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TESI DI LAUREA

DEVELOPMENT OF AN AVIATION-SPECIFIC LIFE CYCLE ASSESSMENT APPROACH FOR THE ECOLOGICAL ASSESSMENT OF UNCONVENTIONAL AIRCRAFT CONCEPTS

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Task description

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Task Description for
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Development of an aviation specific Life Cycle Assessment approach for the ecological assessment of unconventional aircraft concepts

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Master Thesis

Introduction

Research in the field of new aircraft concepts for more sustainable flight operations is becoming increasingly important. Life cycle assessment (LCA) methods are often used to determine the ecological impacts, as they can provide a holistic statement on all life cycle phases. However, these methods cannot sufficiently fulfil the specific requirements with regard to an ecological life cycle assessment of unconventional aircraft concepts and corresponding propulsion technologies. These include, for example, the consideration of complex interactions during operation as well as the long aircraft service life, but also criteria of the circular economy such as the recyclability of components.

Task

Within this Master Thesis an aviation-specific assessment approach shall be developed, that appropriately maps the environmental impacts of new types of aircraft concepts over the entire life cycle. In this sense, the entire life cycle of the aircraft (from manufacturing to disposal/recycling) as well as the associated energy supply and infrastructure are assessed from an environmental point of view and taking into account future technological developments. Through the integrated consideration of the individual life cycle phases and the overall assessment, appropriate recommendations regarding a more sustainable utilization of aircraft and their components can be made.

Work steps

- Familiarization with life cycle assessment including aspects of the circular economy
- Familiarization with the topic of new aircraft concepts (e.g. new aircraft configuration / propulsion types)
- Analysis and evaluation of existing LCA methods to identify existing shortcomings with regard to their application in the aviation sector and unconventional aircraft concepts, respectively
- Identification of specific requirements for an aviation-specific LCA approach, including

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the aspect of circular economy

- Conceptual design of LCA models for the assessment of new aircraft concepts
- Comparison of methodology with LCA in UNICADO
- Detailed mathematical description of new LCA models
- Discussion and documentation of the results

The work should be free of confidential content, if possible, so that publication after submission is not hindered.

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Abstract

Air transport is currently responsible for 2.5% of global CO_2 emissions and 3.5% of the total global warming effect, and it is the means of passenger transport with the largest environmental impact. Since air traffic is not likely to diminish in the future, it becomes imperative to find ways to reduce its impacts. To this end, novel aircraft concepts, particularly for body configuration (e.g. blended-wing body) and propulsion system (e.g. hydrogen as an energy carrier), are emerging; instruments capable of correctly assessing the environmental performance of these new concepts are therefore needed. In this thesis, requirements for such tools are identified. Then, a framework for comprehensive life cycle assessment of unconventional aircrafts is proposed. Finally, a comparison and possible integration of the developed methodology with the UNICADO design tool are presented.

Keywords: life cycle assessment, environmental impact, unconventional aircrafts, methodology, aviation

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Abbreviations

ADEME	Agency for Ecological Transition
AIC	Aircraft-Induced Cloudiness
AQI	Air Quality Index
ATAG	Air Transport Action Group
ATR	Average Temperature Response
BC	Black Carbon
BWB	Blended-Wing Body
CCD	Climb, Cruise, Descent
CFD	Computational Fluid Dynamics
CFRP	Carbon-Fiber-Reinforced Plastics
CTW	Conventional Tube-and-Wing
DAC	Direct Air Capture
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EASA	European Union Aviation Safety Agency
EI	Emission Index
EoL	End-of-Life
ERF	Effective Radiative Forcing
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies model
HC	Hydrocarbons
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
ILT	Institut für Lufttransportsysteme

ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LTO	Landing and Takeoff
MRO	Maintenance, Repair and Overhaul
NASA	National Aeronautics and Space Administration
PV	Photovoltaic
RPK	Revenue Passenger-Kilometer
SAF	Sustainable Aviation Fuel
TUHH	Technische Universität Hamburg
UHC	Unburned Hydrocarbons
VOC	Volatile Organic Compounds

Variables

CF	Characterization factor
d	Distance travelled [km]
E	Energy flow [MJ]
EI	Emission index
$EndI$	Endpoint indicator
m	Material flow [kg]
MI	Midpoint indicator
n	Number of (subscript)
pk	Passenger kilometers
s	Share of energy production [%]
t	Time variable [hours, years]

Superscripts

as	Assembly
de	Design
eg	Energy generation
fp	Fuel production
gbt	Ground-Based Tests
i	Generic process
mm	Materials' manufacture
mro	Maintenance, repair and overhaul activities
olf	Operating life's flights
re	Recycling
tr	Transport
$*$	Specific (normalized) value

Subscripts

h	Altitude class
in	Input
j	Generic material
k	Generic calculation-specific option
out	Output

1 Introduction

Air travel is undoubtedly one of the greatest feats ever achieved by mankind. It enabled us to reach virtually any point of the globe, provided there is a runway, in the space of one day; something unthinkable only a couple of centuries ago. In 2017, over 4 billion passengers and 56 million tonnes of cargo were transported by 37 million commercial flights (ICAO, s.d.). Aviation plays a key role in international tourism and trade, as well as in the world's economy at large: it was estimated that, in 2016, the aviation sector had a contribution of 2.7 trillion $ on the global GDP, corresponding to 3.6% of the total, and supported 65.5 million jobs worldwide (ATAG, 2018). In addition, these figures are only expected to increase: in 2015, air transport's global revenue passenger-kilometer (RPK), a measure of the distance travelled by paying passengers, was predicted to increase at an annual rate of 4.3% until 2035, leading to a doubling in the span of 20 years, as shown in Figure 1 (ICAO, s.d.).

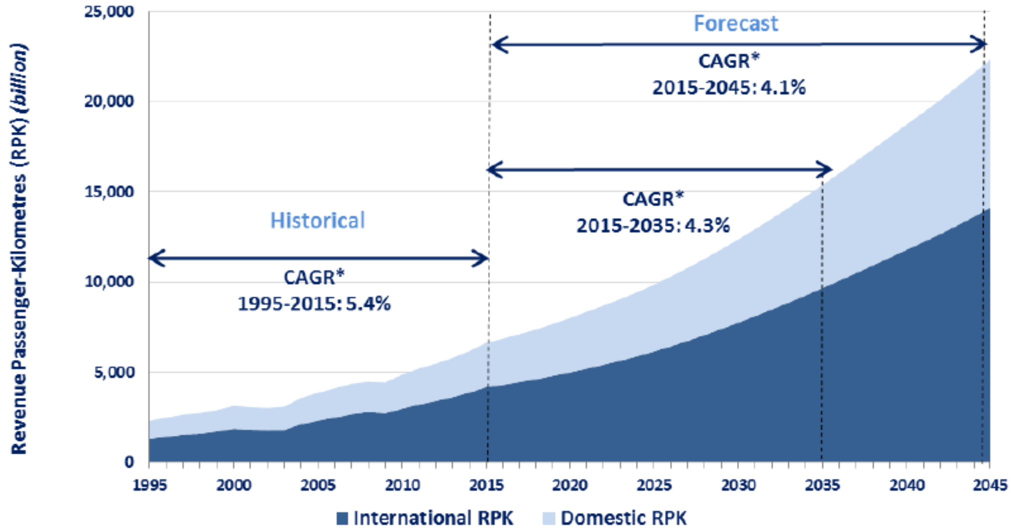

Figure 1. Trend in aviation's global RPKs from 1995 to 2045 (ICAO, s.d.).

Even after the Covid-19 pandemic and its well-known effects on air transport worldwide, aviation's RPKs were estimated to be more than double in 2040 compared to 2019 levels, with the largest relative increase from the Asia-Pacific area (JADC, 2021). The chart below RPKs by continent for the years 1999, 2019 and 2040.

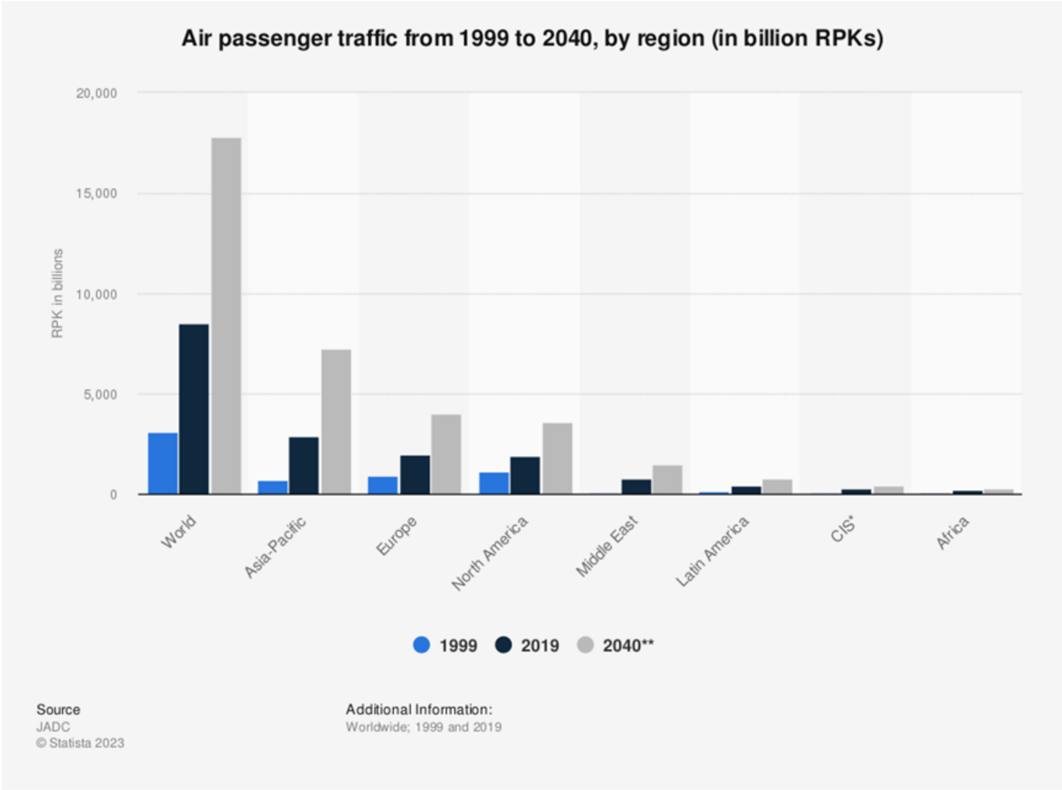

Figure 2. Aviation's global RPK in 1990, 2019 and predicted for 2040 (JADC, 2021).

The benefits and opportunities offered by aviation, however, do not come for free. Notably, among the industry’s costs, there is its considerable environmental impact, described in the section below, which will increase accordingly, unless measures are taken to reduce this impact.

1.1 Air transport’s environmental impact

The best known impact of aviation is on climate: air transport is responsible for 2.5% of global CO_2 emissions, and 3.5% of global warming (Ritchie, 2020), measured through effective radiative forcing (ERF). In fact, other than carbon dioxide, combustion products of conventional jet fuel include CO, NO_x, SO_x, soot, unburned hydrocarbons (UHC) and H_2O, which, under certain atmospheric circumstances, can lead to the formation of contrails and contrail cirrus (Husemann et al., 2017).

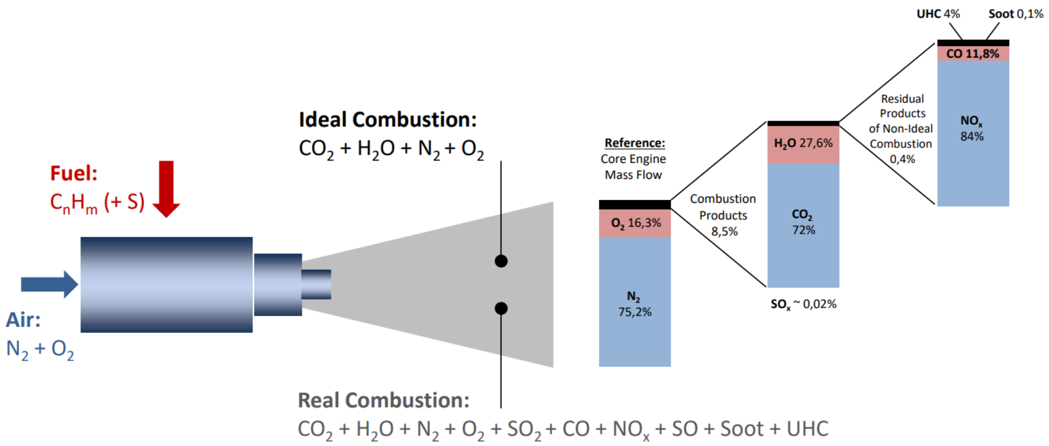

Figure 3. Combustion products of conventional jet fuel (Husemann et al., 2017).

Lee et al. (2021) quantified the ERF of individual emissions and found that non-CO_2 effects account for 66% of aviation's total, with net effects from NO_x and contrail cirrus being the biggest contributors alongside CO_2. However, there is still great uncertainty over the exact magnitude of non- CO_2 effects.

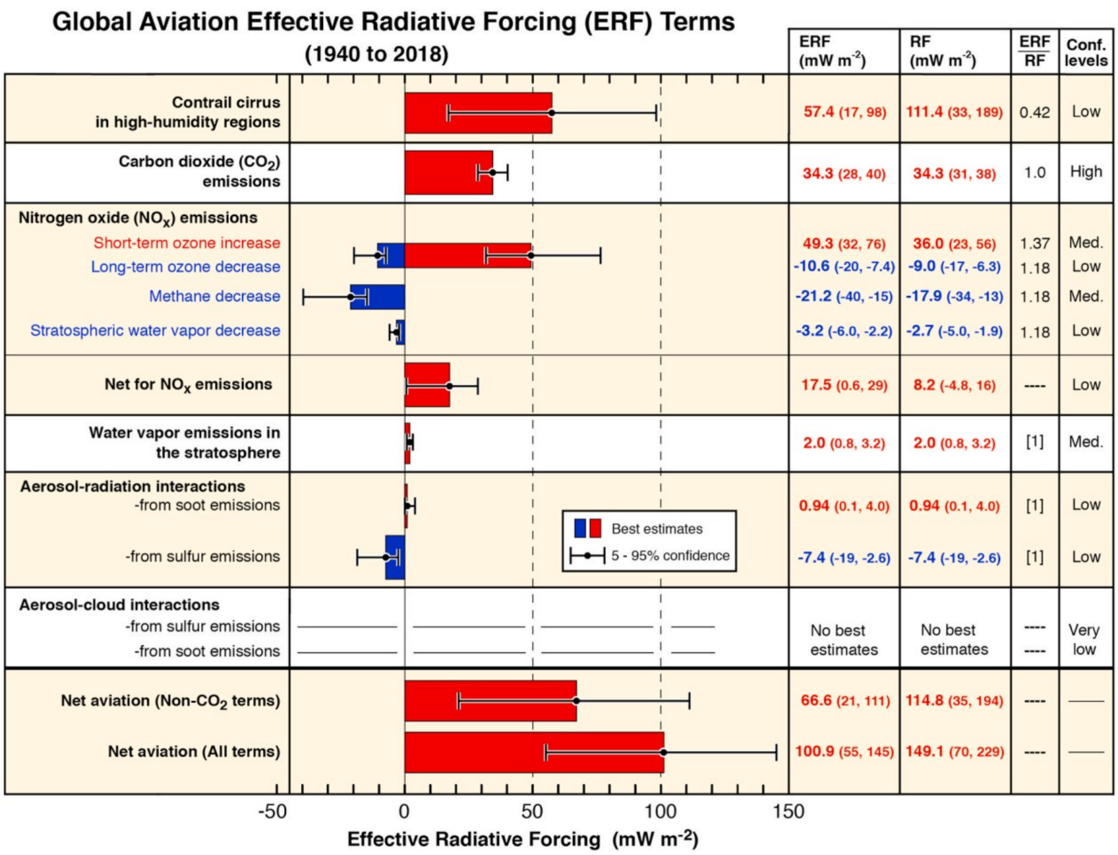

Figure 4. ERF of aviation's different emission pathways (Lee et al., 2021).

When all these effects are taken into account, air travel is found to be the transport mode with the highest emissions. Figure 5 displays emissions (in gCO_2 equivalent) per passenger-km of different means of transport, according to data from UK's Department of Energy Security and Net Zero.

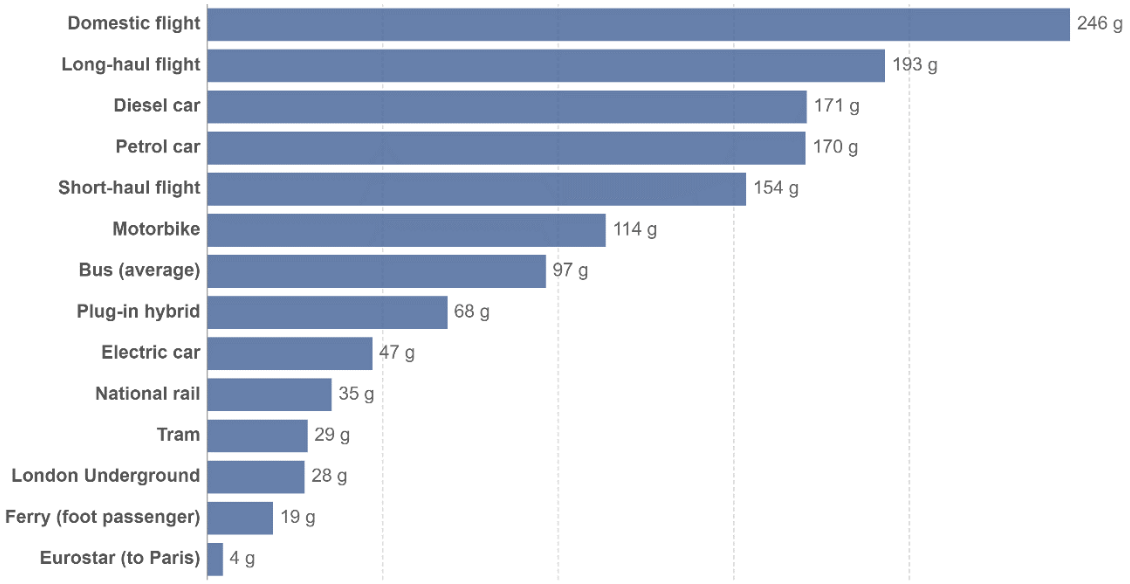

Figure 5. Carbon footprint of travel per kilometer, 2022 (from 'Our World in Data').

Aviation's environmental impact goes beyond climate change: noise levels and air quality are also affected by air traffic (EASA, 2022). Moreover, additional impacts can arise from processes connected to an aircraft's life cycle beyond flying (e.g. the aircraft's manufacture).

At the moment, there is an ongoing international push to minimize said impacts, by developing more eco-friendly aircraft designs, adjusting operations and even adopting cleaner production and disposal processes (ICAO, 2022). That, however, is not enough: to ensure the effectiveness of the measures undertaken, and hence the sustainability of the sector, tools allowing for correct assessment of impacts are required. The most employed methodology to evaluate aviation's sustainability is life cycle assessment, or LCA (Melo et al., 2020), which is described in Chapter 2. This thesis will focus on use of the LCA methodology to assess the ecological performance of emerging aircraft concepts.

1.2 Task description

Plenty of literature on methodological guidelines and LCA studies about conventional aircrafts exists. However, data, practises and considerations employed there might not be directly applicable to the case of emerging aircraft concepts; hence, modifications are required to be able to correctly assess the ecological impact of these novel concepts. Since environmental performance is a decisive aspect for an aircraft's viability, it should be evaluated during conceptual design. The purpose of the present work is to develop a methodology to perform ecological assessment, specific for the field of aviation and capable of evaluating unconventional aircraft concepts, and to provide suggestions on how to integrate the resulting methodology into the design environment UNICADO.

The study was commissioned by, and carried out at, the Institut für Lufttransportsysteme (ILT) of the Technische Universität Hamburg-Harburg (TUHH).

1.3 Structure of the thesis

The remainder of this thesis illustrates the results of the work steps listed in the task description.

Chapter 2 and Chapter 3 describe what is there and what is missing in the field of aircraft's environmental assessment. Chapter 2 contains a general description of the LCA procedure, together with some notes on how it has been applied in the field of aviation and an overview of an aircraft's life cycle and connected processes. On the other hand, Chapter 3 explores the topic of unconventional aircrafts, providing examples of the most prominent emerging concepts, particularly in body configuration and propulsion system, as well as listing the requirements that were identified for an accurate assessment of the environmental performance of such novel designs.

Chapter 4 presents the life cycle assessment framework that was developed in the context of this thesis: qualitative differences relative to the case of conventional aircrafts are outlined and, where appropriate, calculation methods are suggested.

In Chapter 5, the UNICADO design tool is introduced and its ecological assessment module is presented. Then, a comparison with the model developed is offered and a potential integration is proposed.

Finally, Chapter 6 summarizes and discusses the results of the thesis.

2 What is there: the current framework for evaluating aircrafts' environmental impact

The life cycle assessment procedure stems from the concept of life cycle thinking, which is a way of reasoning about the impacts of a product, service or system (in the case of this thesis, an aircraft). It considers all phases of the life cycle and the related processes and elements that enable them (e.g. the presence of an airport allowing the operation of an airplane), as well as the feedback loops of reuse, remanufacturing and recycling (Matthews et al., 2014). Life cycle thinking is essential in shifting from a linear to a circular economy: in order to move away from the "take-make-use-discard" paradigm, it is necessary to optimize the whole system, rather than focusing on one or few of its processes, therefore valorizing aspects such as cleaner production and material recovery, for example through recycling, starting from the design phase (Gheewala & Silalertruksa, 2021). Despite being a robust and comprehensive methodology, LCA can be an exceptionally demanding procedure: that is why, in the field of aviation, simplified, or streamlined, approaches have emerged (Melo et al., 2020). Streamlined assessment may not provide the complete picture of the life cycle of the object of interest, but it still retains one of the characteristics that make LCA so appealing, as to say the possibility of comparing different alternatives.

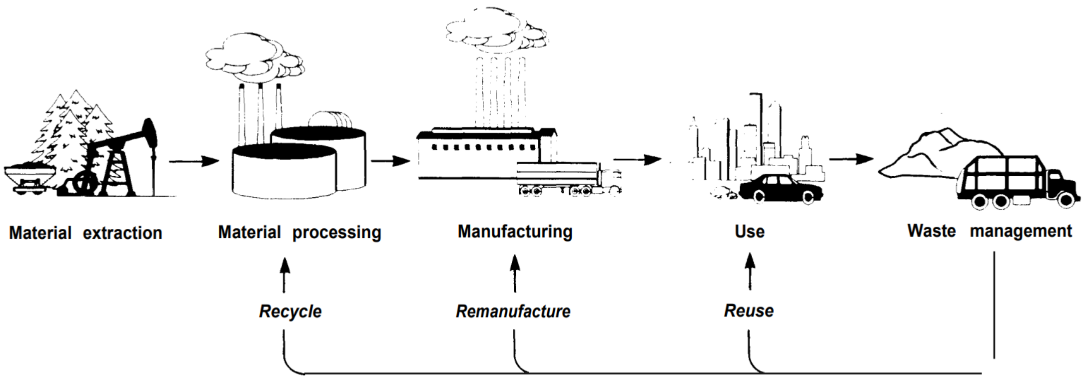

Figure 6. Simplified scheme of a generic product's life cycle with feedback loops (OTA, 1992).

2.1 The life cycle assessment procedure

The reference documents on life cycle assessment practice are the standards by the International Organization for Standardization (ISO), particularly 14040:2006 and 14044:2006. Another source offering useful clarifications that was consulted in the drafting of this thesis is the International Reference Life Cycle Data System

(ILCD) handbook ‘General guide for Life Cycle Assessment : Detailed guidance’; however, because of the methodological nature of this LCA study, it is not possible to claim compliance (Joint Research Centre, Institute for Environment and Sustainability, 2010).

A life cycle assessment consists of four steps: goal and scope definition, inventory analysis, impact assessment and interpretation of results. An overview of these steps, as described in section 4 of ISO 14044:2006, is provided below.

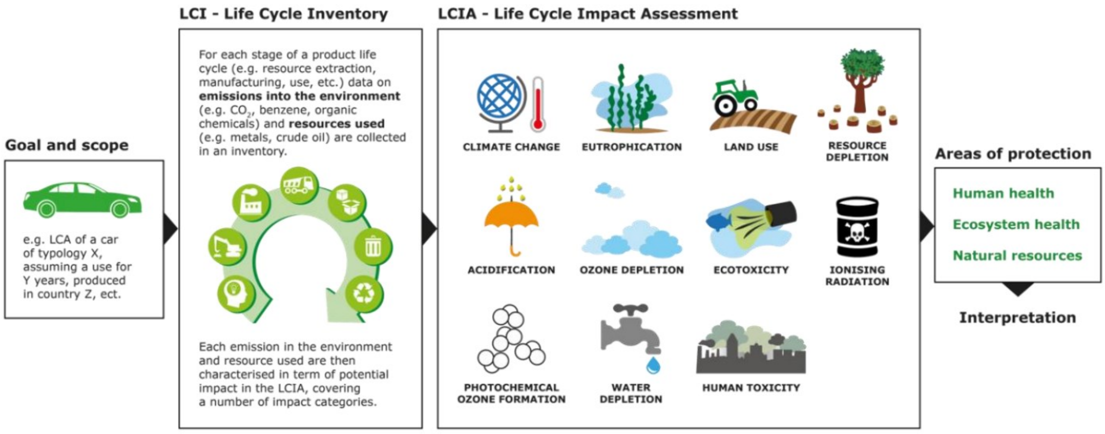

Figure 7. A visual representation of the LCA procedure, with examples (Sala et al., 2016).

Goal and scope definition

In this phase, the objective of the study, together with some of its more general characteristics, should be defined.

The goal definition of an LCA needs to include the following information about the study:

- Intended application
- Reasons for carrying out the study
- Target audience
- Whether or not the results will be publicly available

Afterwards, certain aspects of the study’s scope should be defined:

- Function of the product considered
- Functional unit, based on the product’s function, used to normalize results
- Product system: the set of processes (or process units), having one or more functions, which compose the whole product’s life cycle

- System boundaries, needed to determine which process units should be included in the analysis. Different kind of decisional criteria can be used, such as functional, territorial, temporal, or cut-off rules
- Data quality and quantity requirements
- Impact categories, impact evaluation methodology and associated interpretation strategy
- Allocation procedures: when a process yields different outputs, it may be possible that some of them are not of interest for the case at hand (e.g. transport of different materials, some of which are not used in the considered product's manufacture). It is generally advised to avoid allocation by reconsidering system boundaries; however, when it is not possible to do so, a procedure to deal with this type of situation should be defined. Physical characteristics should be prioritised over economic value
- Assumptions made in the study
- Limitations of the study
- Critical review procedure (necessary only for results of comparison that are to be made public)
- Report's structure

Inventory analysis

Life cycle inventory (LCI) is the most resource-intensive step of an LCA analysis. It involves gathering data and performing calculations to quantity input and output streams of all the process units. Elements to be included in the LCI are:

- Flow chart of the product system
- Detailed description of each process unit, particularly resource use and emissions
- List of measurement units
- Description of data collection and calculations' techniques

Data can be collected from a mixture of sources, like direct measurements, databases, literature, technical coefficients and estimates. During this phase, it is possible to revise system boundaries, particularly to avoid allocation.

Impact assessment

After completing data collection for the inventory, it is possible to select an impact evaluation methodology. This optional step serves to quantify the product's environmental impacts by converting LCI results into impact categories employing characterization factors. Categories can include midpoint and endpoint indicators, which represent different impact levels: the first, in fact, act as an intermediary between inventory items and the second.

A variety of life cycle impact assessment (LCIA) methodologies exist. A synthetic review of such models is present in Wu & Su (2020), while a more comprehensive, though less recent, outlook is available in the ILCD handbook 'Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment' (Joint Research Centre, Institute for Environment and Sustainability, 2010). A selection of LCIA models that are relevant to the context of this thesis (containing at least one of the two categories 'Climate change' and 'Global warming') is provided below:

Table 1 : Selection of LCIA models (adapted from Wu & Su, 2020).

Model	Description	Categories
CML	It assesses specific impact categories (only midpoint), and it is divided into two versions: baseline and non-baseline.	10 midpoint
Eco-indicator 99	It replaces Eco-indicator 95 and covers all emission categories and some resource categories.	11 midpoint 3 endpoint
EDIP 2003	A follow-up of EDIP 97, it covers only emissions as midpoint categories and subcategories.	9 midpoint (18 subcategories)
IMPACT World+	Developed as a joint major update of the models IMPACT 2002+, EDIP and LUCAS, it assesses local and regional impacts.	10 midpoint 3 endpoint
ReCiPe2016	Updated version of ReCiPe2008 (Huijbregts, et al., 2017), which in turn built on CML 2002 and Eco-indicator 99, it integrates and harmonizes midpoint and endpoint impacts.	18 midpoint 3 endpoint

ILCD 2011 Midpoint	It analyses emissions into air, water and soil, as well as resources consumed, in terms of their contribution to different impacts on human health, natural environment and natural resources.	10 midpoint
TRACI 2.1	Midpoint-based tool for assessment and reduction of various environmental impacts.	10 midpoint
LC-Impact	Globally-focused method, with spatially differentiated characterization factors being developed for assessment at a regional scale.	12 midpoint 3 endpoint
Ecological Scarcity 2013	It weights environmental impacts by means of eco-factors, which are derived from political targets or environmental laws.	20 midpoint Environmental loading points as endpoint

At this stage, it is also possible to perform additional calculations (normalization, grouping, weighting) and analyses (gravity, sensitivity, uncertainty).

Interpretation of the results

The final part of an LCA is interpreting the results, which entails identifying and evaluating significant factors, either in the inventory or the LCIA (if present), pointing out the limitations, offering suggestions and conclusions.

It should be noted that LCA is an iterative procedure: while performing the study, it is always possible to go back and redefine a previous step, which in turn influence the subsequent ones, even after results' interpretation. This means that LCA phases influence each other bidirectionally, as it is possible to appreciate from the figure below.

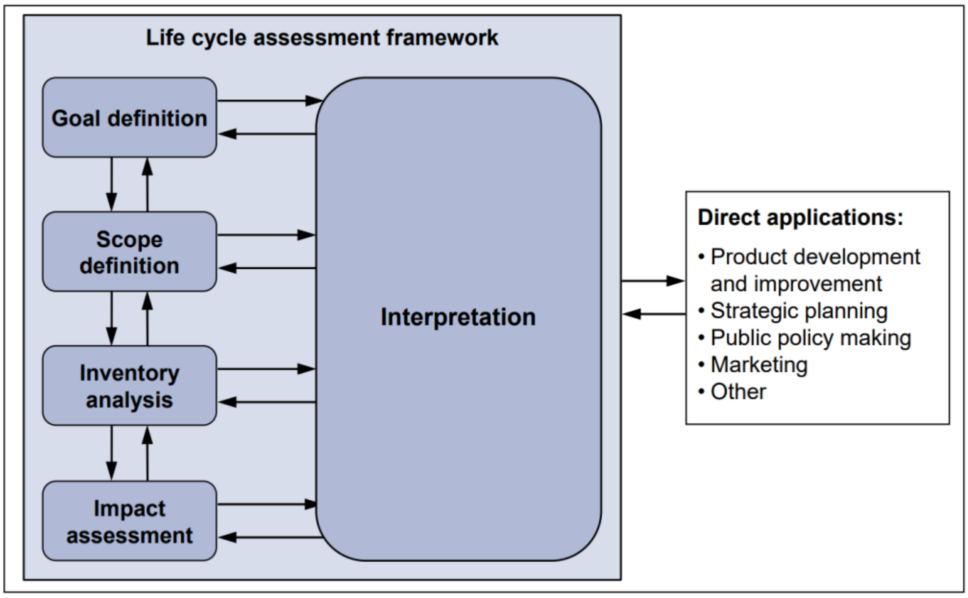

Figure 8. General framework for life cycle assessment, as represented in the ILCD handbook (Joint Research Centre, Institute for Environment and Sustainability, 2010).

2.2 The life cycle of an aircraft

Airbus, one of the largest aircraft manufacturers in the world, lists five stages in the life cycle of an aircraft: design, test and certification, production, delivery and operating life (Airbus, 'The life cycle of an aircraft'). Here is a short description of each stage, provided by the manufacturer:

- *Design*: the first step in the development process is feasibility and concept studies: based on market demands, a preliminary aircraft concept is drawn up. Building on this, elementary aircraft components and their interfaces are subsequently designed in further detail and dimensioned. The final step of this phase is producing and assembling parts for testing at various levels, from small-scale laboratory tests to complete flight tests.
- *Test and certification*: this phase involves actually performing the different tests. Ground-based structural tests include load and fatigue tests. Flight tests include flying in regular conditions, as well as tests in extreme and failure conditions. Global route-proving tours are test flights to selected destinations around the world.
- *Production*: Airbus' production line involves three stages. First, basic elements, such as tubes and panels, are manufactured. These elements are then used in an intermediate assembly, where different parts of the aircraft are assembled in different facilities. All parts are then brought to a specific

location for final assembly, where the manufacturing process is completed and the aircraft becomes ready to take to the skies.

- *Delivery*: the aircraft's functioning is verified by customer representatives at the delivery center, in a procedure that lasts four to five days and includes ground and flight tests. Then, the aircraft is flown to its home base to start its operating life.
- *Operating life*: this phase involves both flights for passenger transport and maintenance, repair and overhaul (MRO) activities.

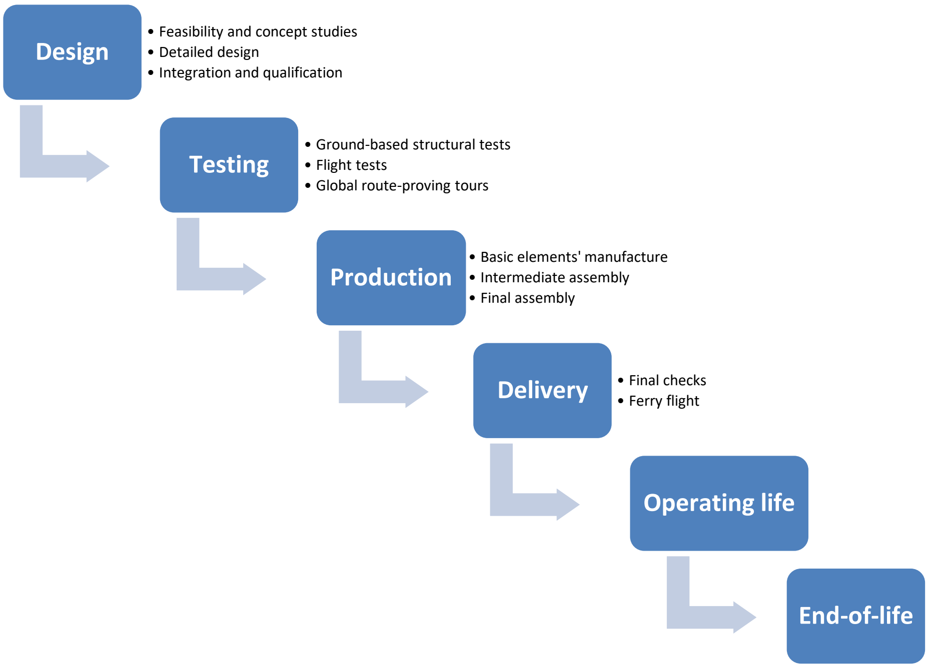

Figure 9. Life cycle of an aircraft according to Airbus, with the addition of the end-of-life stage.

One item that is missing from Airbus' description is End-of-Life (EoL) processes, which tend to get overlooked in some LCA studies, but need to be considered when adopting a cradle-to-grave approach (Matthews et al., 2014). Another aspect to be noted is that the first two phases, design and testing, are model-specific, meaning they are performed once for all aircrafts of the same model, whereas the others occur for each individual aircraft. This is particularly relevant for LCI calculations.

The description above provides a decent overview of an aircraft's life cycle, especially of what, in the ILCD's framework, is called 'foreground system', as to say the processes that are specific to the product system to be assessed. However, in order to perform a complete assessment, it is necessary to evaluate background processes, too (e.g. the extraction of raw materials). To this end, different solutions are adopted by practitioners, and they are seldom equivalent.

2.3 State of the art on aviation-specific LCA methodology

Despite LCA methodologies for the field of aviation have been proposed and are present in the literature (e.g. Johanning, 2017), this practice is still lacking some uniformity. In addition, systematic reviews on the subject are extremely scarce (Keiser et al., 2023). Two examples are the article by Melo et al. (2020), which focused on different propulsion systems, and the one by Keiser et al. (2023), with a more general scope. This section mainly illustrates results from said reviews.

As discussed in the previous section, one of the main methodological issues in aviation's LCA is the conceptualization of an aircraft's life cycle. More than half of the articles conducting LCA in the field of aviation reviewed by Keiser et al. (2023) focus only on a subset of processes ('cradle-to-gate' approach); however, cradle-to-grave studies are more relevant to this thesis' aim. An example of system boundaries from a study assessing the whole life cycle is presented in Figure 10 below. Compared to the scheme in Figure 9, the macroprocesses remain somewhat the same, but connected processes like energy generation are also considered, and operation and EoL are better detailed.

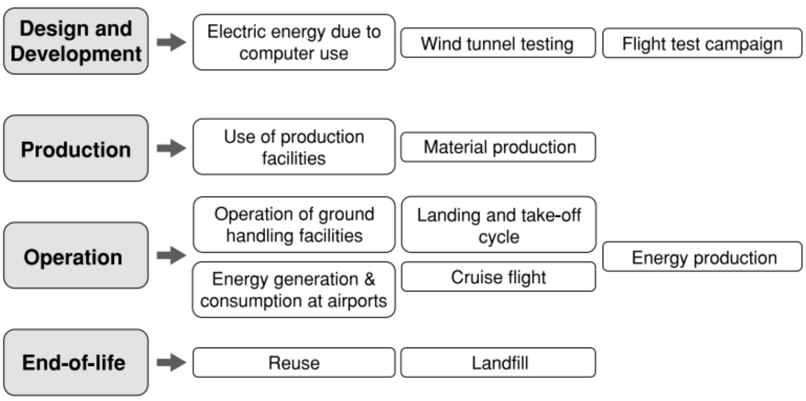

Figure 10. System boundaries in a cradle-to-grave LCA of aircrafts (Kossarev et al., 2023)

Considering the aircraft's different life cycle aspects, in general, aviation fuels have received the most attention in literature recently, especially since 2015, year of the Paris Agreement; though, according to Melo et al. (2020), little focus has been placed on electrified propulsion and fuel cells. Another area that is being investigated intensely is the use of bio-based composite materials, particularly for cabin design, as they show potential for improved environmental performance compared to conventional composites (Gomez-Campos et al., 2021). On the other hand, gaps in research have been identified in EoL practises and modelling, as well as in airport and infrastructure's LCA. Concerning the different aircraft's structural elements, some research on landing gear from a life cycle perspective is still lacking.

A crucial choice in an LCA study is that of the functional unit. Keiser et al. (2023) reported differences based on the life cycle stages considered: the passenger-km (or its variations) used for aircraft operations, an individual component for assembly, a 30-minutes process for maintenance, or even m^2 of runway for an airport, are just a few examples. Such variety hampers the comparison of results from different studies.

As previously mentioned, gathering data is the most demanding task in an LCA. Literature itself is the main source of data for LCA studies in aviation, closely followed by the ecoinvent database. About a third of the articles reviewed by Keiser et al. (2023) also cited primary data, either obtained by stakeholders or from laboratory tests. Databases contained in purchasable softwares, such as SimaPro or GaBi, are mentioned in a small percentage of papers.

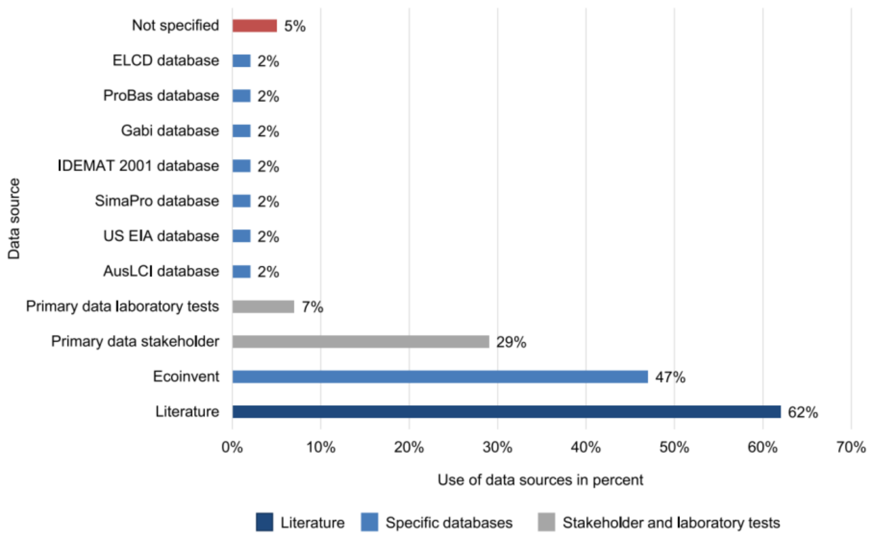

Figure 11. Data sources cited by aviation LCA articles (Keiser et al., 2023).

Figure 14 shows the methodologies employed for impact assessment. The distribution is fairly homogeneous, with the exception of ReCiPe, which was adopted in over a fourth of the cases. A high percentage of studies did not specify a model for LCIA. Figures 12 and 13 display the frequency with which several impact categories were considered: in both charts, climate change is included in most cases; however, there is quite some distance in the average proportion of all the other indicators. The reason might be the different foci of the two reviews: in fact, while emissions and their climate effects constitute the main environmental burden arising from the operation of an aircraft's propulsion system, other significant impacts emerge when taking into account the entire life cycle.

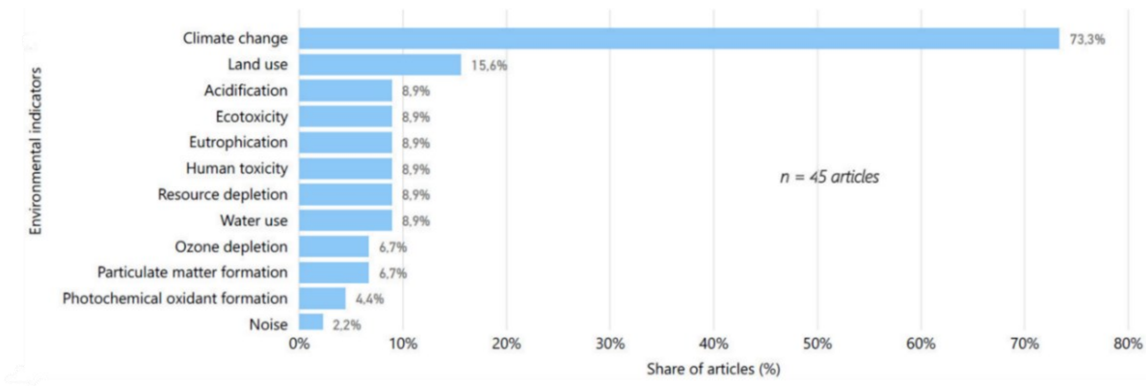

Figure 12. Impact categories considered for aviation LCIA in Melo et al. (2020).

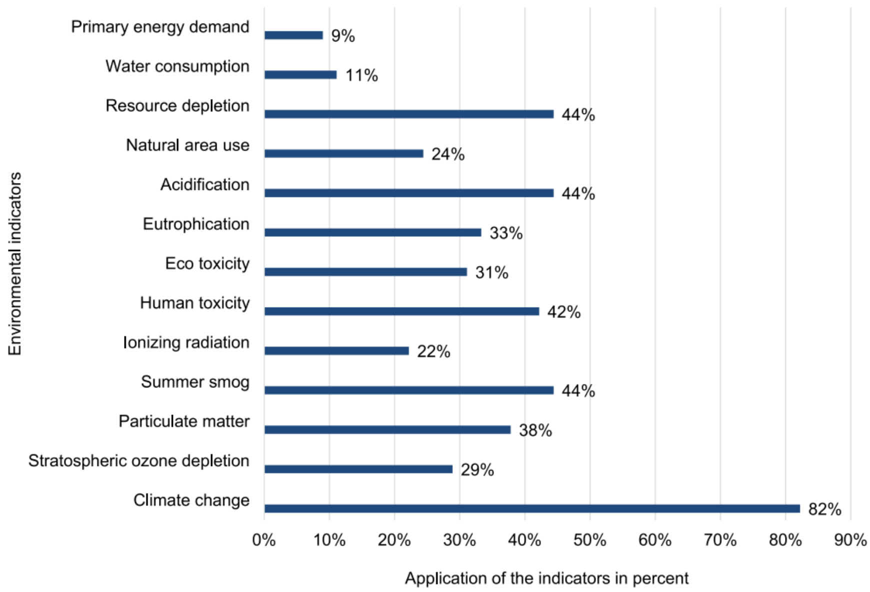

Figure 13. Impact categories considered for aviation LCIA in Keiser et al. (2023).

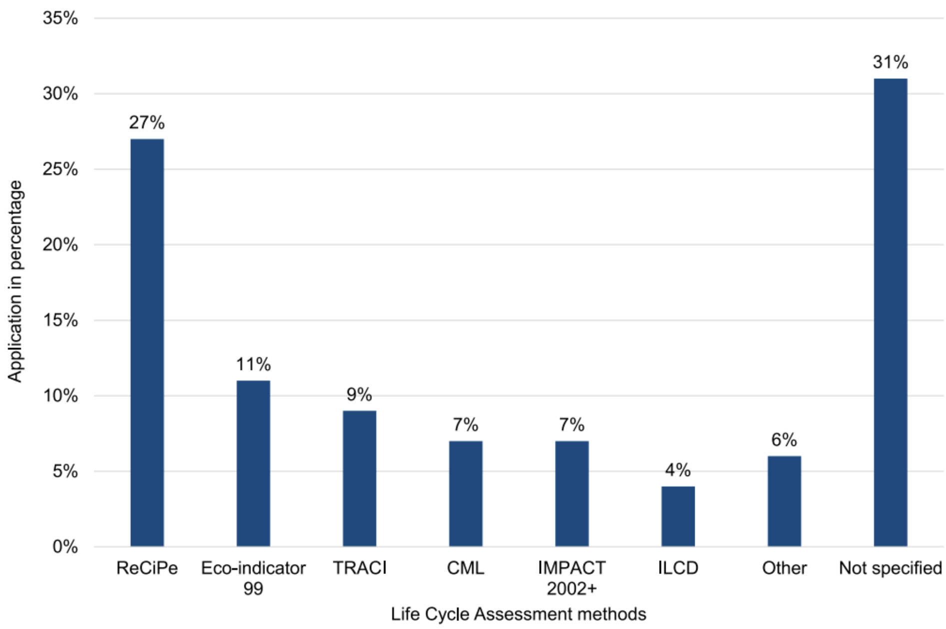

Figure 14. LCIA methodologies used in aviation LCA (Keiser et al., 2023).

The LCA procedure, especially when performed at the design stage, can entail considerable uncertainties; to assess them, additional analyses are typically carried out. In aviation LCA, sensitivity analysis is used in many instances to evaluate parameter uncertainties, while scenario and model uncertainties are also common. Monte Carlo simulations are a powerful tool, yet they are costly and not very accessible (Keiser et al., 2023).

One final remark should be made on multidisciplinary design models for aviation (such as UNICADO, described in Chapter 5). These environments allow for aircraft's conceptual design and optimization, and integrating LCA into them is advocated (Melo et al., 2020). By doing so, the LCA module would need to be specifically tailored to the model, with the advantage that aircraft-specific information (e.g its material composition, fuel consumption) required for the assessment would already be available within the design environment.

3 What is missing: a framework for unconventional aircrafts

A good starting point to develop a framework for assessing unconventional aircrafts is to research and analyze novel concepts, in order to extract information to adapt, extend or generalize current procedures. The first section of this chapter presents emerging trends in aircraft's conceptual design, highlighting differences with airplanes currently in use. Building on this analysis and on a literature review, the second section discusses identified requirements to perform LCA of unconventional aircraft concepts.

3.1 Emerging trends in aircraft design

Novelties in aircraft conceptual design are emerging in two main areas, body configuration and propulsion systems, which are discussed separately in this section.

Body configuration

The entirety of the global civil aviation fleet is currently composed of conventional tube-and-wing (CTW) aircrafts of different sizes (ch-aviation, 2022). CTW has been the dominant structural configuration for decades, and while it might remain relevant in the near future (e.g. for the ZEROe project, discussed under 'Propulsion systems' below), various concepts, promising improved environmental (and economic) performance, are emerging, and could eventually replace CTW as the next-generation airliner (Bravo-Mosquera et al., 2022).

Figure 15 shows examples of such disruptive concepts. Moving anti-clockwise starting from the top-right corner of the picture, surrounding the CTW in the center, the following configurations are depicted: the strut-braced-wing, which enables a wingspan increase alongside weight reduction; the box-wing, which can offer a 30% reduction in induced drag; the hybrid-wing-body, a type of blended-wing body (BWB) with separate, more defined wings, allowing superior aerodynamic performance for regional aircrafts; and the lifting fuselage concept, similar to the previous design, albeit with a narrower center-body (Bravo-Mosquera et al., 2022).

Figure 15. Some examples of unconventional aircraft concepts (Bravo-Mosquera et al., 2022).

Additional configurations are being investigated: for instance, the C-wing presents relatively minor changes to CTW, allowing induced drag reduction and being suitable to current infrastructure (Bikkannavar & Scholz, 2016); while a small-scale prototype of the flying V, a highly energy-efficient long-haul aircraft concept, was built by TU Delft, in collaboration with KLM and Airbus, and completed a successful flight in 2020 (TU Delft, s.d.). However, a comprehensive review of novel aircraft body configurations falls outside the scope of this thesis (for this purpose, see, for instance, Bravo-Mosquera et al., 2022). Instead, the approach adopted here is to focus on the BWB concept, taken as an example to identify areas of LCA that need adaptation compared to the case of conventional aircrafts. The primary reason behind this choice is that this concept has piqued the interest of major aircraft manufacturers: both Boeing and Airbus have built small-scale BWB models, and are considering adopting this design for future passenger aircrafts (NASA, 2020; Airbus, 2020). Additionally, this concept is being researched worldwide: in 2015, Velázquez Salazar et al. identified leading workgroups studying BWB in the USA, the UK, Germany, China, Canada, the Netherlands and Malaysia.

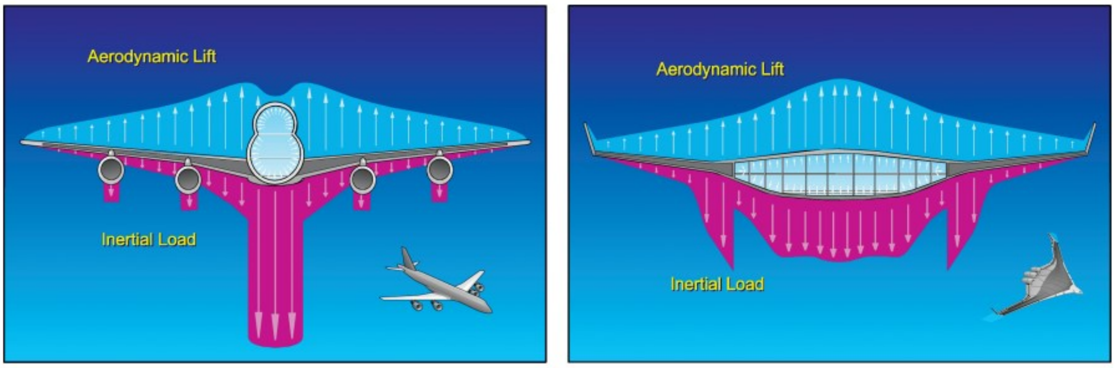

Figure 16. Comparison of lift generation and loads for CTW and BWB aircraft concepts (Liebeck, 2004).

The main characteristic of the BWB design is that, as portrayed in Figure 16, the whole aircraft structure generates lift; a clear advantage over CTW, where only the wings absolve such task (Liebeck, 2004). This ultimately leads to reduced fuel burn, hence lower gaseous pollutant emissions, which, coupled with a reduction in noise generation due to less reliance on trimming devices, results in improved environmental performance. However, developing a BWB commercial airliner still presents challenges, particularly related to control and stability shortcomings, as well as the need to integrate different considerations in a highly-connected configuration (Okonkwo & Smith, 2016). A detailed list of the pros and cons of this configuration (mainly based on Chen et al., 2019) is provided in the table below.

Table 2 : Advantages and disadvantages of the BWB concept (adapted from Chen et al., 2019).

Advantages	Disadvantages
Reduction of skin friction drag due to wetted area reduction	Weight penalty due to non-circular pressurized body
Trim drag during cruise can be avoided by adopting relaxed stability in pitch	Inferior flight and handling qualitites due to relaxed stability, limited control authority and complex flight control system

Lower interference drag given the smooth transition between centerbody and wings	Recovery capability for potential tumbling for tailless aircraft
Reduction of lift-induced drag due to lifting body and improved spanwise lift distribution	Degraded passenger comfort due to scarcity of windows
Lower wave drag at high transonic velocity due to better area-ruled shape	Degraded passenger comfort due to strong acceleration induced by aircraft roll movements, for passengers not sitting in the middle aisle
Simplified high-lift devices, wings' weight reduction and enhanced high-altitude buffet margin can be achieved due to reduced wing loading	Challenges in satisfying requirements on evacuation and airworthiness certification
Engine integration in the aft-upper centerbody has the potential to provide greater noise shielding outside the cabin than in conventional aircrafts	Sensitive to gusts due to low wing loading
Local relieving of aerodynamic loading by local inertia loading can reduce bending and shear loads on the structure	Degraded repairability compared to CTW, suggesting further infrastructure investments
The simplicity of the configuration can yield a reduction in parts needed, with associated lower manufacturing costs	Limitations on BWB size due to taxiway, runway and gate widths, and strenght of wake vortices
Large volume available for hydrogen storage	Potential problems in family development

Propulsion systems

Nowadays, commercial aircrafts' engines typically run on conventional jet fuel, which is a kerosene mixture obtained from crude oil refining, through different possible processes (ChemTero, 2022). Specifications vary based on the area: Jet A-1 is used in Europe, Jet A in North America, TS-1 in Russia and No.3 in

China (Faber et al., 2022). However, the exact composition varies according to source of the oil and production process used; hence, it is generally not defined (Ministry of Defence, 2015).

Recent years have seen a push to substitute fossil-based jet fuel with sustainable aviation fuel (SAF). This term refers to fuels derived either from bio-based feedstock or synthetic processes, having lower sulphur and aromatic content than their fossil counterpart (Faber et al., 2022). SAF is a drop-in solution, meaning it can be employed with little to no changes in aircraft design and fuel supply infrastructure (Kossarev et al., 2023), and it is regarded as a key player in (short-term) decarbonization of the aviation industry: the European Commission, for instance, has set targets for airports' supply share of SAF to be 2% by 2025, 5% by 2030 and a minimum of 63% by 2050 (EASA, 2022). Studies have suggested potential for a reduction in environmental impacts, both during fuel production and operation, by using this type of fuels: savings up to 68% in greenhouse gas (GHG) emissions, for example, were identified by Prussi et al. (2021) in algae-based SAF production, whereas Voigt, et al. (2021) report a concentration of soot and ice number 50 to 70% lower and an increase in ice crystal size, with associated reduced contrail production. Despite the encouraging results, large uncertainties, particularly due to methodological choices, still exist in SAF's life cycle GHG emissions (Seber et al., 2022).

Lately, a transformative alternative for aircrafts' propulsion that has acquired relevance is hydrogen, either for direct combustion or in fuel cells (see figures 17 and 18). The main advantage of using hydrogen as an energy carrier is that it only emits water vapour (and NO_x in the case of combustion) during operation, and its use could be beneficial in various transport sectors (Pirelli, 2023). It is also typically regarded as the best solution to reach decarbonization goals in the aviation sector, both in literature and by the industry. Airbus, for example, aims at developing the first commercial hydrogen aircraft by 2035, with its ZEROe project, for which, incidentally, CTW and BWB configurations are being considered (Airbus, 'ZEROe. Towards the world's first hydrogen-powered commercial aircraft').

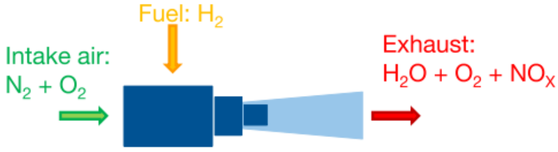

Figure 17. Hydrogen combustion in a gas turbine (Kossarev et al., 2023).

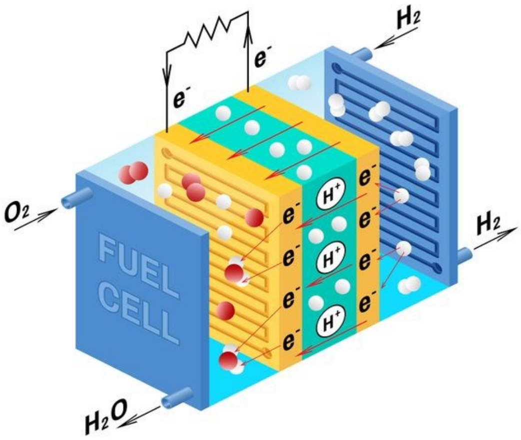

Figure 18. An hydrogen fuel cell's schematic functioning (Airbus, 2020).

However, a switch to hydrogen would not be without issues. First of all, as mentioned in Section 1.1, water vapour and NO_x are emissions whose impact should be quantified. Hydrogen production can occur through different processes, each with its associated impacts (U.S. Department of Energy, s.d.): whether or not the switch would yield benefits largely depends on the chosen production pathway and energy sources. Additionally, adopting this solution presents some technical challenges: as illustrated in Table 3, while hydrogen has a higher energy density compared to kerosene, its density is much lower, so that a volume approximately 4.1 times larger is required for fuel storage (Kossarev et al., 2023). This represents the best-case scenario, where hydrogen has to be kept in its liquid form at a temperature around 20 K (or -253 °C), with connected challenges both for aircrafts and infrastructure design.

Table 3. Properties of liquid hydrogen and kerosene (adapted from Kossarev et al., 2023).

Property	Liquid hydrogen	Kerosene
Density [g/cm^3]	0.071	0.811
Boiling point at 1 atm [K]	20.27	440-539
Specific heat [J/(g K)]	9.69	1.98
Specific energy [kJ/g]	120	42.8

Other substances have received attention, though to a lesser extent than hydrogen, as alternative aviation fuels. Bicer & Dincer (2017) list liquid methane, methanol, ethanol, biodiesel and ammonia.

Lastly, battery-powered aircrafts have also received some attention. Batteries' main appeal, in the case of large passenger aircraft, is not as standalone engines, but rather as auxiliary power units in hybrid systems (Melo et al., 2020; Suungkavatin et al., 2023).

Flight altitude

A separate note on flight altitude should be made. Many novel aircraft designs have an optimal cruise altitude higher than that of CTW (Bravo-Mosquera et al., 2022). Moreover, there has been a renewed interest in supersonic and hypersonic flight (Ros & Close, 2018), which generally require flying in the atmosphere's upper layers. This issue should be addressed in LCA, since emissions' impacts can vary significantly depending on altitude (Husemann et al., 2017).

This section highlighted key differences between conventional and unconventional aircraft concepts, which can ultimately affect all the stages of an airplane's life cycle. A comprehensive description of possible alternations to be made to the LCA procedure as a consequence of these differences is contained in Chapter 4, particularly Section 4.2.3.

3.2 Requirements for unconventional aircraft concepts‘ life cycle assessment

In this section, the background information presented previously is used to identify and list the requirements of an ecological assessment framework for unconventional aircraft concepts.

A key feature of said approach should be comparability (Keiser et al., 2023). This characteristic is a strength in LCA, as it enables comparing and deciding between different alternatives. To this end, results must be normalized according to the same functional unit. In addition, the impact assessment methodology, hence impact categories and categorization factors, should also be the same. Discrepancies in the results could also arise when employing inventory data from different sources, which is why, in Keiser et al. (2023), the creation of a common database for aviation LCAs is advocated.

A potential problem, when dealing with novel aircraft concepts, is that impacts are not actually reduced or eliminated, but simply shifted from one life cycle phase to another, or even outside of system boundaries (Melo et al., 2020); thus, when conducting the analysis, it is important to consider the aircraft's whole life cycle, as well as the connected processes. Melo et al. (2020) suggested a framework, illustrated in Figure 19, including aircraft, fuel and infrastructure's life cycles.

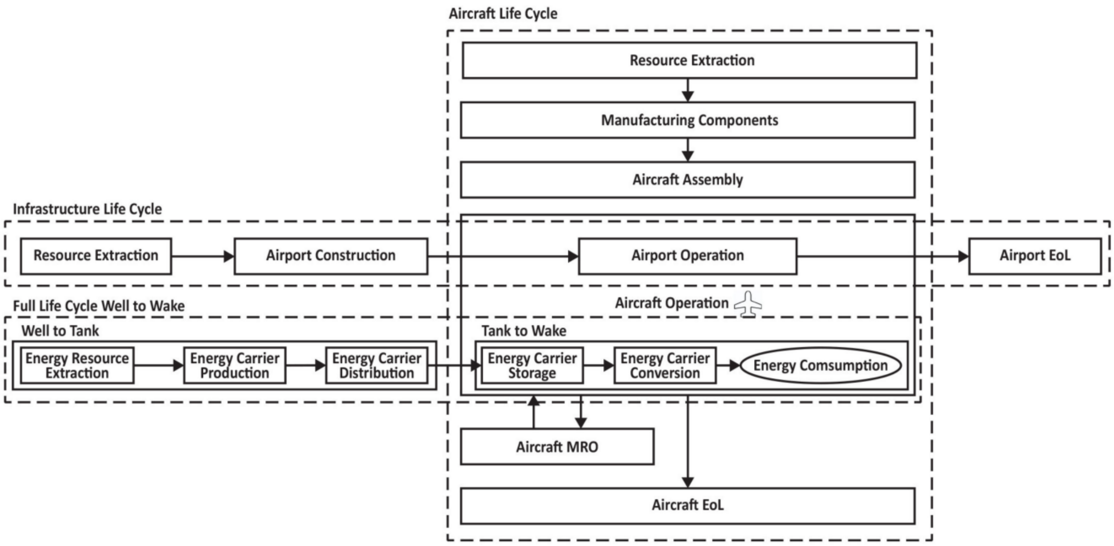

Figure 19. Proposed system boundaries for aviation's LCAs (Melo et al., 2020).

Impact shifting occurs, for instance, in the case of propulsion using hydrogen obtained via electrolysis. In fact, emissions during operation might be less damaging, but the production process is energy-intensive: Kossarev et al. (2023) found a net reduction in environmental impacts only with a higher share of renewable sources. Another aspect that deserves careful consideration is hence the choice of energy mix (Melo et al., 2020).

Particular attention should be placed on modelling the operation phase, as it is deemed to be reponsible for most of an aircraft's climate impacts: Melo et al. (2020) reports values ranging from 77 to 91% of the total, while Keiser et al. (2023) maintains that it could be up to 99% The impact of emissions during operation depends on flight altitude, as mentioned in the previous section, and on geographical location (Grewe et al., 2021). A climate model can be used to achieve an accurate representation of these effects.

One final matter that needs to be addressed by the methodology is credits. It is customary to subtract resources and emissions saved by using secondary instead of primary raw materials (Joint Research Centre, Institute for Environment and Sustainability, 2010), so recyclablity of the aircraft’s parts should be acknowledged. Furthermore, biogenic CO_2 emissions from biofuel combustion should be excluded, as carbon dioxide is first sequestered during biomass growth (Levasseur et al., 2013), and emission credits should be awarded whenever direct air capture (DAC), which can provide carbon for SAF production (Su-ungkavatin et al., 2023), is employed.

4 A life cycle assessment approach for unconventional aircraft concepts

In this chapter, an LCA framework for unconventional aircraft concepts is proposed. Differences with the case of conventional aircrafts are highlighted, with the discussion of examples from specific emerging technologies (such as the BWB design or hydrogen propulsion) where possible, and an attempt at generalizing the procedure is made.

4.1 Goal and scope definition

The following tables illustrate the definitions required for the first step of the LCA approach that was developed.

Table 4 : Goal definition for the developed LCA approach.

Goal definition	
Intended application	The development of a methodology for environmental (ecological) life cycle assessment of unconventional passenger aircrafts (urban mobility is excluded) for assessment and comparison of alternative designs.
Reasons for carrying out the study	Air transport's sizable environmental impacts, coupled with the prediction of increased air traffic in the upcoming years (see Chapter 1 for details), call for an effort to reduce said impacts. Being able to correctly assess them, starting from the aircraft's conceptual design, is of paramount importance to achieve this reduction.
Target audience	Primarily students and research institutes, potentially also companies and other parties involved in the design of novel aircraft concepts.
Publication of results	No plan for publication is currently in place; however, there would be no obstacle in doing so. Results might also be implemented for use in the software UNICADO and published with it as open-source.

Table 5 : Scope definition for the developed LCA approach.

Scope definition	
Product's function and functional unit	This framework focuses on commercial passenger airplanes, whose function is the transport of passengers. Accordingly, the chosen functional unit is the passenger km.[1]
Product system and boundaries	The product system includes all the phases of a passenger aircraft's life cycle, from design and development to end-of-life procedures ('cradle-to-grave' approach), including transport and connected processes, such as energy generation, fuel production and infrastructural aspects related to operation. Input and output flows of individual processes include materials, resources, energy and emissions, as well as the processes' own products. A flow chart representing the whole product system, including flows and relations between the processes, is provided in Section 4.2.2. To avoid modeling life cycles of products external to the system of interest, net benefits derived from recycling components instead of extracting virgin raw material are credited to the system considered.
Data quantity and quality requirements	Collection of primary data falls outside the scope of this work, so secondary sources will be employed. Also, since the methodology targets unconventional aircrafts, little or no directly measured data might be available during the design phase, especially on processes that differ significantly from conventional aircrafts' (e.g. the operation phase). In selecting sources, only free or student-available ones were considered; data behind a paywall was excluded.

[1] If other aircraft types are investigated, it might be necessary to pick a different functional unit. For example, in the case of cargo aircrafts, a possibility would be the tonne-kilometer (Parolin et al., 2021). The comparison of LCA results is not possible when using different functional units.

Impact assessment methodology	Being the most commonly employed in the field (see Section 3.2), the chosen impact assessment methodology is ReCiPe 2016, which is described in Section 4.3.
Allocation procedures	When allocation was not avoidable, masses were considered for the splitting rule.
Assumptions	It is generally assumed that secondary data is representative of primary data, even though, as it is explained later, this might not always be the case. Other assumptions were made throughout the model, but they are mentioned as they become relevant.
Limitations	The methodology is limited in its completeness and complexity by being developed in the context of a master's thesis; however, subsequent improvements remain possible. Also, it was not possible to test the model. Once again, because the methodology targets unconventional aircraft designs, therefore not employing directly measured data, results might not be completely representative of real-life scenarios.
Critical review	The initial review process will be performed internally to the ILT, particularly by supervisor Katrin Bistreck and professor Volker Gollnick. Additional input should be provided by professor Alessandro Manzardo, from the University of Padova.
Report's structure	The model is described in the context of this master's thesis, specifically in the current chapter, following the four steps of the LCA analysis described by ISO 14044. An overview of the whole thesis' structure is provided in Section 1.3.

4.2 Inventory analysis

As previously discussed, the inventory analysis of an LCA has the purpose of collecting data about inputs and outputs of each life cycle stage of the product system considered. This section presents the methodology developed to model the life cycle inventory of unconventional aircrafts, together with data that can be useful to perform the calculations.

4.2.1 Inputs and outputs considered

The starting point of an LCI is to identify flows of interest. In this case, they should cover:

- *Materials*, like fossil resources (i.e. crude oil, natural gas, coal) and other raw materials (e.g. bauxite for aluminium production)
- *Emissions*, including, but not limited to, those during aircraft operation (see Section 1.1)
- *Energy* consumed by processes
- *Other resources*, such as water and land use

The following symbols will be used to refer to resources and emissions, in the formulae suggested to calculate flows:

- $m^{i}_{j,in/out}$ for mass flows, where the superscript *i* refers to the process, the subscript *j* refers to the material, and *in* or *out* indicates whether it is an input (i.e. materials, water) or output (i.e. emissions)
- E^{i} for energy flows, where the superscript *i* refers to the process

4.2.2 Product system and system boundaries

The ensuing step is to determine the product system, identifying phases and processes of which an unconventional aircraft's life cycle consists. Figure 20 depicts a flow diagram, obtained building on knowledge from previous chapters, which illustrates how such product system could look like. An overview of the system is provided in this section, while a detailed description of individual processes is presented in the next.

Life cycle phases are represented by boxes, which are connected by material transport, and can consist of different sub-processes. Almost all phases include energy and resources as inputs, and emissions as outputs. A distinction between model-specific phases (i.e. design and testing) and individual aircraft's phases (i.e. production, operation and disposal) is made: impacts of the former need to weighed by the total number of aircrafts of a certain model to be produced, whereas the latter occur for each individual aircraft.

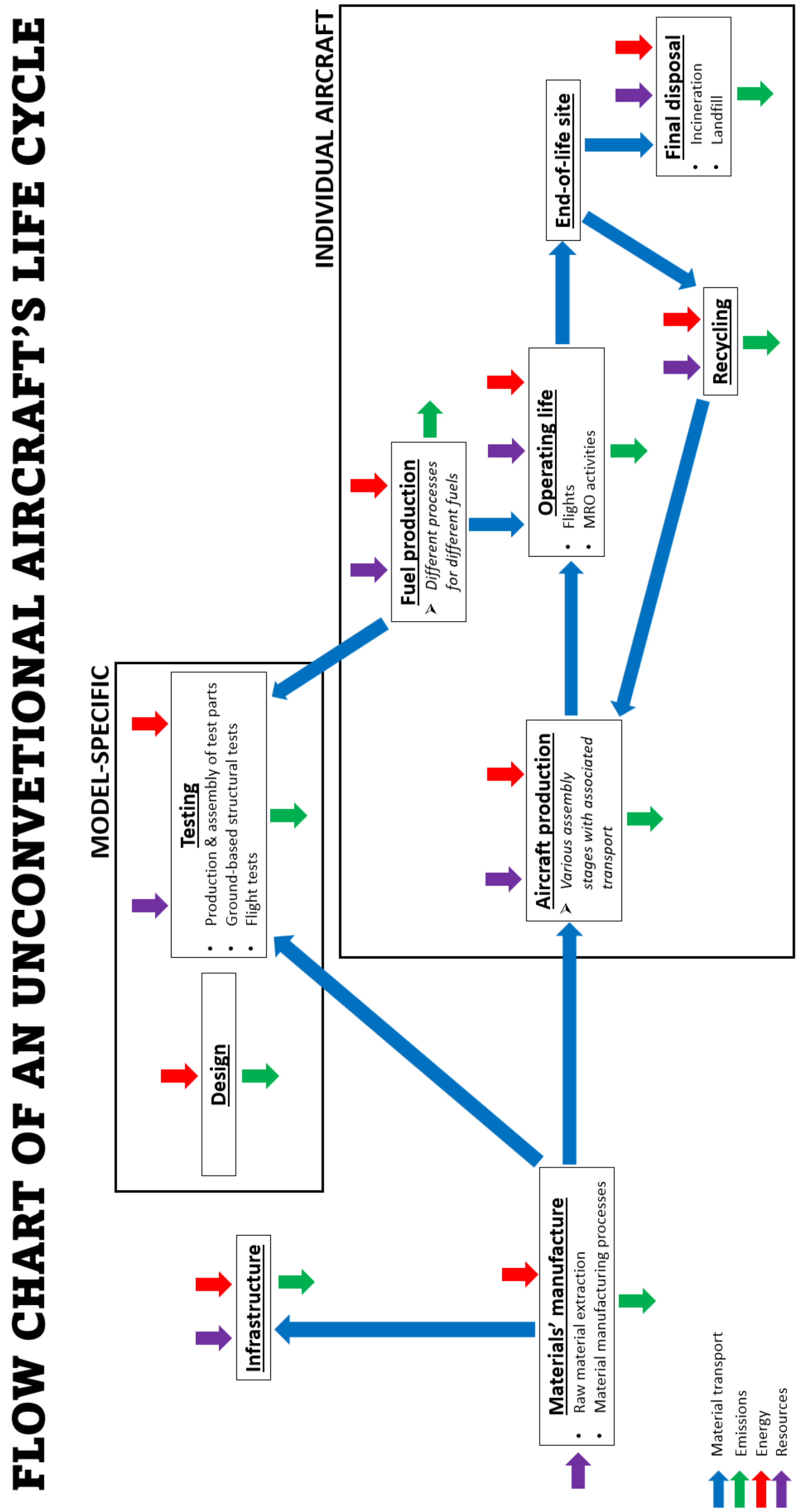

Figure 20. Flow chart of an unconventional aircraft's life cycle.

Two elements are left out of this division: infrastructure, which can serve multiple models, and materials' manufacture, whose output products can be used for a commercial aircraft's production, test components or test aircrafts, or infrastructure construction.

A couple more observations should be made here. Within aircraft production, there can be several assembly levels, with transport occurring from one stage to the next. Also, the transport arrow between aircraft production and operating life represents the delivery flight, and should be modelled as such. Finally, it needs to be specified that, while energy generation and transport are not displayed as boxes in the flow chart, they constitute processes in their own right, and are treated as such in the subsequent inventory characterization.

4.2.3 Life cycle stages' modelling

At this point, it is possible to model and collect data on each process present in the previous section's diagram. Since the collection of primary data falls outside the scope of this thesis, information required for this step was retrieved from literature and digital databases listed throughout the text. The focus was on free or available-to-students sources, those behind a paywall were excluded.

It should be noted that, while the data presented was selected to provide plausible estimations, obtaining and employing data specific for the case at hand might yield results that are significantly different, as well as more relevant.

Below, life cycle phases are discussed one by one.

Design

The main impacts of this phase arise from energy consumption required to perform office work (Schäfer, 2018). To calculate the amount of energy required by development processes, it is possible to use a generic formula similar to the following:

$$E^{de} = E^{*,de} * t^{de}$$

Where:

- $E^{*,de}$ is the time-specific (e.g. yearly) energy consumption required for design processes
- t^{de} is the total time (e.g. in years) required for design processes, which can include correction factors (read more below)

The term $E^{*,de}$ can be obtained differently according to data available: for instance, the Odyssee-Mure project[2] provides yearly energy consumption data by European country, both per employee and per m^2 of office space, which should then be multiplied by office size.

As for the time required, it is possible to start from figures valid for conventional aircrafts. When dealing with unconventional concepts, though, a higher resource demand for development processes is expectable. Kossarev et al. (2023) apply a 1.3 correction factor to development time for the design of a hydrogen-powered CTW aircraft. Other corrections should be applied to account both for configuration design and integration between airframe and propulsion system: as depicted in the figure below, the same concept can differ significantly depending on how it is fuelled.

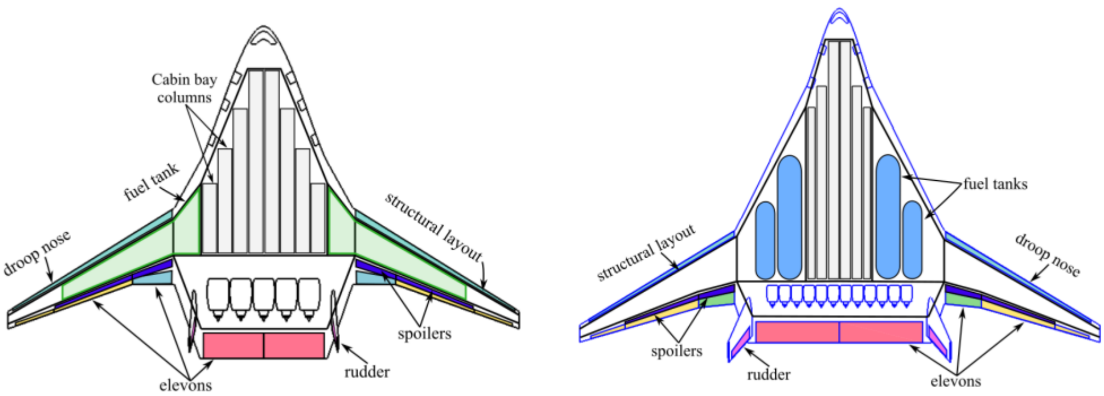

Figure 21. Differences in BWB configuration fuelled by kerosene (to the left) and by liquid hydrogen (to the right), as in Karpuk et al. (2023).

No correction factor specific to BWB was found in literature, mainly because of the lack of LCA studies on this concept. However, due to the highly integrated nature of its design, it is likely to require substantially longer than conventional configurations (Chudoba, 2019).

Testing

First of all, testing requires production and assembly of test parts, which can be modeled similarly to aircraft production, in terms of materials and energy needed.

[2] A project coordinated by the Agency for Ecological Transition (ADEME) and supported by the European Commission.

Two types of tests are then performed: ground-based and flight tests. The first can involve structural loads, vibration, extreme conditions (e.g. of temperature and pressure), engine and avionics tests, as well as various analyses, such as simulations performed with a computational fluid dynamics (CFD) software, and even the use of a flight simulator (Pavlock, 2013). Energy consumption for the use of electrically-powered equipment, which is the main responsible of said tests' impact, can be inventoried as follows:

$$E^{gbt} = \sum_k E_k^{*,gbt} * t_k^{gbt}$$

Where:

- E^{gbt} is the amount of energy, in MJ, required for ground-based tests
- $E_k^{*,gbt}$ is the time-specific energy consumption required for ground-based test *k*
- t_k^{gbt} is the time required for ground-based test *k*

Since each type of test should be considered separately, it is preferrable to consider time-related parameters in hours rather than in years, differently to what suggested in the design phase.

On the other hand, flight tests can be modelled similarly to operation flights, described later. Airbus (2017) reported a total of 1'600 flight hours for the testing of its A350-1000 model.

In the case of unconventional aircraft concepts, correction factors could be applied, as suggested for the design phase, to account for extra testing needed due to the low familiarity with the new concept's real-life behaviour. For instance, a BWB aircraft might require additional structural testing due to its highly integrated configuration and distinctive materials, as well as extra aerodynamic and flight tests to evaluate its challenging in-flight behaviour.

Materials' manufacture

A simple way to account for the production of materials necessary for an aircraft's construction is through the use of generic inventory data on energy, resources and emissions, covering both raw material extraction and subsequent manufacture processes, normalized for unit of mass of material produced (examples in Annex A). Normalized values should then be multiplied by the amount of material required for the whole aircraft.

The first step is to identify materials of interest. Typical structural materials in civil aviation are aluminium, carbon-fiber-reinforced plastics (CFRP), steel, titanium and nickel (Schäfer, 2018). Avionics' materials, which include scarce resources such as some semiconductors (Encyclopaedia Britannica, 2023; Henckens, 2021), must also be inventoried.

Adopting novel aircraft concepts can entail the use of additional materials. In-aircraft storage of hydrogen requires tanks: structural materials are similar to those cited above, but insulation layers can involve the use of foams, perlites and aerogels (Kossarev et al., 2023). Different composites materials are being investigated to meet the particular demands of the BWB concept (Chen, et al., 2019), as they should constitute most of this configuration's structure (Liebeck, 2004); Karpuk et al. (2023) characterizes hybrid materials based on carbon nanotubes and nanofibers as being the most promising for this purpose. Also, elements like lithium and sulphur can be present in batteries of hybrid-electric aircrafts (Ribeiro et al., 2020).

After having identified materials, quantities required for each need to be calculated. Design environments can provide data on aircraft's weight and composition (Schäfer, 2018; Kossarev et al., 2023), which should then be multiplied to obtain amounts of each material. Table 6 offers an example of material composition of a CTW aircraft, alternatively using conventional jet fuel or hydrogen for combustion.

Table 6 : Material mass percentage composition of a CTW aircraft, employing either conventional jet fuel or hydrogen for propulsion (Kossarev et al., 2023).

Fuel	**Aluminium [%]**	**Steel [%]**	**Composites [%]**	**Titanium [%]**	**Miscellaneous [%]**
Conventional jet fuel	53.5	19.6	11.6	8.9	6.4
Hydrogen (with CFRP tank)	55.7	16.2	12.0	7.7	8.4

Once amounts of all the materials are available, the following equations can be used to calculate this phase's contribution to LCI:

$$m_{j,in/out}^{mm} = \sum_k m_{j,k,in/out}^{*,mm} * m_k^{mm}$$

$$E^{mm} = \sum_k E_k^{*,mm} * m_k^{mm}$$

Where:

- $m_{j,in/out}^{mm}$ is the mass flow of resource or emission *j* for materials' manufacture
- $m_{j,k,in/out}^{*,mm}$ is the normalized amount of resource or emission *j*, required or generated to produce 1 kg of material *k*
- m_k^{mm} is the amount of material *k* to be produced, in kg
- E^{mm} is the total amount of energy required for materials' manufacture
- $E_k^{*,mm}$ is the specific amount of energy required to produce 1 kg of material *k*

As a final remark, if an assessment of the stress on natural resources is also desired, it is important to distinguish between primary raw materials and recycled ones used in this phase.

Aircraft production

In addition to materials coming from the previous step, aircraft production requires energy and transport between different assembly locations (Howe et al., 2013). Energy required for assembly can be calculated as follows:

$$E^{as} = \sum_k E^{*,as} * t_k^{as}$$

Where:

- E^{as} is the amount of energy, in MJ, required for assembly
- $E^{*,as}$ is the time-specific energy consumption required for assembly stage *k*
- t_k^{as} is the time required for assembly stage *k*

Schäfer (2018) suggests using values of energy consumption per employee to obtain $E^{*,as}$, as advised for the design phase, whereas it is preferrable to measure the time parameter in hour, as for ground-based testing. As discussed in Section 2.2, Airbus ('Production', s.d.) lists three stages of current CTW aircraft production. The first is manufacture of basic elements, like panels, pipes and shells, which is mostly outsourced to suppliers. Then, there is an intermediate step consisting in the assembly of five separate aircraft sections: wings, nose, forward section, center fuselage and rear section, or aft; Howe et al. (2013) also mentions engine and landing gear. Lastly, all sections are taken to a certain location where final assembly occurs.

Unconventional configurations clearly have the potential to affect the manufacturing process. While the complex shape of the BWB may pose design challenges (Liebeck, 2004), a study on manufacturing aspects of low-curvature panels for this aircraft concept suggested reduced labor requirement and costs for this process (Dubovikov et al., 2019); this might be due to BWB's highly integrated structure, which might eliminate the need for an intermediate assembly. A NASA project also produced an extensive report on the assembly of a multi-bay box for a hybrid wing body commercial airplane (Velicki et al., 2017).

In any case, the impact of aircraft manufacture tends to represent a very small portion of the total: Howe et al. (2013) report a value of 0.089% for the Airbus A320 over a 20-year period.

Fuel production

The process of fuel production entails the use of resources, energy consumption and the generation of emissions, which can be calculated by using the equations below:

$$m_{j,in/out}^{fp} = \sum_k m_k * m_{j,k,in/out}^{*,fp} * n_{flights} * t_{aircraft}$$

$$E^{fp} = \sum_k m_k * E_k^{*,fp} * n_{flights} * t_{aircraft}$$

Where:

- $m_{j,in/out}^{fp}$ is the mass flow of resource or emission *j* for fuel production
- m_k is the amount of fuel, in kg, consumed in a single flight by propulsion system *k* (same as in the operation phase)
- $m_{j,k,in/out}^{*,fp}$ is the normalized amount of resource or emission *j*, required or generated to produce 1 kg of fuel *k*
- $n_{flights}$ is the aircraft's number of yearly flights over the chosen route (same as in the operation phase)
- $t_{aircraft}$ refers to the aircraft's service life, measured in years (same as in the operation phase)

- E^{fp} is the total amount of energy required for fuel production
- $E_k^{*,fp}$ is the specific amount of energy required to produce 1 kg of fuel k

Normalized values, $m_{j,k,in/out}^{*,fp}$ and $E_k^{*,fp}$, depend on the type of fuel, an overview of which is provided in Section 3.1 under 'Propulsion systems', and on the process employed for its production. Examples of such values for selected processes are provided in Annex A.

Carbon dioxide captured through biomass growth or DAC, used in the production of fuel, should also be credited to the system during this phase. Similarly, land used for biomass growth should be accounted for here. Zhao et al. (2021) tried to estimate this parameter for 17 SAF production pathways.

Finally, in case of electric propulsion, the inventory of the energy required to charge the system can be modelled as proposed for 'Energy generation', later in this section.

Operating life

An airplane's operating life involves flights and MRO activities, which are treated separately below.

Flights

To calculate the inventory of flights during operation, it is best to start by modelling a single flight; to do so, a route should first be chosen. Cui et al. (2023) suggest dividing the flight into segments, using ICAO's landing and takeoff (LTO) cycle, as shown in the image below, plus climb, cruise and descent (CCD).

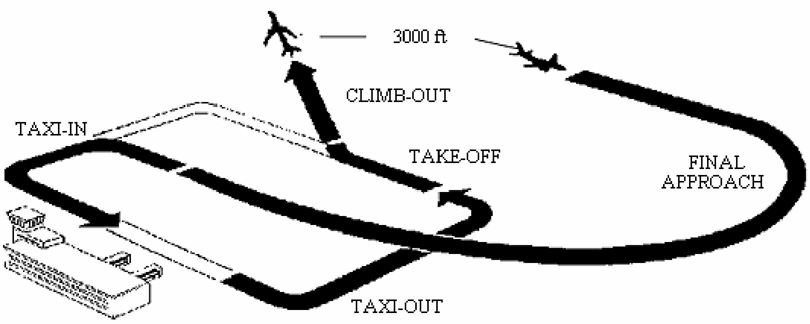

Figure 22. ICAO's LTO cycle (Briceno & Mavris, 2002).

Fuel consumption also needs to be determined: design environments like UNICADO can have a built-in capability to perform such calculation (Schäfer, 2018). Bicer & Dincer (2017) report values of 0.21 and 0.07 kg of fuel per tonne-km for Jet A and hydrogen respectively, which might be used in the absence of more precise data. Then, in order to obtain single flight's emissions, fuel consumption must be multiplied by emission indexes (EI), which depend on propulsion system and flight conditions. The 'ICAO Aircraft Engine Emissions Databank' is an Excel database, prepared by EASA and available on its website (EASA, s.d.), containing EIs of selected emissions at ground level[3] for conventional jet fuel, which are differentiated according to LTO cycle segments and can be used as a reference. However, this database only considers fixed values of thrust settings, which influence EIs and, in reality, can vary from those applied by EASA in some cases. Therefore, to obtain precise estimations of EIs, it is necessary to use calculation methods like the 'P3T3' or Boeing's 'Fuel Flow Method2', which apply corrections to ground-level EIs based on combustion parameters (DuBois & Paynter, 2006), and can also be used to calculate EIs for CCD conditions. Additional emission data can be retrieved from NASA's 'Alternative Aviation Fuel Experiment (AAFEX)' project's report (Anderson et al., 2011). Table 7 provides EI values for conventional jet fuel combustion, averaged from all flight conditions.

Table 7 : EIs for kerosene combustion, in g/kg fuel (Koch, 2013).

	CO_2	H_2O	NO_x	CO	SO_x	UHC	Soot
Emission index (g/kg kerosene)	3'160	1'240	14	3	0.8	0.4	0.025

Adjustments should be applied when SAF is considered: Kossarev et al. (2023), for instance, lists reductions in CO_2, NO_x and soot emissions and an increase in H_2O emissions.

The same authors provide EI estimations for hydrogen combustion, displayed in the table below.

[3] Altitude is not taken into account.

Table 8 : Emission indexes for hydrogen combustion according to Kossarev et al. (2023).

	H_2O	O_2	NO_2[4]
Emission index (g/kg H_2)	8.94	7.94	3.14

Electric engines do not produce in-use emissions (Oğuz, 2023). Given the rising interest in the matter, Su-ungkavatin et al. (2023) suggests a method to deal with hybrid propulsion systems in LCA, consisting in splitting the quantities of energy provided by each system.

As discussed in Section 3.1, to obtain an accurate evaluation of impacts, it is important to take emission altitude into account. During this phase, this parameter should be recorded alongside emission generation. For instance, flight altitude can be divided into range classes, taking the middle point as representative for the class (e.g. 31'000 ft for the range 30'000-32'000 ft), and emissions quantities should be calculated for each class.

Finally, as in fuel production, single-flight emissions have to be multiplied by the aircraft's total amount of flights, which can be obtained by multiplying the yearly flights by the aircraft's life span, as in the following equation:

$$m_{j,h,out}^{olf} = \sum_k m_{k,h} * EI_{j,k} * n_{flights} * t_{aircraft}$$

Where:

- $m_{j,h,out}^{olf}$ is the mass of emissions of substance *j*, at altitude *h*, caused by the aircraft's operating life's flights throughout its entire service life
- m_k is the amount of fuel, in kg, consumed at altitude *h* in a single flight by propulsion system *k* (same as in the fuel production phase)
- $EI_{j,k}$ is the emission index of substance *j* for propulsion system *k*, usually provided in g of substance *j* over kg of fuel
- $n_{flights}$ is the aircraft's number of yearly flights over the chosen route (same as in the fuel production phase)
- $t_{aircraft}$ refers to the aircraft's service life, measured in years

[4] EI valid during cruise, ranges between 1.10-8.02 for other flight conditions. The authors consider this as being a conservative estimate.

The value assumed for $t_{aircraft}$ can have a considerable effect on LCA results, especially on the relative contribution of different life cycle phases. Howe et al. (2013) set this parameter to 20 years, a somewhat conservative estimate, while Airbus ('Operating life', s.d.) claims that an aircraft's service life can last over 30 years. The average age of aircrafts retired in 2019 was around 22.8 years (Statista Research Department, 2023). In unconventional aircraft configurations like the BWB, operating life's duration might be negatively affected due to higher loads acting on the airframe.

If needed, it is possible to calculate total emissions for operation flights by simply adding up quantities at different altitudes:

$$m_{j,out}^{olf} = \sum_h m_{j,h,out}^{olf}$$

Where:

- $m_{j,out}^{olf}$ is the mass of emissions of substance *j* caused by the aircraft's operating life's flights throughout its entire service life

MRO activities

These activities mainly involve utilization of spare parts, whose production is modelled in previous phases, and energy consumption (Schäfer, 2018), to be calculated with the formula below:

$$E^{mro} = E^{*,mro} * t^{mro} * n_{mro} * t_{aircraft}$$

Where:

- E^{mro} is the energy, in MJ, required for MRO activities
- $E^{*,mro}$ is the hourly energy consumption for MRO activities
- t^{mro} is the duration, in hours, of a single MRO procedure
- n_{mro} is the yearly number of MRO procedures performed on the aircraft
- $t_{aircraft}$ refers to the aircraft's service life, measured in years

Maintenance frequency is influenced by aircraft's characteristics and flights per year. For instance, compared to CTW, BWB aircrafts are subjected to higher loads (Shrivastav & Pandey, 2018), which can increase MRO's frequency: if the number of flights remains constant, a correction factor, to be applied to n_{mro} for conventional aircrafts, could be derived simply by the ratio between loads acting on BWB over those acting on CTW.

End-of-life

The process of aircraft decommissioning is illustrated in Figure 23. There are three possible pathways for aircraft parts at EoL: reuse, recycling or final disposal. Table 9 provides an example of proportions of different aircraft materials going to each disposal route, which can be multiplied by the amount of material present in the aircraft to obtain the quantities in unit of mass, necessary to perform inventory calculations. Transport can occur multiple times during the decommissioning phase, and disassembly and dismantling, which require energy consumption (Schäfer, 2018), also need to be considered.

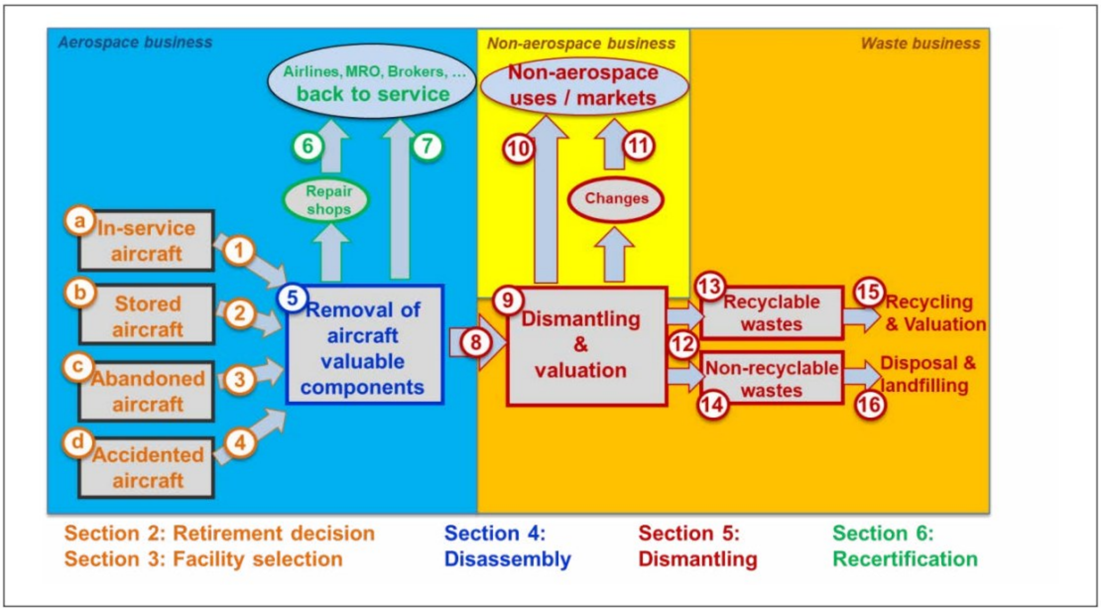

Figure 23. Scheme of an aircraft's decommissioning process (Elsayed et al., 2019).

Table 9 : Disposal scenarios for different aircraft materials, in mass percentage (adapted from Howe et al., 2013).

Material	Recycling	Incineration	Landfill
Aluminium [%]	75	0	25
CFRP [%]	0	50	50
Steel [%]	75	0	25
Titanium [%]	75	0	25
Rubber (tyres) [%]	75	0	25

As previously mentioned, there is a lack of EoL data specific to aircrafts, and extensive assumptions might be required to model this phase. For the same reason, considerations offered in this section are mainly qualitative.

Reuse and recycling

Practises of reuse and recycling contribute to minimize the stress on natural resources by reducing the need for virgin raw materials. However, they are convenient only when technically and economically feasible, and when their impacts are lower than those of primary raw material extraction; in fact, these practises entail energy consumption, and possibly additional resource use. When this last condition is met, and reused or secondary raw materials meet at least part of the market demand, credits can be awarded to the system (Joint Research Centre, Institute for Environment and Sustainability, 2010), in an amount equivalent to the savings. The ILCD handbook distinguishes between closed- and open-loop recycling, where the former refers to secondary materials being used to substitute primary materials in an earlier process of the same system, while the latter refers to secondary materials being modified before being reused in the same system, or even transferred to an external system. In order to avoid the need of modelling external systems, it is preferrable to consider a semi-closed loop instead of open-loop recycling, so as to assign credits the product system under study (Schäfer, 2018). Credits to the system due to recycling can be calculated as follows:

$$m_{j,in/out}^{re} = \sum_k (m_{j,k,in/out}^{*,re} - m_{j,k,in/out}^{*,mm}) * m_k^{re}$$

$$E^{re} = \sum_k (E_k^{*,re} - E_k^{*,mm}) * m_k^{re}$$

Where:

- $m_{j,in/out}^{re}$ is the mass flow of resource or emission *j* credited to the system due to recycling
- $m_{j,k,in/out}^{*,re}$ is the normalized amount of resource or emission *j*, required or generated to recycle 1 kg of material *k*
- $m_{j,k,in/out}^{*,mm}$ is the normalized amount of resource or emission *j*, required or generated to produce 1 kg of material *k* (same as in materials' manufacture)
- m_k^{re} is the amount of material *k* to be recycled, in kg
- E^{re} is the total amount of energy required for recycling

- $E_k^{*,re}$ is the specific amount of energy required to recycle 1 kg of material k
- $E_k^{*,mm}$ is the specific amount of energy required to produce 1 kg of material k (same as in materials' manufacture)

Each material can have its own specifities in the recycling process; Frees (2008), for example, proposes a framework for aluminium recycling, usually greatly advantageous compared to virgin raw material extraction, taking into account market mechanisms. On the other hand, composite materials like CFRP present more challenges for recycling (e.g. Wu et al., 2023), which could hinder the environmental performance of aircrafts that make broad use of such materials, like the BWB.

When considering unconventional aircraft concepts, plausible scenarios for recyclability should be crafted, pondering future developments in recycling technologies and aircraft EoL practises.

Final disposal

Final disposal of aircraft parts can involve incineration and landfilling (Elsayed, et al., 2019), both of which cause impacts of their own. Incineration's LCI includes air and water emissions, bottom and fly ash production with associated necessary treatment, and energy generation, which can be credited to the system as added value (Morselli et al., 2008). Landfill's environmental impacts are generated by gaseous emissions (mainly methane), leachate production and energy and fuel consumption associated with landfill operations (Obersteiner et al., 2007).

While impacts for general plant operation should be attributed to the product system through allocation procedures (e.g. by dividing the mass of EoL aircraft components sent to landfill or incineration by the total amount of waste treated there), in order to attain higher modelling accuracy, it might be possible to obtain emission values specific to the material to be treated.

Infrastructure

As discussed in Section 3.2, it has been suggested that airports should be included in aircraft's LCA. Greer et al. (2020) carried out a systematic review of literature on environmental sustainability of airports, discussing various aspects. However, despite it would be theoretically possible, through extensive use of assumptions, to try and assess an airport's life cycle impact, it could result being overly complicated and time consuming. Issues could arise in estimating the infrastructure's life span, or in allocation procedures (i.e. how many aircrafts does the airport serve), to name a couple. Additionally, a comprehensive airport LCA might not be of much value to a comparative assessment between concepts.

Within the scope of this thesis, it appears reasonable to consider only infrastructural changes directly related to the unconventional nature of the aircrafts under scrutiny. To make hydrogen available at an airport, for example, changes to the fuel supply system, as well as new storage and liquefaction structures, with associated energy consumption, might be required (Steer, 2023). Adjustments to airport infrastructure might also be necessary to accommodate different aircraft configuration (see Figure 24 for an example).

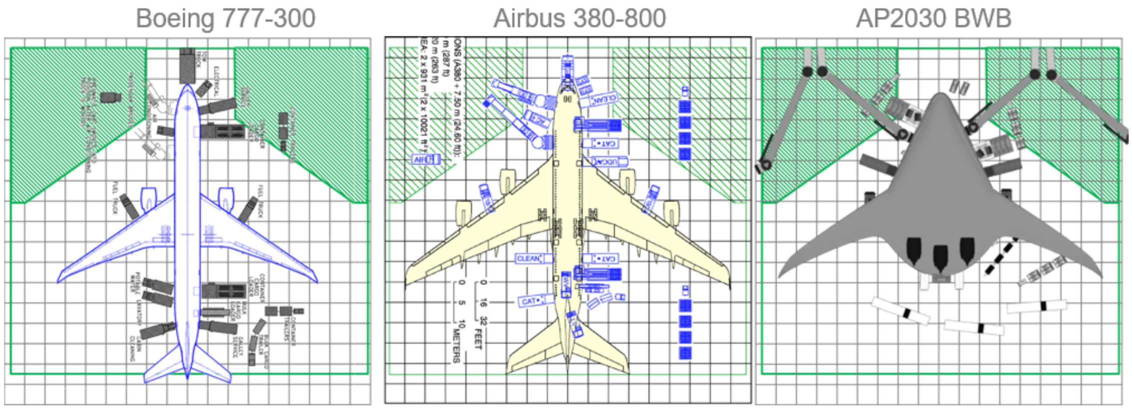

Figure 24. Two CTW aircrafts and a BWB at an airport gate (Pfeiffer, s.d.).

Energy generation

The generation of energy would deserve to be considered as a process itself, because, in addition to causing emissions and impacts, it can also require material inputs (such as fuels); extraction and production of these materials, which in turn consume energy, would then also need to be modeled. Therefore, the risk in using this conceptualization is to create an infinite loop. In order to avoid such short-circuiting of the system, a simplification is made: resources and impacts caused by energy generation are attributed to the process that consumes the energy. This solution allows, for example, to ascribe the impacts of energy consumption associated with hydrogen production to the fuel production phase itself, consequently granting the possibility to quantify how much of the impacts of such novel technology is shifted from airplane operation to fuel production, which is one of the issues mentioned above in the assessment of emerging aircraft technologies.[5]

The calculation of a process' energy flow's inventory is computed as follows: first, the quantity E^i is split using an energy mix, which gives information about the sources of energy. As an example, Germany's 2022 energy mix is illustrated in the chart below. Other national electricity mixes are available on the International Energy Agency (IEA) website.

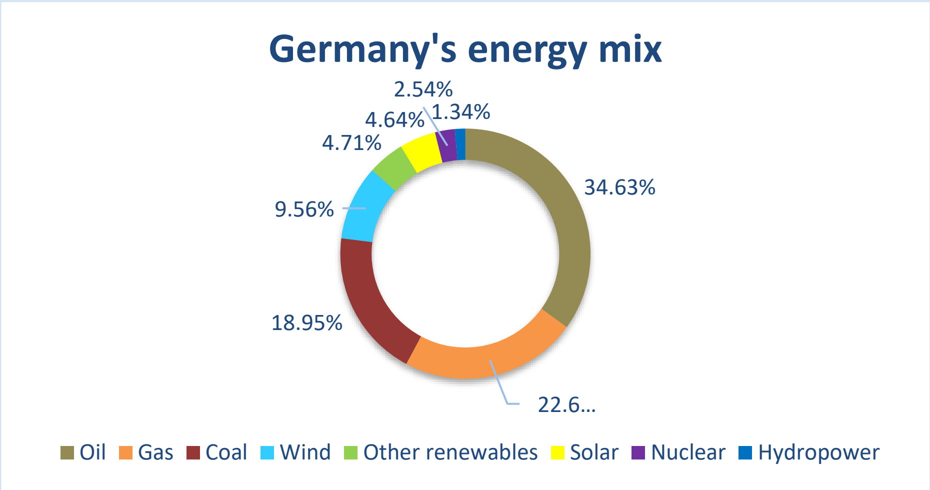

Figure 25. Germany's energy mix in 2022 (Ritchie et al., 2022).

The energy mix should be selected by the practitioner according to the intended goal (e.g. evaluating an aircraft's life cycle impact using only renewable energy), and it could also vary from one process to another.

After process energy is divided according to energy source, each split is used, together with the energy source's specific (i.e. normalized by an energy measurement unit) resources use and emissions, to calculate the total values due to energy generation for a certain process. Examples of inventories for different energy sources are provided in Annex A. The following formula represents the calculation to be performed:

$$m_{j,in/out}^{i,eg} = \sum_{j} \sum_{k} E^i * s_k * m_{j,k,in/out}^{*,eg}$$

[5] Notably, the power plant's whole life cycle was excluded from the scope of this methodology, including only the phase of actual energy generation in the calculations; however, other studies have highlighted issues with renewable energies installations that go beyond energy production itself (e.g. Galparsoro et al., 2022, for wind turbines; Vellini et al., 2017 for PV panels), which may need to be considered in a comprehensive impact assessment of passenger aviation's industry.

Where:

- $m_{j,in/out}^{i,eg}$ refers to the input or output mass flow of material j in process i due to energy generation
- s_k refers to the share of energy source k in a energy mix
- $m_{j,k,in/out}^{*,eg}$ refers to the specific (normalized) input or output mass flow of material j for energy source k

Transport

Transport of materials or parts can occur in-between processes several times throughout the life cycle of an aircraft, and different means of transport can be employed (i.e. road, rail, ship or freight aircraft). Assuming inventory data, normalized for weight carried and distance travelled, are available for each means of transport (some examples are provided in Annex A), it is possible to use the following formula to calculate fuel consumed and emissions produced for each transport process:

$$m_{j,in/out}^{tr,i-i'} = \frac{m^{tr,i-i'}}{payload} * m_{j,k,in/out}^{*,tr} * m^{tr,i-i'} * d^{tr,i-i'}$$

Where:

- $m_{j,in/out}^{tr,i-i'}$ refers to the input or output mass flow of material j due to transport from process i to process i'
- $m_{j,k,in/out}^{*,tr}$ refers to the specific (normalized) input or output mass flow of material j for transport mode k
- $m^{tr,i-i'}$ is the mass of components transported from process i to process i'
- $d^{tr,i-i'}$ is the distance covered in the transport from process i to process i'

The factor $\frac{m^{tr,i-i'}}{payload}$ can be used to solve allocation issues: it is a ratio between the mass of components of the aircraft to be transported over the total payload of the cargo vehicle, including materials or products that fall outside the aircraft's product system. If the cargo consists only of the individual aircraft's components, this factor can simply be set equal to 1.

Results from each transport operation should be added up to obtain the total of all transport processes.

4.2.4 Aggregation and normalization

The final step in LCI is to calculate total values of resource use and emissions. The following formula can be used:

$$m_{j,in/out} = \sum_i m^i_{j,in/out}$$

Where:

- $m_{j,in/out}$ is the total mass flow of resource or emission *j* over the life cycle of the aircraft concept considered
- $m^i_{j,in/out}$ is the mass flow of resource or emission *j* for process *i*

It can be interesting to analyze total values of emissions; however, during impact assessment, in-flight emissions should be considered separately from the rest. Also, the following quantity should be calculated:

$$m'_{j,in/out} = m_{j,in/out} - m^{olf}_{j,out}$$

Where $m'_{j,in/out}$ is the total mass flow of resource or emission *j* over the considered aircraft concept's life cycle, excluding operating life flights.

To allow comparison of inventory results between different aircraft concepts concepts, each inventory item should be normalized by passenger kilometer. To this aim, $m_{j,in/out}$ should be divided by the following quantity:

$$pk = n_{passengers} * n_{flights} * t_{aircraft} * d_{flight}$$

Where:

- pk is the total number of passenger kilometers
- $n_{passengers}$ is the number of passengers per flight
- $n_{flights}$ is the aircraft's number of yearly flights over the chosen route (same as in the previous section)
- $t_{aircraft}$ refers to the aircraft's service life, measured in years (same as in the previous section)
- d_{flight} is the distance covered by the aircraft in one flight , in km

4.3 Impact assessment

Once the inventory phase is complete, it is possible to proceed with impact assessment. As already mentioned in Section 2.3, the ReCiPe model was identified as being the most employed in aviation LCA studies for this purpose (Keiser et al., 2023); hence, it was the chosen methodology here.

ReCiPe is an LCIA method first developed in 2008 through a cooperation between the Netherlands' National Institute for Public Health and the Environment, Radboud University Nijmegen, Leiden University and PRé Sustainability (PRé Sustainability, 2016). Here, the 2016 version is adopted: it consists of 18 midpoint and 3 endpoint categories, connected by damage pathways as depicted in Figure 26.

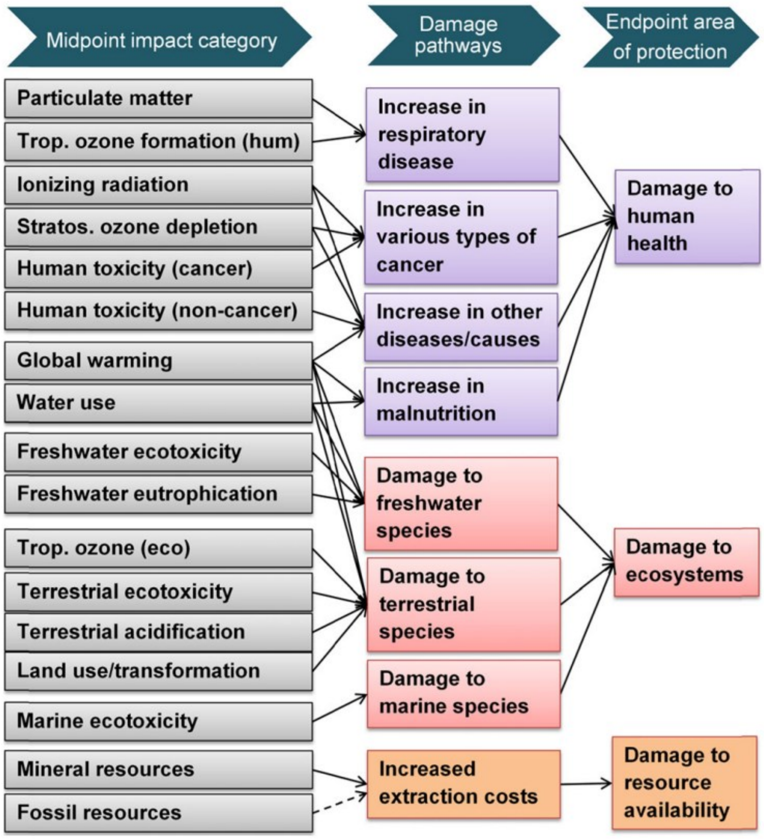

Figure 26. ReCiPe's midpoint and endpoint categories and how they are connected (Huijbregts et al., 2017).

Midpoint categories are characterized by indicators and units to quantify impact, listed in the table below.

Table 10 : ReCiPe's midpoint categories with related indicators and units (adapted from Huijbregts et al., 2017).

Midpoint impact category	Indicator	Unit
Climate change	Infrared radiative forcing	kg CO_2-eq to air
Ozone depletion	Stratospheric ozone decrease	kg CFC-11-eq to air
Ionising radiation	Absorbed dose increase	kBq Co-60-eq to air
Fine particulate matter formation	PM2.5 population intake increase	kg PM2.5-eq to air
Photochemical oxidant formation: terrestrial ecosystems	Tropospheric ozone increase	kg NO_x-eq to air
Photochemical oxidant formation: human health	Tropospheric ozone population intake increase	kg NO_x-eq to air
Terrestrial acidification	Proton increase in natural soils	kg SO_2-eq to air
Freshwater eutrophication	Phosphorous increase in freshwater	kg P-eq to freshwater
Human toxicity: cancer	Risk increase of cancer disease incidence	kg 1,4-DCB-eq to urban air
Human toxicity: non-cancer	Risk increase of non-cancer disease incidence	kg 1,4-DCB-eq to urban air
Terrestrial ecotoxicity	Hazard-weighted increase in natural soils	kg 1,4-DCB-eq to industrial soil
Freshwater ecotoxicity	Hazard-weighted increase in freshwaters	kg 1,4-DCB-eq to freshwater
Marine ecotoxicity	Hazard-weighted increase in marine water	kg 1,4-DCB-eq to marine water
Land use	Occupation and time-integrated land transformation	m^2*year annual cropland-eq
Water use	Increase of water consumed	m^3 water-eq consumed
Mineral resource scarcity	Increase of ore extracted	kg Cu-eq
Fossil resource scarcity	Upper heating value	kg oil-eq

Characterization factors are used to calculate midpoint indicators, converting values of different inventoried substances into category-specific units. The calculation to be performed for a generic midpoint indicator is the following:

$$MI_k = m'_{j,in/out} * CF_{j,k}' + \sum_h m_{j,h,out}^{olf} * CF_{j,h,k}'$$

Where:

- MI_k is the value of midpoint indicator *k*
- $m'_{j,in/out}$ is the total mass flow of resource or emission *j* over the considered aircraft concept's life cycle, excluding operating life flights
- $CF_{j,k}'$ is the inventory-to-midpoint characterization factor for resource or emission *j* and indicator *k*
- $m_{j,h,out}^{olf}$ is the mass of emissions of substance *j*, at altitude *h*, caused by the aircraft's operating life's flights throughout its entire service life
- $CF_{j,h,k}'$ is the inventory-to-midpoint characterization factor for emission *j* at altitude h, and indicator *k*

General characterization factors ($CF'_{j,k}$) are provided in the method's report according to three different approaches, individualist, hierarchist and egalitarian, which are increasingly conservative (Huijbregts et al., 2017). These factors do not consider emission altitude, which, as already discussed, influences impacts. Therefore, characterization factors of in-flight emissions ($CF'_{j,h,k}$) should be modified, mainly for the 'Climate Change' category: Schwartz Dallara (2011) provides factors to correct aircraft emissions' radiative forcing for altitude (see figure below); the corrected values should then be divided by CO_2's radiative forcing value to obtain characterization factors, in kg of CO_2 equivalent over kg of emissions, for a certain chemical species at a given altitude.

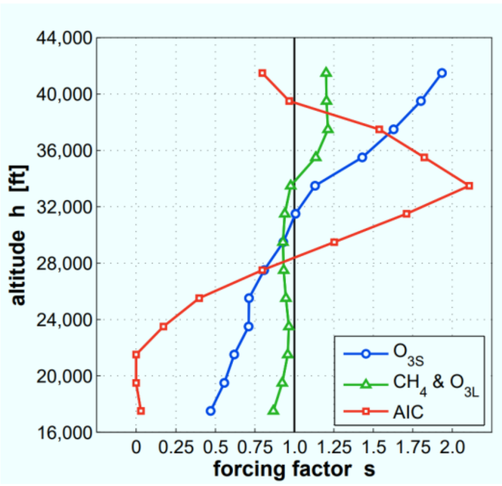

Figure 27. Radiative forcing factors based on emission altitude (Schwartz Dallara, 2011).

Research on emission altitude’s effect on other impact categories has not been identified; hence, $CF'_{j,h,k} = CF_{j,k}'$ for categories other than ‘Climate Change’.

Damage pathways connect midpoint to endpoint categories through further characterization factors, also described in the aforementioned report, as in the equation below:

$$EndI = \sum_k MI_k * CF_k''$$

Where:

- $EndI$ is the value of one of the endpoint indicators
- MI_k is the value of midpoint indicator *k*
- CF_k'' is the midpoint-to-endpoint characterization factor for midpoint indicator *k*

Endpoint categories are listed in Table 10, together with the units used to measure them.

Table 11 : ReCiPe's endpoint categories with related units (adapted from (Huijbregts et al., 2017).

Endpoint category	Unit
Damage to human health	Disability-adjusted loss of life years
Damage to ecosystem quality	Time-integrated species loss
Damage to resource availability	Surplus cost

Midpoint and endpoint indicator values can also be normalized by the selected functional unit, simply by dividing total values, as calculated above, by the factor pk, defined in Section 4.2.4.

4.4 Interpretation of results

The final step in an LCA is to interpret results. A possible approach on how to perform this procedure in the field of aviation is discussed below, with data from UNICADO’s standard simulation used to exemplify informative graphical representations.

The first step is to observe inventory results, such as emissions produced, both by process and in total, which can give an idea of the respective weights of different phases and of the overall magnitude of the defined system product.

Mass quantities of chemical species, however, are not enough to assess an aircraft's impact, which is why impact indicators should be evaluated next. Figure 29 depicts effects of different emissions on temperature in the UNICADO simulation: it is possible to note that aircraft-induced cloudiness (AIC) and short-term ozone increase ($O_{3,s}$) exert their impact in a limited amount of time and have the highest shares of the total, while CO_2 is also responsible for a significant portion, but keeps exerting its impact for hundreds of years; additionally, decreases in methane and long-term ozone ($O_{3,l}$) concentrations, both influence by NO_x emissions, actually have a cooling effect.

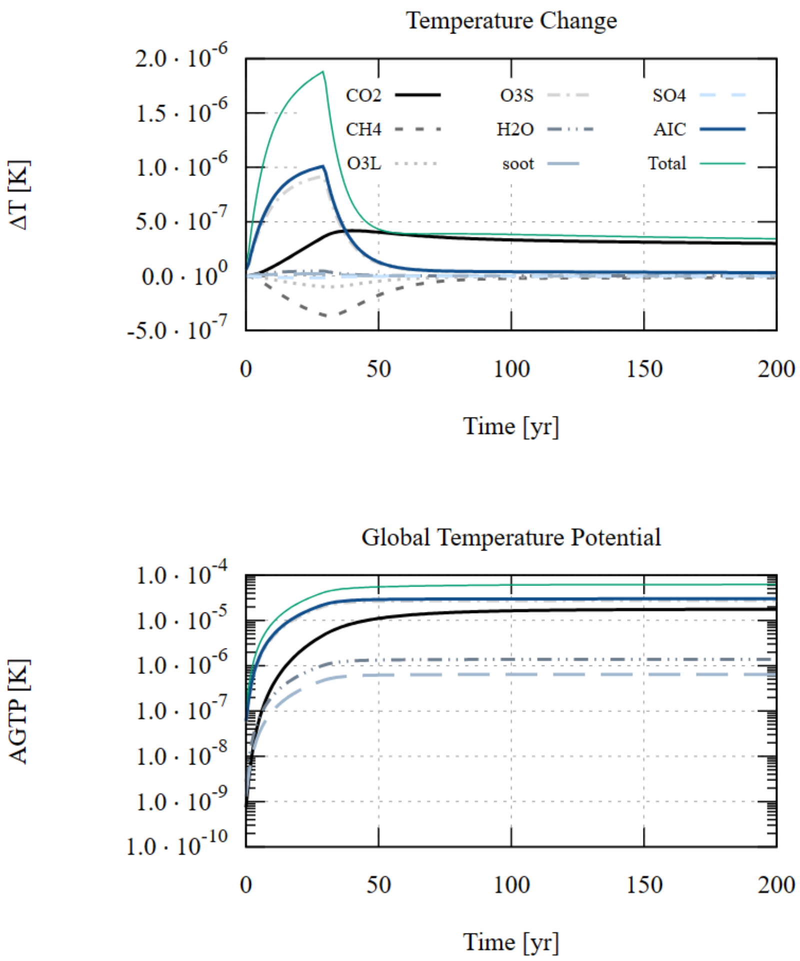

Figure 28. Temperature change and global temperature potential for different emissions in UNICADO's standard simulation.

Impacts can also be analyzed by life cycle phase. Figure 30, for instance, shows relative contributions of different aircraft's life cycle phases to global warming potential over a 100-year period (GWP 100), in a logarithmic scale: operation is by far the one with the highest climate impact, with development having a sizable contribution of around 5% of the total. Neither production nor EoL react 0.1%, with the latter actually providing credits to the system, possible due to the added value of secondary raw materials obtained from recycling.

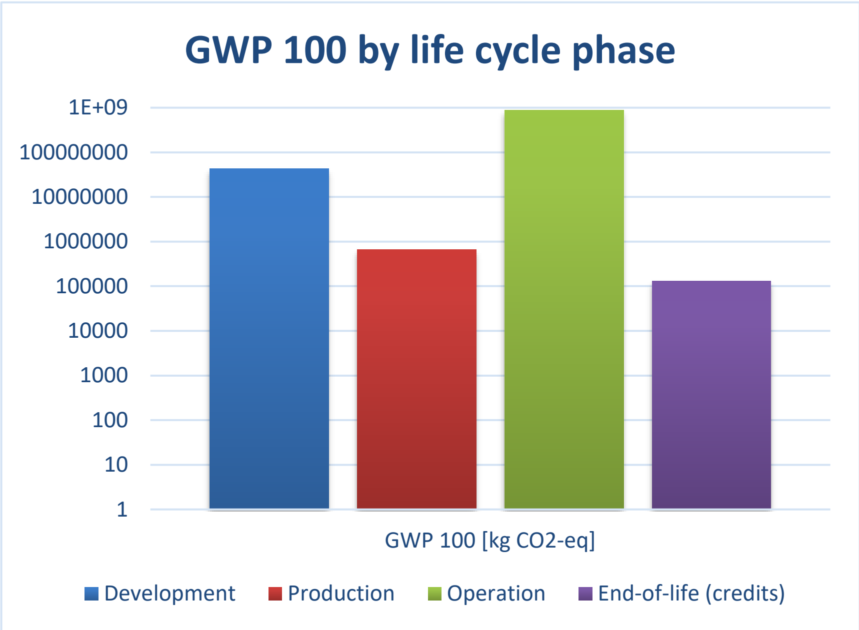

Figure 29. UNICADO's standard simulation's total GWP 100 by aircraft's life cycle phases, in logarithmic scale.

The same analysis can be applied to other impact categories, both at midpoint and endpoint, to identify hotspots throughout the life cycle with and check for impact shifting (e.g. reduced in-flight emissions versus higher impacts of fuel production).

Moreover, in order to have a unitary value to facilitate comparison, indicators can be created: inventory items or impact categories of interest should be included, with higher weights assigned to those who need to be prioritized. A selection of midpoint categories, such as climate impact, air quality, land use, mineral and fossil resources scarcity, can be particularly relevant in environmental assessment and comparison of different aircraft concepts. Endpoint categories can offer extremely comprehensive results, though they may be better apt to comparing products that cause impacts on different categories to one another.

5 The UNICADO design environment

UNICADO, which stand for university conceptual aircraft design and optimization, is a project which aims at joining competencies from different German universities to develop an environment for aircraft conceptual design, to be viable long-term (ILR, s.d.). The resulting software is derived from RTWH Aachen University's multidisciplinary integrated conceptual aircraft design and optimization (MI-CADO), it is developed in C++ and it comprises stand-alone modules representing different aircraft design aspects, whose parameters are exchange via an XLM file (Zimmnau et al., 2023). The figure below depicts UNICADO's modules and design procedure.

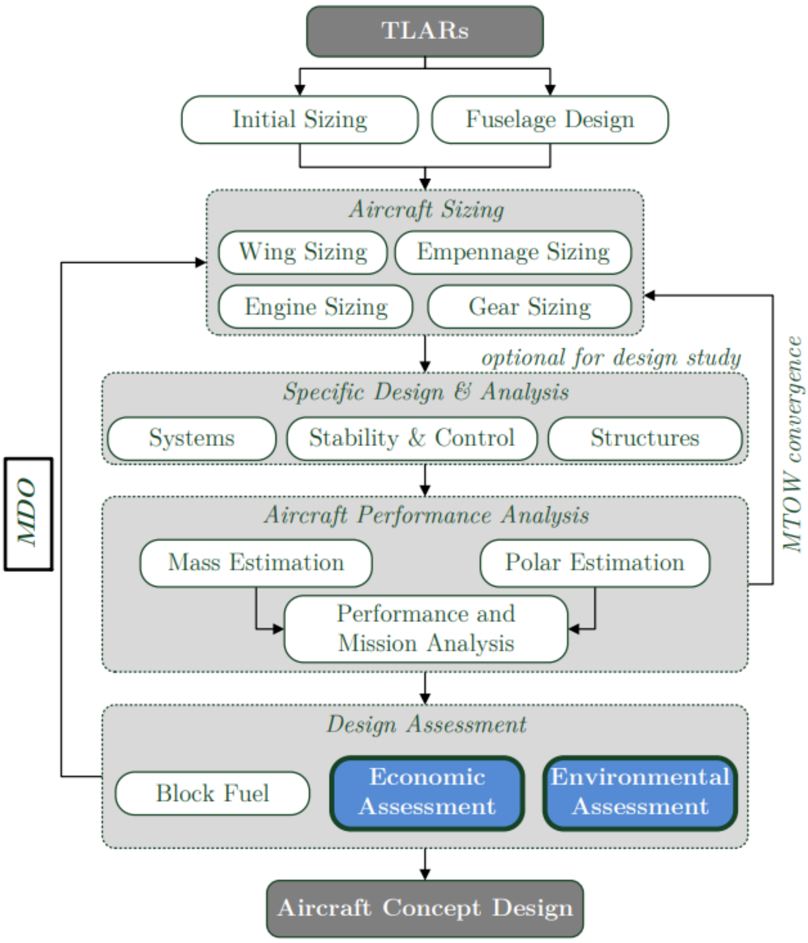

Figure 30. Overview of the design algorithm implemented in UNICADO (Schäfer, 2018).

5.1 LCA in UNICADO

As it is possible to see in Figure 31, UNICADO's design procedure includes an environmental assessment module, which is schematically represented in the image below.

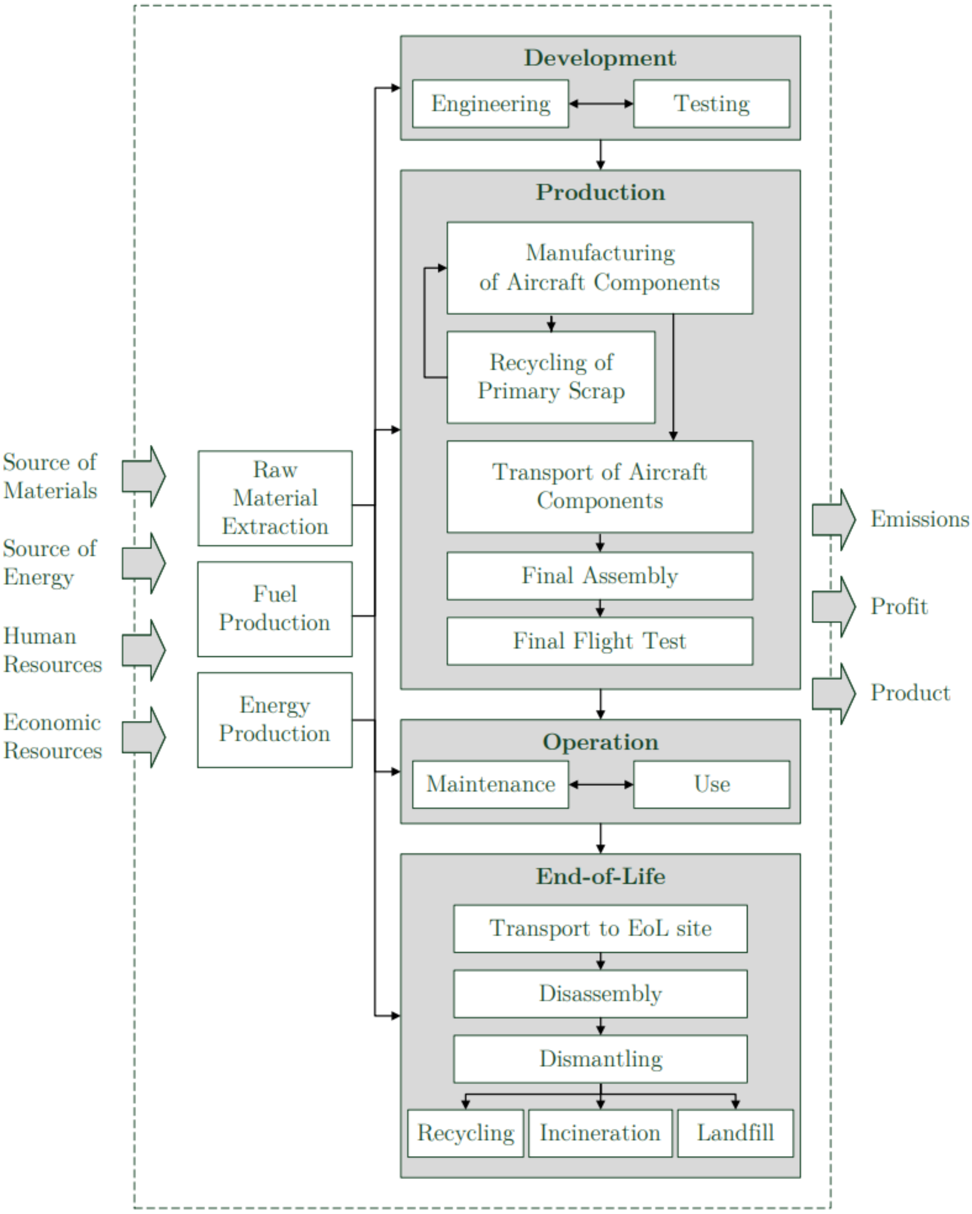

Figure 31. System boundaries for LCA in UNICADO (Schäfer, 2018).

Raw materials, fuels and energy used, as well as emissions generated, are computed for the aircraft's life cycle, including development, production, operation and EoL phases, and the supporting processes of raw material extraction, fuel and energy production. Results are then translated into three impact categories: global warming, air quality and cumulative energy demand. A full description of the module is present in Schäfer (2018).

The procedure implemented in UNICADO is tailored to conventional aircrafts; hence, it needs adjustments to enable assessment of non-conventional concepts.

5.2 Integration of the developed model

Table 13 below describes synthetically how individual processes are modelled in UNICADO's LCA module, and discusses the potential integration of the framework developed for unconventional aircrafts in this theses, providing some examples.

Table 12 : Implementation of aircraft's life cycle phases in UNICADO's LCA and adjustments for unconventional aircraft concepts, based on the developed methodology.

Life cycle phase	Implementation in UNICADO	Adjustments for unconventional aircrafts
Design	Energy demand for electricity and heating is calculated starting from consumption per employee.	Correction factors can be applied to account for additional development time required for novel concepts.
Testing	Resources for the manufacture of test parts, together with energy and fuels required for testing procedures, are inventoried. Wind tunnel tests, structure tests, system tests, ground tests, engine tests and flight tests are considered.	Similarly to the design phase, correction factors can be applied.
Aircraft production	Resources and emissions for manufacture of structural materials, including aluminium, CFRP, steel, titanium, nickel and epoxy resin, are calculated. Quantities of each material are determined	Additional materials should be considered: • Structural materials for unconventional aircrafts, such as composites for

	by aircraft composition, computed in separate modules, taking into account the recycling of primary scraps. Energy for manufacture and assembly, transport and the final flight test are also considered here.	the BWB configuration or foams for the insulation of hydrogen tanks • Materials for avionics, such as semiconductors • Materials for batteries, which are appealing for hybrid electric propulsion Variations in aircraft composition and manufacture process should be taken into account.
Fuel production	Energy production and emissions are calculated for the production of conventional kerosene, which is assumed to fuel the aircraft to be designed.	Data on production of alternative fuels, particularly SAF and hydrogen, should be added. To increase modelling precision, different production pathways for a given fuel (e.g. steam reforming and electrolysis for hydrogen) might be included, as this choice can influence subsequent impacts.
Operation	Emissions due to fuel burn during a flight are calculated starting from fuel consumption, obtained through the mission analysis tool, and emission indexes. Energy consumption and manufacture of spare parts for maintenance purposes are also attributed to this phase.	Emission indexes for alternative propulsion systems (e.g. fuel cells) should be added. Modifications to the maintenance routine should be applied where appropriate (e.g. increased frequency due to higher loads acting on BWB aircrafts).
End-of-life	Transport to the EoL site is modelled as a flight. Electrical energy for disassembly and dismantling is calculated. Lastly, scenarios for final disposal are determined for each materials, with different shares going to recycling, incineration or	Disposal scenarios, together with associated inventory data, for materials added in aircraft production should be determined.

	landfilling. Energy consumption and emissions are calculated for all of these options. Secondary raw materials obtained from recycling processes are considered as added value, which is credited to the system.	
Infrastructure	Not included in UNICADO.	Infrastructural aspects related to the unconventional nature of aircrafts, such as energy required for cryogenic storage of liquid hydrogen, should be modelled and added.
Energy generation	Data on emissions associated with energy production are taken from the GaBi software. More precisely, the European Union mix is considered for electricity, while natural gas is used for heating.	Since the choice of energy mix can strongly influence the results of an LCA, having the possibility to select it during aircraft conceptual design would enable more precise modelling of the desired scenario, as well as comparing the outcomes of using different mixes.
Impact assessment	Impact categories include global warming (measured through average temperature response, ATR), air quality (measured through an index, AQI, taking into account regulatory levels of several emissions), and cumulative energy demand, in kWh.	The framework proposed in this thesis suggests using the complete ReCiPe methodology for LCIA. However, it would be sufficient to include categories relevant to measure aspects specific to unconventional aircraft concepts, such as land use/change for biomass growth used in fuel production, and fossil resources, to quantify the reduction of stress on natural resources due to adopting non-fossil fuels.

The 'calculateEmissions' module, in the UNICADO software, contains code files that are responsible for the implementation of the environmental assessment module. Data flow between these files is schematized in Figure 33, and they are also listed and described individually in Table 14, together with suggestions on how to modify them to allow applying the assessment to unconventional aircrafts.

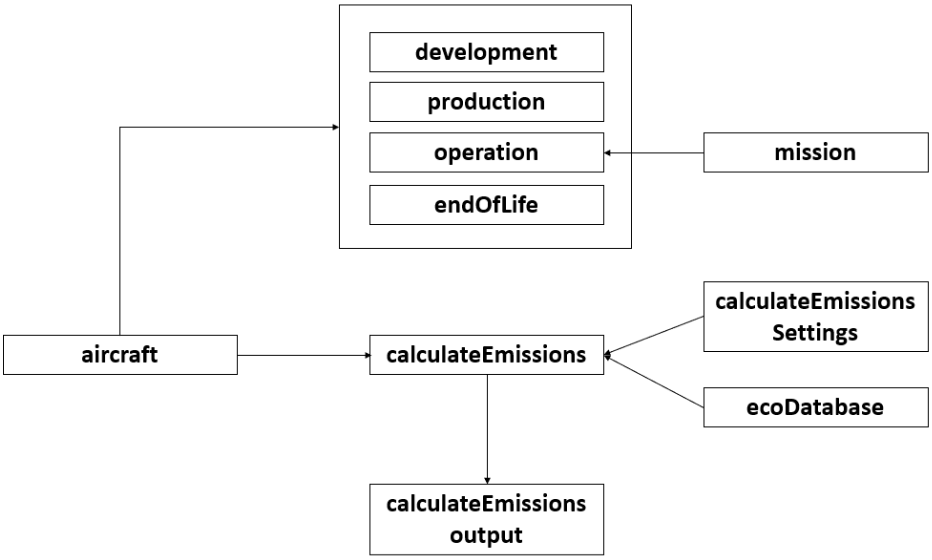

Figure 32 : Schematic representing data flow in UNICADO's calculateEmissions module.

Table 13 : Description of UNICADO's 'calculateEmissions' module's files and possible adjustments for unconventional aircrafts

File name	Function	Adjustments for unconventional aircrafts
aircraft	Reads CSR-02.xml to import aircraft parameters calculated in other modules.	Aircraft parameters would need to be modified or added in CSR-02.xml. For example, type of propulsion system and fuel used would have to be specified.
calculateEmissions	Sums emissions from all life cycle phases. Calculates climate impact and AQI.	The selection of propulsion system should be operated here. A loop should be added in the case of hybrid propulsion.

calculateEmissions Output	Displays results of the module's calculations, as explained in Section 4.4.	Results of added subprocesses and impact categories should be included.
calculateEmissions Settings	Reads calculateEmissions_config.xml. Defines: • Data set of emissions' forcing factors for different height steps • Phase-specific variables • Values of phase-specific parameters (e.g. aircraft material compositions for the production phase)	Values of phase-specific parameters of unconventional aircraft concepts should be added, and it should be possible for the user to select them
development **production** **operation** **endOfLife**	Calculate resources required for each phase, as described in Table 13.	Modify inventory input calculations as suggested in Table 13.
ecoDatabase	Calculates inventory for auxiliary processes (raw materials extraction, fuel production, disposal, energy generation, transport).	Data on unconventional aircrafts' materials (for raw material extraction, disposal) should be included. Calculations for alternative fuels' production pathways should be added. The possibility of choosing an energy mix should be implemented.
mission	Calculates EIs, fuel flow and emissions' masses.	Calculations for alternative propulsion systems should be added.

6 Conclusion

Air travel is currently deemed to be the means of transport with the highest emissions per passenger, and it is responsible for a significant share of worldwide emissions and global warming, alongside other environmental impacts. In an attempt to reduce these impacts, novel aircraft concepts are being studied, especially through the use of design environments such as UNICADO. In order to identify more sustainable solutions, the availability of robust decision making tools is of paramount importance. Life cycle assessment has been employed in literature to evaluate the environmental performance of aircrafts. The goal of this thesis was to adapt and extend current practises in the field of aviation LCA to the case of unconventional aircraft concepts. The resulting framework, presented in Chapter 4, examines the life cycle of an aircraft from cradle to grave, including associated fuel production and infrastructural aspects, to minimize the risk of impacts being shifted outside of the system. General formulae for inventory calculations are proposed, and differences with conventional aircrafts are pointed out, throughout the life cycle, for the cases of hydrogen propulsion systems and blended-wing body configuration, two of the most promising concepts to achieve the desired reduction. Measures to enable seamless comparability were suggested, including adopting the passenger km as functional unit, and the ReCiPe method for impact assessment.

In Chapter 5, possible integration of the proposed framework into the environmental assessment module of UNICADO was discussed. Despite a moderate amount of data specific to new aircraft technologies is provided here, this contribution is mainly qualitative, and the integration work would benefit from additional research and data gathering on selected aircraft concepts.

Lastly, it should be noted that, while the present work dealt with environmental aspects, a complete sustainability assessment needs to include the economic and social sides, too.

Annex

A GREET's inventory data

This annex provides examples of data on emissions and resources required for various life cycle processes, which can be used to perform the inventory analysis. The data comes from The Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model, a free software developed by the Argonne National Laboratory, which allows simulating LCI of various fuels and transport systems. Though aircrafts are not yet included as vehicles in the software's database, it still contains useful information on resource use and emissions of different processes. Results on emissions already include those caused by energy generation.

Once again, it should be noted that these are simply examples, which may differ significantly from data found in other sources, due to variations in measurement methodology or the specifics of the process considered.

Materials' manufacture

Emissions, water and energy consumption for the production of 1 kg of the main aviation structural materials, as discussed in Section 4.2.3, are provided in the table below. This selection excludes mineral resources required in manufacture processes, such as bauxite for aluminium, which should be calculated if quantifying the impact on natural resources is of interest.

Table 14 : Inventory data for structural materials' manufacture.

Material	Aluminium	CFRP	Steel	Titanium	Nickel
Resources					
Water	122.2 l	1.32 l	1.08 l	224.6 l	61.01 l
Energy	98 MJ	12 MJ	21 MJ	825 MJ	280 MJ
Emissions					
CO_2	5.97 kg	0.78 kg	1.99 kg	53.02 kg	11.05 kg
Biogenic CO_2	0.04 kg	0 kg	0 kg	1.52 kg	0.17 kg

CO	2.80 g	0.45 g	22.23 g	26.71 g	12.19 g
CH_4	-	-	3.57 g	118.7 g	52.47 g
VOC	1.10 g	0.10 g	3.13 g	6.99 g	4.91 g
NOx	6.05 g	1.01 g	2.11 g	53.55 g	13.09 g
SOx	15.27 g	0.63 g	9.27 g	48.57 g	30.62 g
N_2O	108.1 mg	18.39 mg	12.86 mg	946.1 mg	469.2 mg
BC[6]	28.72 mg	7.18 mg	6.29 mg	248.3 mg	102.7 mg
PM2.5	1.205 g	0.087 g	0.712 g	3.433 g	1.017 g
PM10	1.280 g	0.153 g	1.507 g	6.167 g	1.459 g

Fuel production

The table below displays inventory data for the production of different types of aviation fuels, namely conventional jet fuel obtained from crude oil, SAF obtained from biomass via Fischer-Tropsch process, and liquid hydrogen produced through electrolysis using hydropower as energy source.

Table 15 : Inventory data for the production of different types of aviation fuels.

Fuel type	**Conventional jet fuel**	**SAF (Fischer-Tropsch)**	**Liquid hydrogen (electrolysis)**
Resources			
Water	3.22 l	0.04 l	1’280.8 l
Energy	49 MJ	21 MJ	277 MJ
Emissions			
CO_2	373.8 g	36.96 g	220.4 g
Biogenic CO_2	0.74 g	0.01 g	1.6 g
CO	423.0 mg	80.90 mg	239.6 mg
CH_4	4’159.8 mg	45.85 mg	387.4 mg
VOC	282.6 mg	10.42 mg	28.96 mg

[6] BC: black carbon.

NOx	663.3 mg	100.2 mg	227.7 mg
SOx	175.4 mg	2.33 mg	95.12 mg
N_2O	6.69 mg	0.42 mg	3.03 mg
BC	5.64 mg	3.41 mg	0.64 mg
PM2.5	35.96 mg	5.06 mg	10.48 mg
PM10	42.75 mg	6.59 mg	22.38 mg

Energy generation

The tables below list emissions and resources required by different energy sources. Data was taken from the GREET's software database. Results are normalized for 1 MJ of electrical energy produced.

Table 16 : Inventory data by energy source (conventional fuels and nuclear).

Type of power plant	**Coal**	**Oil**	**Natural gas**	**Nuclear**
Resources				
Water	0.46 l	0.56 l	0.19 l	0.49 l
Crude oil	34.31 kJ	2'519 kJ	0.74 kJ	2.18 kJ
Natural gas	9.81 kJ	251.29 kJ	2'315 kJ	13.41 kJ
Coal	2'900 kJ	25.89 kJ	1.85 kJ	6.61 kJ
Uranium	0.01 mg	0 mg	0 mg	9.49 mg
Emissions				
CO_2	278.7 g	282.3 g	130.5 g	1.58 g
Biogenic CO_2	0 g	0 g	0 g	0 g
CO	87.57 mg	173.0 mg	70.74 mg	3.15 mg
CH_4	449.4 mg	313.1 mg	371.1 mg	4.39 mg
VOC	23.94 mg	43.29 mg	20.91 mg	0.82 mg
NOx	211.9 mg	1.09 mg	92.60 mg	3.17 mg
SOx	280.3 mg	656.0 mg	24.14 mg	0.81 mg
N_2O	6.46 mg	4.04 mg	2.00 mg	0.03 mg

BC	0.81 mg	6.30 mg	0.44 mg	0.02 mg
PM2.5	19.82 mg	63.84 mg	6.39 mg	0.15 mg
PM10	44.63 mg	71.69 mg	6.58 mg	0.22 mg

Table 17 : Inventory data by energy source (renewables).

Type of power plant	Hydropower	Solar PV[7]	Wind	Biomass
Resources				
Water	0 l	0.9 l	0 l	0.43 l
Crude oil	8.36 kJ	4.83 kJ	-	79.51 kJ
Natural gas	15.95 kJ	44.41 kJ	-	12.20 kJ
Coal	3.12 kJ	73.96 kJ	-	0.96 kJ
Uranium	0 mg	0.04 mg	-	0 mg
Emissions				
CO_2	1.80 g	10.37 g	-	431.5 g
Biogenic CO_2	0 g	0.13 g	-	423.6 g
CO	6.64 mg	38.92 mg	-	347.0 mg
CH_4	6.28 mg	20.24 mg	-	41.92 mg
VOC	0.71 mg	5.95 mg	-	11.25 mg
NOx	3.83 mg	11.69 mg	-	211.6 mg
SOx	4.23 mg	25.34 mg	-	184.3 mg
N_2O	0.03 mg	0.36 mg	-	16.80 mg
BC	0.16 mg	0.06 mg	-	3.42 mg
PM2.5	0.34 mg	2.13 mg	-	20.30 mg
PM10	0.57 mg	4.08 mg	-	21.91 mg

[7] Polycrystalline silicon photovoltaic (PV) panels were chosen over monocrystalline ones as the baseline here, since they are cheaper, more common and less efficient (Marsh, 2023).

Transport

The table below contains data on emissions, normalized by 1 km of travel distance, for diesel-fuelled heavy-duty long-haul trucks and freight trains.

Table 18 : Emission inventory by means of transport.

Transport mode	Long-haul truck	Rail
CO_2	1'074.2 g	15.47 g
Biogenic CO_2	0.38 g	0 g
CO	2.06 g	0.01 g
CH_4	1.35 g	0.02 g
VOC	198 mg	6.16 mg
NOx	1.39 g	0.07 g
SOx	165 mg	0.98 mg
N_2O	4.74 mg	0.40 mg
BC	2.56 mg	0.12 mg
PM2.5	24 mg	1.32 mg
PM10	33 mg	1.40 mg

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