enough". For that reason, it is not correct to conclude that a product is environmentally sustainable, in absolute terms, in the case of an LCA study stating that a certain product has a lower environmental impact than another product.

3 Literature Research

The purpose of this literature research is to provide an overview of published papers regarding life cycle assessment in aviation, with a strong focus on Life Cycle Inventories and holistic studies (cradle-to-grave). Hence, the search terms are gathered and then fed into common search engines, such as Scopus and Web of Science (WoS). At last, a detailed overview of the found publications is given.

3.1 Determination of Search Terms

The following section outlines the search terms used in the present literature search. Such terms are relevant in order to identify relevant publications regarding both life cycle assessment and aviation. The suitable synonyms were identified and the number of matches in the databases Scopus and Web of Science is presented in the following tables.

Aviation - search terms

As means to find the suitable search terms to aviation, different synonyms to *aviation* are analysed and used. The complete list of all search terms can be found in Appendix A, whereas the six most frequent results are presented in table 3.1.

Table 3.1: Aviation search terms

Search Term	Scopus	Web of Science	Sum
aircraft	336,142	100,175	436,317
aerospace	156,801	47,299	204,100
aviation	99,380	25,657	125,037
aeronautic*	83,388	15,672	99,060
airplane	30,713	9,847	40,560
flight operation*	3,642	1,383	5,025

Comparing the number of matches in Scopus and Web of Science, it yields that Scopus returns significantly more results. The sum in the right column represents the total of the entries in the two databases, without taking any duplicated publications into account. The most commonly used terms in literature are *aircraft*, *aerospace* and *aviation*. These three search terms are in the following used in combined form:

Search Term
aircraft OR *aerospace* OR *aviation*
→ 521,001 publications in Scopus (02/2023)

Life Cycle Assessment - search terms

Similarly to aviation search terms, the suitable LCA synonyms are defined and then used to determine the number of publications in the two search engines. The numbers are shown in table 3.2. It is important to note that the term *LCA* was previously used to denominate *light combat aircraft* in the late 1990s and early 2000s.

Table 3.2: Life cycle assessment search terms

Search Term	Scopus	Web of Science	Sum
life cycle assessment	35,052	29,827	64,879
LCA	37,541	22,580	60,121
life cycle analysis	18,558	3,294	21,852
life cycle inventory*	3,214	2,005	5,219
lifecycle inventory*	48	25	73

The combination of the different search terms yields:

Search Term
life cycle assessment OR *LCA* OR *life cycle analysis* OR *lifecycle assessment*
→ 55,987 publications in Scopus (02/2023)

Life Cycle Assessment - Synonyms

Since the term Life Cycle Assessment can limit the scope of the results, different terms regarding ecological impacts were analysed. The synonyms of LCA in Scopus and Web of Science are shown in table 3.3. The complete list of the investigation is presented in Appendix B.

Table 3.3: Life cycle assessment synonyms

Search Term	**Scopus**	**Web of Science**	**Sum**
enviromental impact*	235,026	77,853	312,879
carbon footprint	26,756	10,476	37,232
environmental assessment	27,162	8,214	35,376
ecological impact	19,839	2,876	22,715
ecological footprint	5,584	2,863	8,447
environmental footprint	5,209	2,657	7,866

The combination of the different terms yields a total of 287,614 publications in Scopus. In the following section, the relevant results are analysed statistically.

Search Term
life cycle assessment OR *LCA* OR *life cycle analysis* OR *lifecycle assessment* OR *environmental impact* OR *environmental assessment*
→ 287,614 publications in Scopus (02/2023)

The combination of the following search terms results in 27,885 publications.

Search Term
(*lifecycle* OR *life cycle*) AND (*assessment* OR *analysis*) AND *LCA*
→ 27,885 publications in Scopus (06/2023)

3.2 Statistics

In order to identify relevant papers regarding both LCA and aviation, the following search terms were used:

Search Term
(*aircraft* OR *aerospace* OR *aviation*) AND (*life cycle assessment* OR *LCA* OR *life cycle analysis* OR *lifecycle assessment*)
→ 592 publications in Scopus (05/2023)

The search resulted a total of 592 publications. Due to the holistic nature of the present study, an additional search field was used in order to exclude the studies regarding biofuels or aviation fuels (AND NOT). Hence, the search term yielded 337 publications.

Search Term

(*aircraft* OR *aerospace* OR *aviation*) AND (*life cycle assessment* OR *LCA* OR *life cycle analysis* OR *lifecycle assessment*) AND NOT (biofuel* OR fuel*)

→ 337 publications in Scopus (05/2023)

The abstracts of such publications were then read and sorted to be either relevant or disregarded. From the 337 papers, 122 were found to be irrelevant or inconsistent with the intended goal of the present study. In addition, the term LCA was used to denominate *light combat aircraft* during the 1990s and 2000 (34 publications were then disregarded). The 180 remaining publications were then grouped in the different subjects. Figure 3.1 illustrates the main findings:

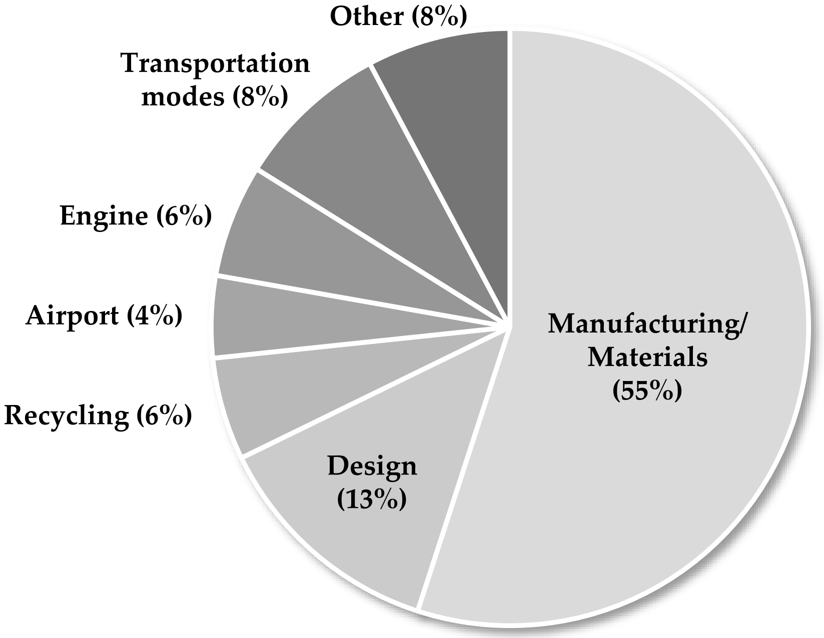

Figure 3.1: Life cycle assessment studies in aviation

Since publications regarding the study of aviation fuels and biofuels were out of scope, the greatest share of papers were focused in manufacturing and materials (55%), followed by early stage LCA during the design phase (13%) and transportation modes. The remaining publications were comprised of recycling, engine and airport infrastructure, respectively. Studies considering a holistic analysis of the aircraft life cycle, i.e. a cradle-to-grave LCA, were analysed in detail and will be described in the following section.

3.3 Detailed Literature Review

Façanha et al. [24] conducted an LCA study on the transportation of goods by road, rail, and air (Boeing 747-400) in the U.S., including the manufacturing, use, maintenance and end-of-life stages for both vehicle and infrastructure life cycle. The authors used a hybrid LCA methodology, combining both process-based LCA and economic input-output analysis-based LCA (Economic Input-Output Life Cycle Assessment (EIO-LCA)) and the functional unit is of grams of air pollutant per ton-mile of freight activity.

The manufacturing phase was assessed via EIO-LCA method, considering the total aircraft costs, while the fuel consumption and emissions are calculated with pLCA with data from IPCC (1996) [27]. The results show that fuel combustion accounts for around 70% of life-cycle CO_2 emissions. The manufacturing phase has a relatively high energy demand (19% of the total).

Similarly, Chester [30] compares the environmental impacts of different transportation modes in the United States. The system boundaries include the entire life-cycle (vehicle, infrastructure, fuel production) except for the end-of-life phase, using a hybrid LCA assessment approach to estimate the components in the inventories. Aircrafts with different ranges were analysed in the study: Embraer 145 (short-haul), Boeing 737 (medium-haul) and Boeing 747 (long-haul). For the manufacturing phase, EIO-LCA was used considering the sectors *Aircraft Manufacturing* and *Aircraft and Engine Parts Manufacturing* for representing the manufacturing processes. As for the operation phase, emissions at non-cruise stages (at or near-airport) and cruise phase are considered separately.

The GHG emissions associated to aircraft manufacturing are significantly different between the aircrafts in scope. The lowest manufacturing emissions are experienced with the Boeing 737, whereas 747 shows the highest impact (43% larger than non-cruise operational emissions and 6% of total). The cruise phase accounts for between 55% (Embraer 145) and 74% (Boeing 747) of total energy consumption and GHG emissions. As for fuel production, this phase accounts for about 8% of total energy consumption for all aircraft and 10% for GHG emissions.

Lopes [36] performed an LCA of an Airbus A330-200 in a cradle-to-grave approach. The inventory is comprised of confidential data from an airline and the results were obtained using the SimaPro software. The chosen functional unit was Passenger-Kilometre (PKM). The material and weight breakdown was gathered by the author based on both manufacturer data (Weight and Balance Manual (WBM)) and literature (specially for the engine material breakdown), as well as with inputs from industry partners such as TAP Airlines. The author compares the sum of the weight from the different materials to the actual Manufacturer Empty Weight (MEW), extracted from the WBM. The value corresponds to 98%, which is reasonably approximate. Aircraft elements such as electronics, navigation instruments and closed system fluids (e.g. hydraulic fluids) were not taken into account, which can explain the 2% difference.

Subsequently, the author transferred the information into materials available in the ecoinvent database. However, the necessary information for Carbon Fibre Reinforced Polymer (CFRP) was not included, and for that reason the author modelled the production of 1 kg of CFRP based on [63], considering both the material and energy consumption.

The operation phase was based on confidential information provided by an airliner, comprised of number of flights, passengers transported, travelled distances, among others as well as the fuel consumption. The author then used the ecoinvent database for aircraft operation. At last, the end-of-life phase was modelled according to [38]. The operation stage accounts for 99,9% of the aircraf environmental burden, whereas the manufacturing stage is responsible for only $4.86 \times 10^{-6}\%$, followed by end-of-life ($1.23 \times 10^{-6}\%$). From this study, the relevance of reliable input data arises, since material breakdown, CFRP production and flight operations data are not detailed enough or are not available via open access due to airline data confidentiality. Both aspects of the aircraft life cycle are increasingly becoming more important.

Howe [39] conducted an LCA of an Airbus A320 during all the life-cycle stages (manufacturing, operation, decommissioning), with a strong focus on materials and components breakdown. For the manufacturing phase, the assembly masses were obtained (split into wings, fuselage, engines, main and nose landing gear, as well horizontal and vertical stabilizers) as well as the material composition data, divided into aluminium, composites, steel, titanium and miscellaneous. The authors split the aircraft into major structural components, which can be divided into separate sub-assemblies. Transportation between production sites (except for the engine) are taken into account. The ecoinvent database is used for characterizing all materials and components, except for CFRP and aviation biofuel production. In that case, custom unit processes were built based on sources for biofuel [63] and CFRP [64]. In addition, the authors rely on Operational Empty Weight (OEW) data for the A320, and assume that systems aboard the plane account for 10% of overall OEW.

As for flight operations, the fuel consumption data was modelled considering a 20-year aircraft lifespan. Similarly to the previous studies, the end-of-life stage was based on PAMELA (2008) [38]. The results show that the main contribution for an aircraft environmental impact is from the operations phase, accounting for 99% of all impacts. The manufacturing phase accounts for less than 0.1%, with the disposal scenario providing a 10% positive return. Similarly, the authors Howe (2013) [60] and Kolios (2013) [65] develop further studies using the same approach.

Dallara [46] develops a streamlined LCA tool called "qUWick" applicable to multi-disciplinary design optimization of aircraft, in a cradle-to-grave perspective combining both process-based LCA and EIO-LCA. The results from the tool are then compared to previous LCA studies such as [30], [36] and [39]. For aircraft manufacturing and operation phases, the author uses the ecoinvent database for "*aircraft production, medium haul*" and *"operation, aircraft, passenger, Europe"*, from [48]. Each aircraft is assumed to be composed of 90% aluminum and 10% and the buy-to-fly ratio is assumed to be 1. Such assumptions and simplifications can interfere in the resulting environmental impacts, since the material breakdown as well as the BTF are parameters which have high influence on LCI analysis and consequently the final results.

Jordão [51] analyses the contributions to climate change of an Airbus A330-200 and a Boeing 777-200, covering the whole lifespan of each aircraft (embodied CO_2 emissions during manufacturing and maintenance and $CO_2\,eq$ emissions during the operational phase). The defined functional unit, as most of LCA studies in aviation, is the PKM (referring to the transportation of one passenger through a travelled distance of 1 km). Due to data scarcity, the end-of-life phase as well as airport construction are not in the scope of the study. The approach used is based on the calculation of embodied energy (MJ) and embodied emissions ($kg\ CO_2\ eq$). For manufacturing phase, the author refers to different sources for A330-200 and Boeing 777-200 material breakdowns, embodied energy and emission factors, respectively ([36, 52, 53, 54, 55]). As most previous LCA studies have shown, flight operations have the highest contribution to the environmental impacts when compared to manufacturing and maintenance phases.

Lewis [59] compares three different flight scenarios for the Airbus A320, A330 and A380, considering fuel production, aircraft manufacturing and operation and airport construction and operation. The author combines two LCA methods: Economic Input-Output Life Cycle Assessment (EIO-LCA), utilizing U.S. economic input-output data and Process-based Life Cycle Assessment (pLCA), based on the ecoinvent database. The functional unit is also PKM. For the manufacturing phase, [36] was adopted as baseline for the materials input in the pLCA and then translated into ecoinvent input flows. As for the EIO-LCA, similarly to [30], the author utilized the sectors *Aircraft Manufacturing* and *Aircraft and Engine Parts Manufacturing* for representing the manufacturing processes in SimaPro software. As for the aircraft operation, the author uses the Eurocontrol's Advanced Emissions Model (AEM) [61]. This tool calculates the total emissions generated by a specific aircraft type over a defined distance, based on flight profile data.

Timmis [66] performs a life cycle assessment of a Boeing-787 Dreamliner considering an all-composite airplane. The author utilizes SimaPro software in combination with ecoinvent databases and the LCIA method is Eco-indicator 99. The study shows the comparison of equivalent sections manufactured from CFRP and aluminium alloy through manufacturing and disposal phases as well as operational emissions. CFRP manufacturing represents the most prominent environmental impact, since the manufacturing processes are more energy-intensive due to complexity. However, during the use phase, the introduction of composite materials to the airframe architecture represents a reduction of carbon emissions due to reduced material weight.

Jemioło conducts a life cycle assessment of air transportation, using a generic aircraft model created based on certain characteristics and parameters. The author uses the ecoinvent database and Lopes [36] as a reference while assessing the manufacturing phase. As for the operating phase, the author refers to the European Environmental Agency (EEA) inventory guidebook [75]. The study compares the results obtained for $CO_2\ eq/PKM$ emissions with other publications as [30], [36], [59] and [48].

Similarly, in his doctoral thesis, Cox [77] compares the environmental impact of current and future passenger transportation by motorcycle, aircraft, urban bus, and passenger car. The ecoinvent datasets are used by the author for the different transportation modes. For aircraft production, the dataset *aircraft production, medium haul* is used in combination with the Operational Empty Weight (OEW). In addition, for fuel production, the *market for kerosene* dataset is applied. Aircraft emissions are calculated based on the EEA/EMEP inventory guidebook [75].

In her publication, Bongo [80] addresses the environmental impact of utilizing aircrafts of various types. The author performs a life cycle assessment of an Airbus A320 and A330. Since the scope of the study focuses on commercial air travel, the functional unit is the operation of an aircraft delivering air passengers to and from the same airport. The system boundaries are comprised of fuel production, cruise phase and respective emissions (other flight phases are out of scope).

The aircraft construction, maintenance and end-of-life are excluded from the study. For the flight operations phase, the author utilizes the ecoinvent database as well as data gathered by [77], based on [75].

Lastly, Fabre [81] performs a life cycle assessment for overall aircraft design. The reference aircraft used is an Airbus A320 and the non-CO_2 effects are not considered in the study. As for the manufacturing phase, the material breakdown is gathered based on [36, 73, 83, 82] and then ecoinvent database is used to consider the extraction, transportation and transportation of raw materials. For composite materials such as CFRP and Glass Fibre Reinforced Polymer (GFRP), the data available in the ecoinvent dataset regards to injection moulded manufacturing process, which does not translate well the processes used in the aviation industry. For the operation phase, the author addresses the fuel production as well as the fuel combustion and tyre and brake emissions.

Table 3.4 shows an overview of the literature presented previously, including the study objective and a brief summary of the inclusion of manufacturing, flight operations and end-of-life phases. In addition, table 3.5 presents the different references used in each publication. At last, table 3.6 summarizes the different software, databases and LCIA methods used in each study.

Table 3.4: Scope of study among the literature on LCA in aviation

Publication	Study Objective	Database	Manufacturing	Operations	Maintenance	End-of-Life
Façanha et al.(2006)	comparison of different freight transportation modes in the US	N.A.	●	●	●	●
Chester (2008)	comparison of different transportation modes	N.A.	●	●	●	○
Lopes (2010)	life cycle assessment of an Airbus A330-200	ecoinvent	●	●	◑	●
Howe (2011)	life cycle assessment of an Airbus A320	ecoinvent	●	●	○	●
Dallara et al. (2013)	comparison of different life cycle assessment approaches and applicabilities	N.A.	●	●	●	●
Jordão (2013)	life cycle assessment and comparison of an Airbus A330 and a Boeing B777	N.A.	●	●	◑	○
Lewis (2013)	comparison of different flight scenarios (A320, A330 and A380)	ecoinvent	●	●	●	○
Howe (2013)	relative environmental impact of each service life phase	ecoinvent	●	●	○	●
Kolios (2013)	relative environmental impact of A320 during manufacturing phase	ecoinvent	●	○	○	○
Timmis (2014)	life cycle assessment of an all-composite airplane based on a Boeing 787 Dreamliner	ecoinvent	●	◑	◑	◑
Jemiołо (2015)	life cycle assessment of air transportation	ecoinvent	●	●	●	○
Cox (2017-18)	comparison of different transportation modes	ecoinvent	●	●	●	◑
Bongo (2020)	life cycle assessment of Airbus A320 and A330 family	ecoinvent	○	●	○	○
Fabre (2022)	life cycle assessment of aircraft similar to an Airbus A320	ecoinvent	●	●	◑	○

● included; ◑ partially included; ○ not included

Table 3.5: References used in each aviation study

Publication	Manufacturing	Operations	End-of-Life
Façanha et al. (2006) [24]	[25], [26]	[27], [28]	[29]
Chester (2008) [30]	[31], [32], [33], [34]	[35]	N.A.
Lopes (2010) [36]	A330-200 WBM, [37]	confidential data from airline	[38]
Howe (2011) [39]	[40], [41], [42]	[43], [44], [45]	[38]
Dallara et al. (2013) [46]	[30]*, [36]*, [39]*, [47]	[30]*, [36]*, [47], [48], [49]	[30]*, [36]*, [50]
Jordão (2013) [51]	[36], [52], [53], [54], [55]	[43], [56], [57], [58]	N.A.
Lewis (2013) [59]	[30], [36], [60], [42]	[61], [62]	N.A.
Howe (2013) [60]	[42], [40], [41], [63], [64]	[43]	[38]
Kolios (2013) [65]	[42], [40], [41], [63], [64]	N.A.	N.A.
Timmis (2014) [66]	[67], [68], [69], [70]	[67], [71]	[72]
Jemioło (2015) [73]	[30], [36], [60]*, [74]*, [48]	[30]*, [59]*, [48], [75]	only airport E-o-L
Cox (2017-18) [76, 77]	[73], [48]	[75], [78], [79]	N.A.
Bongo (2020) [80]	N.A.	[76], [77], [62], [75],	N.A.
Fabre (2022) [81]	[36], [73], [82], [83]	[84]	N.A.

*Comparison basis

Table 3.6: Overview of softwares, databases and LCIA methods used in the different publications

Publication	**Software**	**Database**	**LCIA Method**
Façanha et al. (2006) [24]	N.A.	N.A.	N.A.
Chester (2008) [30]	SimaPro	N.A.	ReCiPe
Lopes (2010) [36]	SimaPro	ecoinvent	ReCiPe
Howe (2011) [39]	SimaPro	ecoinvent	Eco-Indicator 99
Dallara et al. (2013) [46]	N.A.	N.A.	N.A.
Jordão (2013) [51]	N.A.	N.A.	N.A.
Lewis (2013) [59]	SimaPro, Arda[a]	ecoinvent	ReCiPe
Howe (2013) [60]	SimaPro	ecoinvent	ReCiPe
Kolios (2013) [65]	SimaPro	ecoinvent	ReCiPe
Timmis (2014) [66]	SimaPro	ecoinvent	Eco-Indicator 99
Jemioło (2015) [73]	SimaPro	ecoinvent	ReCiPe
Cox (2017-18) [76, 77]	Brightway2	ecoinvent	ReCiPe
Bongo (2020) [80]	openLCA	ecoinvent	CML-2001
Fabre (2022) [81]	openLCA	ecoinvent	ReCiPe

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[a] Arda is an LCA software developed by the Norwegian University of Science and Technology's Industrial Ecology Department

4 Research Gap

This literature review aimed to provide an overview of publications concerning the life cycle assessment applied to aviation. A greater focus was given to life cycle inventories for aviation-specific studies, considering the manufacturing and flight operations phases. The publications which were considered relevant in this context were described and analysed in detail in Chapter 3.

Regarding the studies' scope, most authors conducted an LCA with a holistic approach for specific commercial aircraft types [36, 39, 51, 59, 60, 80, 81], while others focus on the comparison of the environmental impacts for different transportation modes [24, 30, 77] or air transportation [73, 76] as well as on the manufacturing phase only [65, 66].

For the Life Cycle Inventory phase, most of the data was gathered either from confidential data, aircraft manuals (such as WBM), expert knowledge, or from estimates using the OEW from the aircraft. The material breakdown presented by Lopes [36] is later used by most of the subsequent studies [51, 59, 73, 76, 77, 81]. Hence, a better characterisation of materials applied to the different structures, components and systems in the aircraft is relevant for achieving more accurate results. When analysing the environmental impacts from novel technologies, it is important to build a framework which allows more adaptable and flexible calculations based on new inputs on materials and components weight.

In addition, some authors used the hybrid LCA, combining Economic Input-Output LCA and Process-based LCA [24, 30, 59]. The EIO-LCA combines the economic output of a given sector (for the aviation case, *Aircraft Manufacturing and Aircraft and Engine Parts Manufacturing*). Nevertheless, since this method is relying mostly on economic datasets, the accuracy and transparency of such results can represent an issue. Lewis [59], while comparing the results obtained via EIO-LCA and PLCA, explains the significant difference due to the high level of uncertainty associated to the EIO-LCA method.

Most studies, however, were conducted using the so-called Process-based LCA combined with the ecoinvent database. Ecoinvent provides a good level of information on materials production, however the most frequently used such as CFRP or some Aluminum alloys are not yet well defined in the database. For instance, the available activity for CFRP is based on the injection moulded manufacturing process, which does not represent well aviation-specific production chains. In addition, most publications have a high-level approach and do not specify how the different components are manufactured or assembled. Including this information may lead to more detailed and complete results.

The operations phase is defined using different methods. The ecoinvent activity for aircraft operation is applied by some authors [36, 46, 80], while the EEA/EMEP inventory guidebook [75] is referenced by [73, 77]. Most authors also refer to ecoinvent for kerosene production.

Table 4.1 illustrates the connection between the different studies analysed in this literature review. The publications shown in the column are the seen as the "origin" and are referenced by the subsequent studies. They can either be referenced, not referenced, be used as comparison basis or act as primary/secondary source (referenced by other studies used by the author). It can be seen that Lopes [36] is frequently cited by other researchers. Since the author relies on either confidential or aircraft manual data, as well as expert knowledge, specially regarding material breakdown and components weight, such source may not be as transparent. Such issue could be solved combining data models for virtual product design such as DLR's Common Parametric Aircraft Configuration Schema (CPACS) and environmental impacts calculations tools. This can also be beneficial while assessing current and novel technologies and parametric design approaches.

Table 4.1: Publications on LCA in aviation overview

Study	**Dallara* [46]**	**Jordão [51]**	**Lewis [59]**	**Howe [39, 60, 65]**	**Timmis [66]**	**Jemioło [73, 77, 76]**	**Bongo [80]**	**Fabre [81]**
Spielmann [48]	◑	◑	○	○	○	●	◐	◐
Chester [30]	◑	○	●	○	○	●	◐	◐
Lopes [36]	◑	●	●	○	○	●	◐	●
Lewis [59]	○	○	-	○	○	◑	◐	◐
Howe [39, 60, 65]	◑	○	●	-	○	◑	◐	◐
Timmis [66]	○	○	○	○	-	◑	◐	◐
Jemioło [73, 76, 77]	○	○	○	○	○	-	●	●

● referenced; ○ not referenced; ◑ comparison basis; ◐ primary/secondary source

As mentioned in the previous chapters, the different impact categories from LCA are able to cover aviation-related environmental impacts until certain extent. The manufacturing and end-of-life phases are well represented by such categories. However, the emissions caused during the flight operations are not well defined using conventional metrics. For that reason, an aviation-specific metric such as the Average Temperature Response (ATR) can be a powerful asset while analysing the impacts caused by the sector.

Appendix A

Search Term	Scopus	Web of Science	Sum
aircraft	336,142	100,175	436,317
aerospace	156,801	47,299	204,100
aviation	99,380	25,657	125,037
aeronautic*	83,388	15,672	99,060
airplane	30,713	9,847	40,560
aeroplane	30,713	9847	40,560
air traffic	25,007	8,541	33,548
air transport*	27,705	4,954	32,659
aeronautical	14,552	6,368	20,920
air travel	5,301	2,659	7,960
flight operation*	3,642	1,383	5,025
airliner	2,504	938	3,442

Appendix B

Search Term	Scopus	Web of Science	Sum
enviromental impact*	235,026	77,853	312,879
life-cycle assessment	35,100	29,902	65,002
life cycle assessment	35,052	29,827	64,879
LCA	37,541	22,580	60,121
carbon footprint	26,756	10,476	37,232
environmental assessment	27,162	8,214	35,376
ecological impact	19,839	2,876	22,715
life cycle analysis	18,558	3,294	21,852
ecological footprint	5,584	2,863	8,447
environmental footprint	5,209	2,657	7,866
life-cycle inventory*	3,216	2,007	5,223
life cycle inventory*	3,214	2,005	5,219
ecological assessment	2,521	1,272	3,793
life cycle approach	1,766	861	2,627
lifecycle assessment	825	370	1,195
lifecycle analysis	579	190	769
lifecycle approach	338	117	455
life cycle evaluation	251	129	380
lifecycle inventory*	48	25	73
lifecycle evaluation	41	16	57

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