Life Cycle Assessment of Inflight Services and Measures to Reduce Their Carbon Footprint

MSc Industrial Ecology Thesis Project

Maria Evgenia Papavasileiou

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By

M. E. (Maria) Papavasileiou

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Student Number Leiden: 2676303

Student Number TU Delft: 5437601

Graduation Committee:

First supervisor: Dr. B.R.P. Steubing, CML, Leiden University

Second supervisor: Dr.ir. Bruno Lopes Dos Santos, Aerospace Engineering, TU Delft

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Ithaca by C.P. Cavafy

As you set out for Ithaca
hope your road is a long one,
full of adventure, full of discovery.
…
Hope your road is a long one.
May there be many summer mornings when,
with what pleasure, what joy,
you enter harbors you’re seeing for the first time;
may you stop at Phoenician trading stations
to buy fine things,
mother of pearl and coral, amber and ebony,
sensual perfume of every kind-
as many sensual perfumes as you can;
and may you visit many Egyptian cities
to learn and go on learning from their scholars.

Keep Ithaca always in your mind.
Arriving there is what you’re destined for.
But don’t hurry the journey at all.
Better if it lasts for years,
so you’re old by the time you reach the island,
wealthy with all you’ve gained on the way,
not expecting Ithaca to make you rich.

Ithaca gave you the marvelous journey.
Without her you wouldn't have set out.
She has nothing left to give you now.

And if you find her poor, Ithaca won’t have fooled you.
Wise as you will have become, so full of experience,
you’ll have understood by then what these Ithacas mean.

Executive Summary

Aviation is an important sector and one of the key contributors to today's economy. With a forecasted annual growth rate of 4.4%, the sector is expected to expand even more in the coming years. This expansion is however followed by the environmental burdens aviation causes to the environment. Following the anticipated growth of the aviation industry, action to avoid the same trend in emissions is critical.

One of the main impacts of aviation is climate change. Although this is mostly attributed to emissions from fuel consumption, there are other aviation sectors associated with climate change such as inflight services waste management and disposal. To mitigate the environmental impact, ICAO and the EU have established action plans and set aspirational goals such as achieving net zero emissions by 2050. One of the action plans employs the concept of circular economy.

Circular practices have already been part of aircraft manufacturing and repair for a long time. However, the introduction of circularity in inflight services is more recent. Airlines are taking more circular measures, often labeled as sustainable, seeking ways to reduce their carbon footprint. It is important to evaluate whether these measures improve the environmental performance of inflight services or not. To achieve that, the cradle-to-grave approach of the Life Cycle Assessment (LCA) method is recommended. Furthermore, there is little to no research on quantifying the overall climate impact of inflight services. This thesis is therefore aiming to fill this research gap by conducting an LCA on inflight services offered to passengers and the research question is formed as: "*How do inflight services, and measures intending to reduce their climate impact, perform in terms of carbon footprint and to what extent do they enable sustainability?*".

Two baseline cases were evaluated to answer the research question, a short-haul, and a long-haul flight, representing conventional inflight service practices. For each case, five scenarios were constructed based on measures aiming to reduce the carbon footprint of inflight services, namely single-use plastic reduction, food waste reduction, lightweight materials introduction, carbon offsetting and a combination of all the measures. The analysis aimed to quantify the impact of inflight services, in terms of contribution to climate change, and compare the applied measures to the baseline cases, assessing whether they enable sustainability or not.

Despite the modelling limitations and data gaps, interesting results were observed. The five measures were assessed, and a ranking based on their performance was provided. An intriguing finding was that reducing single-use plastic was not the best-performing alternative. On the contrary, the use of lightweight materials, as a result of material substitution practices, displayed a higher impact reduction. This can be explained by the strong relationship between weight transportation and fuel emissions. Moreover, carbon offsetting via reforestation was ranked as the most effective alternative. This finding needs to be interpreted with caution and from a critical perspective due to the long-term nature of the carbon uptake by biomass and the uncertainty carbon credits calculations are based on. Nonetheless, it highlights the effectiveness a more direct and immediate carbon capture application could have.

Finally, the analysis revealed environmental impact hotspots throughout the life cycle of inflight services. By far, the most impactful process was identified as the emissions release due to fuel burn. Other hotspots were the electricity use of the cleaning process of the used service equipment and the transportation of equipment and waste from the aircraft to the cleaning facilities and landfill respectively. Furthermore, processes related to dairy products used in catering and waste treatment processes were also amongst the most impactful.

Overall, the study can conclude that the evaluated inflight service measure scenarios performed better than the business-as-usual inflight service practices. The total carbon footprint of inflight services per passenger on a short-haul flight was calculated as 10.9 kg CO2-Eq and on a long-haul flight as 50.2 kg CO2-Eq. The combined measures carbon footprint reduction potential could reach the impressive 96% for a long-haul flight and 89% for a short-haul flight reduction. Most of this reduction is mainly attributed to carbon offsetting, 82% for the long-haul flight and 69% for the short-haul flight. The second best-performing scenario was the lightweight materials measure which could reduce carbon footprint by 13% and 19% for the long-haul and the short-haul flight respectively. Single-use plastic and food waste reduction measures did not exceed a 0.4% reduction of the impact. Although carbon emissions of inflight services entail a small fracture of the overall aviation carbon footprint, the studied measures can contribute to notable environmental impact reductions with immediate results.

Keywords: Carbon Footprint, Aviation, Inflight Services, Circular Economy, Life Cycle Assessment

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1. Introduction

1.1 Background

1.1.1 Aviation trends

The nature of the civil aviation industry facilitates the progression of a contemporary world. Air transport not only contributes to global economic growth but also represents one of the major employers worldwide. According to the Air Transport Action Group, "If aviation were a country, it would be the 17th largest economy in the world, supporting 87.7 million jobs and nearly 3.5 trillion dollars in economic impact" (Social and economic benefits of aviation, n.d.). In addition, airplanes transport over 10 million passengers and around USD 18 billion worth of goods every day (Future of aviation, n.d.). Between April and May 2020, air traffic shrunk by more than 75% due to the Covid-19 pandemic (IEA, 2021). Despite that tremendous contraction, passenger numbers are increasing again and are expected to double by 2035 following the pre-covid annual average growth rate of 4.4% (IEA, 2021; ICAO, 2019).

The main driver of civil aviation is the passengers. Inflight services play an important role in passengers' choice of airlines while they have a significant impact on perceptions of the overall airline's service quality (Romli et al., 2016; Prentice et al., 2019). To be competitive, an airline should provide high-quality service since there are numerous alternative airlines or routes that would take passengers to their intended destinations. During flights, different types of services are provided to passengers that range from fulfilling basic needs, such as hygiene and catering, to helping improve the inflight experience with the provision of entertainment and comfort. The focus of the present study is the provision of inflight services and their environmental impact.

1.1.2 Aviation and the environment

General Impact

The economic and social benefits of aviation are evident. However, it's the environmental impact of aviation that has always been in the headlines (Timperley, 2020; Gayle, 2022; Boyd, 2017; Stroh, 2021). This impact includes air pollution and climate change, waste generation, and noise pollution (European Aviation Safety Agency & EAA, 2019). Emissions from aviation fuel combustion contribute to global warming and the degradation of air quality and have a negative impact on human health. More specifically, the carbon dioxide (CO_2) emissions from aviation operations were approximately 1 Gt in 2019 and represented 2.8% of the global CO_2 emissions from fossil fuel combustion (IEA, 2020). Given the expected expansion of the aviation industry, action to avoid the same trend in its emissions is crucial.

Despite the high-emitting profile of the sector, due to the continuous technological improvements in airframes and engines, today's aircrafts are approximately 85% more efficient than the models flying in the 1960s (IEA, 2021). This efficiency can be translated into less fuel burn and consequently fewer emissions. Based on Kharina and Rutherford (2015), an annual reduction rate of 1.3% in fuel consumption per passenger-km has been achieved between 1960 and 2014. The same rate is expected to apply until 2037 according to the International Civil Aviation Organization (ICAO), (2019), assuming technological improvements continue taking place. However, relying on the current rate of technological innovations is not enough to reach ICAO's ambitious goal of a 2% annual average efficiency improvement until 2050 (Climate Change, n.d.). Therefore, aircraft technology should be further researched, and substantial improvements should be achieved.

Aviation and climate change

It has been estimated that since pre-industrial times, aviation has contributed 4% to the total anthropogenic warming (Skeie et al., 2009). Following the projections for a 4.4% annual growth of the sector, aviation's contribution to climate change is expected to increase. Air transport contributes to climate change mostly due to the emissions from aircraft engines that, by altering the atmosphere's chemical composition, cause imbalances in the climate system. These emissions are carbon dioxide (CO_2), carbon monoxide (CO), water vapor (H_2O), hydrocarbons (HC), nitrogen oxides (NOx), sulfur oxides (SOx), and non-volatile particulate matter (black carbon or soot) (Brasseur et al., 2016).

Aircraft emissions in the atmosphere influence the radiative balance between the incoming solar radiation and outgoing infrared radiation emitted by the Earth. The metric used to express the net change in the radiation behavior is called radiative forcing (RF) and due to its linear relationship with Earth's surface temperature, is used as an indicator of climate change (Lee et al., 2010; Dessens et al., 2014). A positive change in radiative forcing indicates an increase in the atmospheric temperature while a negative change indicates a cooling effect. Emissions like CO_2 absorb and trap solar radiation in the atmosphere and therefore contribute directly to global warming by increasing the RF effect. Emissions of nitrogen oxides (NOx) react with and alter the concentrations of greenhouse gases such as ozone (O_3) and methane (CH_4). These complex chemical reactions cause an imbalance in the atmosphere which also increases the RF effect.

Another way aircraft emissions increase the RF is through the formation of line-shaped ice clouds, known as condensation trails (contrail) cirrus clouds. These aircraft-induced clouds are formed during the cruise phase of the aircraft (high altitude and low temperatures) by water vapor, and although they have both warming and cooling effects, they overall contribute to a positive RF (Kärcher, 2018). Other emissions like Soot and SOx have a relatively smaller impact, while in some cases their effect on radiative forcing cancel each other out.

Aviation cabin waste

Emissions from aircraft fuel combustion are not the only source of environmental impact. One of the most pressing issues in the airline industry's environmental management is solid waste management and disposal (Li et al., 2003). Inflight services create different waste flows such as packaging waste, food waste, and cabin cleaning waste (see Figure 1). According to IATA (2017), 5.7 million tons of cabin waste were generated by the airline industry in 2017, while approximately 20% of the waste consisted of unconsumed food and beverages. Additionally, it has been estimated that each passenger generates on average 1.43 kilograms of cabin waste per flight, including toilet waste (IATA, n.d.). Considering the forecasted growth of air traffic in the next years, the generation of waste is expected to increase accordingly.

Figure 1. Combined cabin waste by weight (WRAP, 2017)

Cabin waste management is a challenge for airlines due to the different regulations that apply to each region. There is a distinction between international and national or domestic cabin waste and their management depends on the destination (WRAP, 2017). Most countries have introduced special legislation for waste handling, especially for the international cabin waste (ICW) flows that might pose a risk to local animals and plant species by potentially introducing invasive species and microorganisms. Some countries, such as Australia, have enforced strict legislation and treat ICW as biosecurity waste. In Europe, ICW is considered waste from flights arriving from countries outside the European Union (EU), however not all member states make the distinction between international and domestic waste flows and take a risk-based approach. According to the EU 1069/2009 Regulation about animal by-products (European Parliament, 2009), ICW is classified as Category 1 (Cat1) animal by-product containing waste, a category that reflects the highest level of risk to public and animal health. Cat1 waste must be disposed of by burial in an authorized landfill. On the contrary, domestic cabin waste falls under Category 3 (Cat3) and can be treated as municipal waste based on each country's waste treatment approach.

1.1.3 Climate change mitigation actions

Global level

To counteract the effects of aviation on climate change and the environment, a series of legal and operational solutions have been implemented on a global level. The legal aspect of environmental impact mitigation includes measures by actors such as the United Nations (UN), the European Union (EU), ICAO, and nations around the globe. More specifically, ICAO in collaboration with the UN and other international organizations formulates policies, and develops Standards and Recommended Practices (SARPs), while it has also established a set of global aspirational goals to promote sustainable growth in the sector of aviation. Examples of these goals are a 2% annual fuel efficiency improvement through 2050 and carbon-neutral growth from 2020 onwards (ICAO, 2019).

To achieve these goals, ICAO is promoting sets of measures including a) advances in aircraft technology, b) operational improvements, c) sustainable aviation fuels (SAFs), and d) market-based measures such as carbon offsetting via the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) scheme (see Figure2).

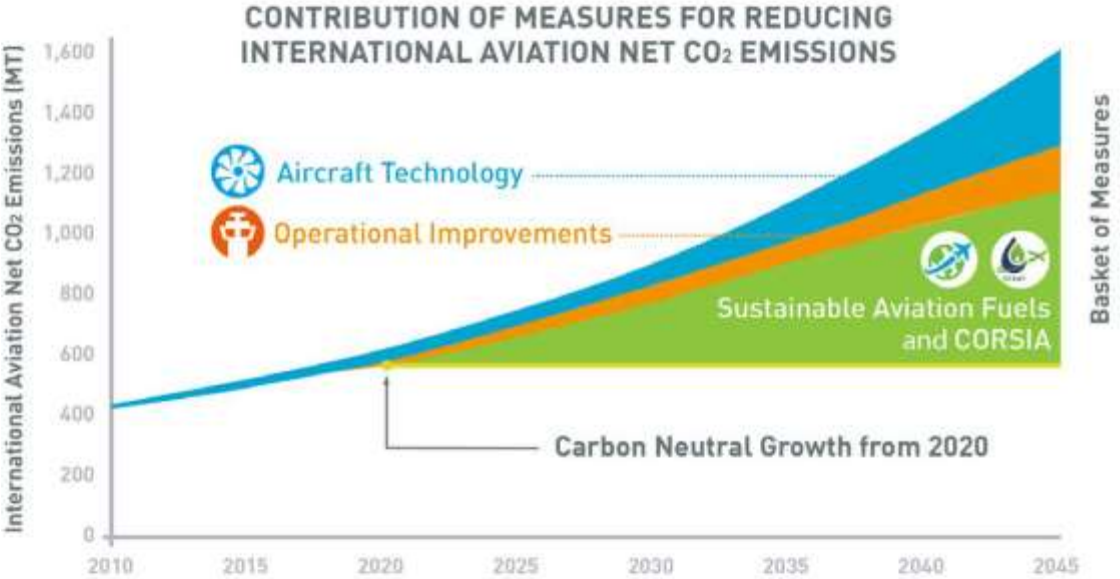

Figure 2. ICAO Global Environmental Trends on CO_2 Emissions and Contribution of Measures for Reducing International Aviation Net CO_2 Emissions (ICAO, 2019).

Advances in aircraft technology measures include the latest technological improvements in fuel burn efficiency, lightweight materials, and innovative structural technologies, as well as aircraft end-of-life (EOL) best practices. Operational improvements are considered the optimization of air traffic management and the improvement of ground practices such as airport operations. As illustrated in Figure 2, SAFs have a key role in the success of the Carbon Neutral Growth plan. Although the use of SAFs has already started, the amount of production is still small. ICAO is already working on incentives and policy frameworks to boost the use of SAFs. Finally, an important step to achieving net zero is the global market-based measure CORSIA. CORSIA is an offsetting mechanism that allows international airlines to offset CO_2 emissions that exceed the relevant baseline by carbon credits. Carbon offsetting can be achieved through investment in project activities such as wind energy, forestry, clean cookstoves etc.

European Union level

In alignment with ICAO's actions, the European Commission has adopted the European Green Deal (A European Green Deal, 2022), the Climate Law (European Commission, 2021), and the 2030 Climate Target Plan (CTP)(European Commission, 2021a), aiming at enhancing the Union's climate commitment under the Paris Agreement. Reducing net greenhouse gasses from all sectors by at least 55% by 2030 (compared to 1990 levels) and achieving net-zero emissions by 2050 are two of the main objectives of the framework (European Commission, 2021b). This can be achieved through emissions reductions, investments in green technologies, and environmental protection schemes. The European Green Deal focuses on decoupling economic growth from resource use and keeping track of the progress of its member states, ensuring the equal implementation of the framework. For the aviation sector, the European Green Deal is highlighting the obligation of EU-based airlines to offset their carbon emissions and participate in the CORSIA mechanism. It also promotes the use of sustainable fuels by obliging airplanes departing from EU airports to use fuel containing SAF. On an operational level, airlines and related stakeholders, such as catering facilities, are starting to adopt circular alternatives to their current practices in an attempt to become more sustainable.

1.1.4 Circular economy applications in aviation

Circular economy has become an emerging economic model that offers solutions to global challenges such as climate change, biodiversity loss, waste, and pollution (Ellen MacArthur Foundation, 2022). The concept of circular economy is a way to apply sustainability in the current linear economic model. This can be achieved by keeping resources in use for as long as possible while extracting the maximum value from them and recovering and regenerating products and materials at the end of their lifespan (WRAP, 2021).

In the aviation sector, the current economic model relies on linear activities following the pathway of 'creation, consumption, and disposal'. The growth rate of air traffic suggests an increase in material and fuel consumption as well as waste and emissions generation. Transitioning to a circular model would therefore benefit aviation with the reduction of the impacts associated with the resource's consumption, emissions, and waste generation. From product design to EOL management, a circular economy has the potential to transform the entire supply chain of aviation. Some of the core circular economy concepts are already applied in the sector; the repair, refurbishment, and remanufacturing processes of aircraft parts, enabled via 3D printing technologies (Sustainair or Donnerer, 2022), as well as the development of environmental product declarations for aircraft products, which facilitates the evaluation of their environmental performance (Bombardier, 2022).

Nevertheless, the implementation of circular activities in aviation could be improved. The Association of European Research Establishments in Aeronautics - EREA, (2019) has identified the 'Circular Aviation Action Lines' as priority topics for research and development projects that can contribute to making aviation more circular. These topics are:

- Designing and producing the circular aircraft
- Flying circular
- Circular life cycle of aviation
- Circular Policies and regulations
- Airports and airlines as circularity ambassadors

Designing a circular aircraft requires a careful selection of materials and design practices aiming at extended durability, easy repair and disassembly, and reuse of components. Circular aircraft manufacturing includes approaches that minimize manufacturing waste and scrap such as the closed system approach. 'Flying circular' includes all the circular activities that can be applied to aircraft operations. Although propulsion and reduction of fuel consumption are the most popular fields for circularity applications, other solutions could be beneficial including aircraft part recycling, changes in maintenance, repair, and overhaul (MRO) practices, aircraft electrification, and the use of alternative fuels. The 'Circular life cycle of aviation' action line focuses on considering the full life cycle of an aircraft during the design phase. Special attention should be given to the incorporation of the EOL phase in those calculations. Circular policies and regulations are suggested as an action line to ensure the transition to a circular economy model has no impact on the aviation industry's current safety standards. Finally, the role of airports and airlines as circularity ambassadors can be supported by sustainable initiatives such as circular architecture and zero-emission transportation networks in airport infrastructure, circular aviation business models, and synergies between airlines, airports, and local communities.

1.2 Thesis motivation

In line with EREA's suggestion on research priorities, this project will focus on the action lines 'Flying circular' and 'Airports and airlines as circularity ambassadors'. Although recycling activities are the most widely implemented circular practice, there are more circular strategy components that can be identified according to ICAO (ICAO, 2019). These components are redesigning catering services, reducing food packaging, and reusing seats and entertainment equipment in other systems. ICAO suggests that circular economy principles should focus on two core elements of aviation: aircraft and airports (ICAO, 2019). Circularity on an aircraft level can be applied to aircraft operations and management of aircraft EOL levels. This project focuses on the aircraft level and more specifically on the inflight services part.

Currently, airlines are adopting more circular practices, often labeled as sustainable, seeking ways to leave the linear economy behind and embrace circularity. Initiatives like reduction of waste and food waste and ban of single-use plastic items (Aviation Benefits, 2022, Ryanair, n.d., Etihad Aviation Group, n.d., Etihad Aviation Group, n.d.) are featured already in their websites and sustainability reports. However, although recycling waste can be considered part of a circular economy strategy, its practice does not render an airline sustainable. The measurement and communication of sustainability in the aviation industry have not been consistent in the past years, giving airlines the freedom to be selective with sustainability indicators and present their results in a more favorable way (Zieba & Johansson, 2022). Therefore, a standardized and transparent sustainability reporting scheme is needed.

It is important to investigate how the current practices, that airlines adopt in an attempt to embrace circularity, affect environmental sustainability. According to Rigamonti & Mancini (2021), there is always the risk of problem shifting and rebound effects, both of which can introduce new environmental issues. As a result, each circular economy strategy should be carefully evaluated because it could not always lead to environmental benefits. To clearly show whether these practices lead to an improvement in environmental performance or not, the quantitative method of Life Cycle Assessment (LCA) is recommended in combination with other circularity indicators (Rigamonti & Mancini, 2021). The method's cradle-to-grave approach avoids problem-shifting (Guinée, 2002), and renders the assessment more complete. Moreover, the Ellen MacArthur Foundation suggests LCA as a tool that can be used to support and inform the transition towards a circular economy (Ellen MacArthur Foundation, 2022). This can be done by highlighting areas of improvement through impact hotspot identification, by comparing similar solutions to see which one is less impactful, and by testing whether external factors, such as material substitution, would affect the environmental impact of a solution.

1.3 Methods

1.3.1 Life Cycle Assessment

The LCA method is a quantitative method that assesses the environmental impacts of a product throughout its lifecycle (manufacturing, use phase, EOL), offering this way a holistic approach. The method makes it feasible to connect a product to its environmental impacts by bringing environmental impacts into one consistent framework (Guinée, 2002). The total impact of a product is expressed in a selection of impact categories that represent environmental issues such as climate change. The LCA method can be used to analyze the origins of problems related to a product, design a product, compare products, or compare improvement variants of a product (Guinée, 2002).

The LCA method is standardized, following the International Organization for Standardization (ISO) LCA-related standards series (ISO 14040) (2022). More specifically, the Environmental management – Life cycle assessment – Principles and framework standard (ISO 14040:2006) offers a straightforward synopsis of LCA practice, applications, and limitations addressed to stakeholders of any background, while the Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006), consists of a complete guide on all LCA stages including interpretation of the results (ISO, 2022). The present study is following the four LCA stages as defined by ISO: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results (see Figure 3).

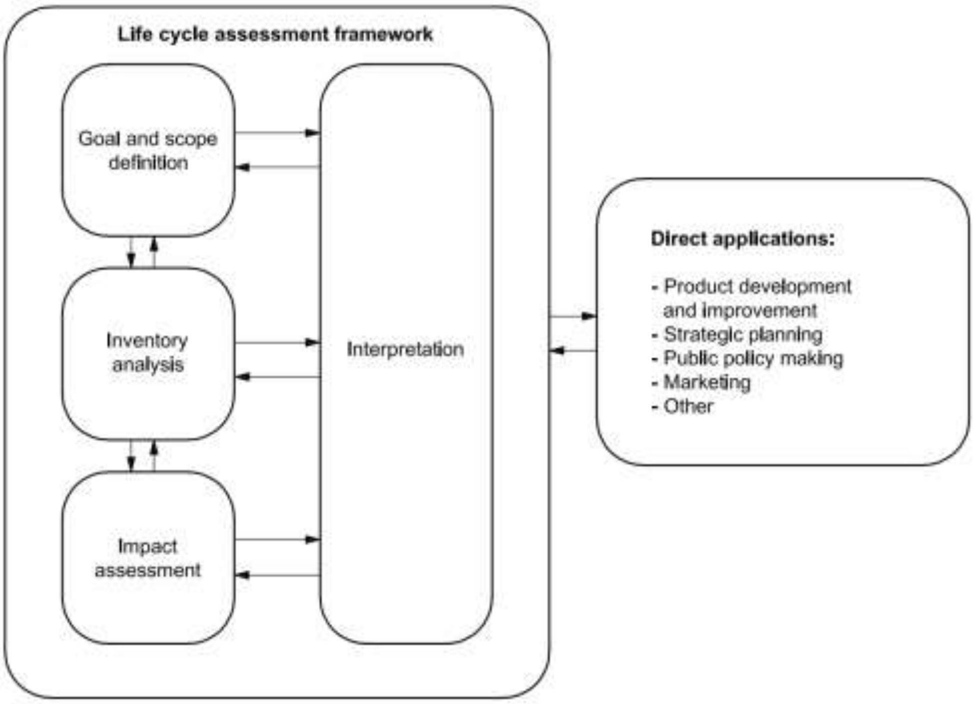

Figure 3. Life Cycle Assessment framework (ISO 14040).

Firstly, in the goal and scope definition phase, the foundations of the study are set in terms of functional unit definition, target audience, and intended application. Secondly, the inventory analysis phase is used to define and design the product system, collect the necessary data, and perform calculations. The initial LCA results or inventory analysis results are generated at this phase of the analysis and consist of quantified flows related to the functional unit.

During the impact assessment phase, the inventory analysis results are assigned to selected environmental impact categories. This process is called classification. There are various impact categories representing different types of environmental impact such as climate change, resource depletion, land use, eutrophication, and acidification. The selection of impact categories depends on the goal of each analysis. After the classification of the results, the characterization process takes place. During characterization, the results assigned to each impact category are aggregated under a common unit which allows obtaining a common result for each category: the category indicator result. Further numerical manipulation of the results is possible through processes like normalization, weighing, and grouping. However, these processes are optional according to the ISO standards.

The final step of results interpretation consists of the evaluation and analysis of the results as well as the formulation of conclusions and recommendations. During the evaluation process, the consistency and completeness of the assessment are examined. The analysis of the results includes a contribution analysis where the contribution hotspots, in terms of the impact of each process, are highlighted. Moreover, a sensitivity analysis is recommended to assess the robustness of the results. Lastly, conclusions are drawn, and recommendations are made based on all the previous phases.

1.3.2 Data requirements

To increase the accuracy of the results, the present study requires detailed data about innumerous processes and products. Without a case study and data directly from an airline and due to the scale of the system, it was deemed impossible to obtain detailed information on all the products involved. As discussed in subsection 3.2.4, critical assumptions had to be made and some aspects had to be excluded from the research. Most data utilized in this study are secondary data from other LCA studies, literature review, and airline-related websites.

1.4 Literature Review

1.4.1 Life Cycle Assessment in aviation

Aviation can be divided into three stages from an LCA perspective: manufacturing, operation, and EOL or decommissioning. The operation phase was found to be the most impactful, being accounted for up to 79% of the life-cycle energy consumption (Chester & Horvath, 2009) while operation-related emissions are contributing up to 99% to the overall environmental impact (Howe et al., 2013). It is therefore important to mention that processes related to operations occurring on every flight, have a significantly higher environmental impact throughout the life cycle of an aircraft, than the manufacturing and decommissioning stages, due to their frequency. In addition, emissions from the operations stage are directly connected to the weight of transported items (Blanca-Alcubilla et al., 2020). Therefore, lower emissions could be achieved with the use of lightweight materials, regardless of the manufacturing and disposal stages.

As expected, most LCAs in the aviation sector focus on the aircraft structure and lightweight materials such as composites (Timmis et al., 2015; Bachmann et al., 2017; Scelsi et al., 2011), as well as on aviation fuels and sustainable alternatives (Cox et al., 2014; Enes, 2021; Oehmichen et al., 2022; Koroneos et al., 2005; Elgowainy et al., 2012). The literature review has resulted in very limited LCA studies in the field of inflight services. The majority of these LCAs focus on specific aspects of the services, such as catering and food, packaging, and waste management while an LCA focusing specifically on in-flight services has yet to be performed.

1.4.2 Life Cycle Assessment in food and catering

Given the link between weight and fuel combustion emissions, at a first glance, inflight catering is expected to contribute to the environmental impact of a flight in terms of weight. The number of meals uplifted on aircrafts every year is massive. In 2019, 93.5 million meals were uplifted by one single airline (Emirates Group: Number of uplifted catering meals 2021, n.d.). The production of these meals leads to emissions associated with food preparation and agriculture that could contribute to the overall inflight catering impact. Therefore, it is important to investigate inflight catering’s environmental impact beyond the expected weight-fuel combustion emissions-related results.

Catering is a part of the food production supply chain. Most of the emissions associated with food production have already been emitted before the food reaches the caterer (Blanca Alcubilla, 2021). Agriculture, an important part of the food production chain, is a large contributor to climate change, being responsible for 10-12% of the anthropogenic greenhouse gas emissions globally (IPCC, 2014). Most of the agriculture-related emissions that contribute to climate change come from fuel consumption through machinery use (CO_2), digestion of ruminants (CH_4), and fertilizer application (N_2O) (Blanca Alcubilla, 2021). Food manufacturing and transportation are also considered high GHG contributors to the overall impact of the food supply chain (Garnett, 2011; Wallgren, 2006). The study of Cerutti et al., (2018), identified the three top GHG emitting stages of catering provision in public schools: meat consumption (related to conventional agriculture practices), cooking, storing, and serving procedures (mostly related to energy use), and waste management. Another study on school catering provision highlighted the importance of analyzing the life cycle stage of the food supply chain and identified meat consumption and waste management as the top contributing processes to climate change (Caputo et al., 2014). It is therefore clear from the literature that the top environmental impact hotspots of catering are agriculture, food processing, transportation, and waste treatment.

1.4.3 Life Cycle Assessment in equipment and packaging

From a service equipment perspective, a comparative study on single-use and reusable tableware indicated that reusable equipment has a significantly lower impact than single-use ones (Pro.mo/Unionplast, 2009). Most emissions related to single-use service items are connected to their production process, while for the reusable items, the largest share of impact was from the washing process. Another study on single-use and reusable cups, both made of plastic, concluded that for the reusable cup to be less impactful than the single-use one, it has to be reused at least 10 times (Garrido & Alvarez del Castillo, 2007). The highest impact was again associated with the production phase of both cups, while the impact from the washing phase of the reusable cup kept on increasing as the number of uses increased. However, when the assessment includes inflight service equipment, the results can change dramatically due to the weight-fuel emissions factor. The study of Blanca-Alcubilla et al. (2020) investigated the environmental impact of single-use and reusable inflight service equipment. The results showed that the reusable items generate most of the impact which can be associated with their weight and therefore fuel emissions. These findings highlight the unique nature of environmental impact quantification assessments of aviation products and services.

1.4.4 Life Cycle Assessment in waste management

The LCA method has been widely used in the waste management sector. Landfilling has been identified as the most impactful waste treatment method in several impact categories (Cherubini et al., 2009). The same authors suggested the combination of a municipal waste sorting plant with electricity and biogas production is the least impactful option. However, a review of LCAs on waste management systems concluded that there is a strong dependence of the results on local conditions, and results shouldn’t be generalized (Laurent et al., 2014). Each waste treatment case is unique in terms of waste composition, local energy mix, and treatment efficiency, suggesting that an LCA should be performed tailored to each specific case study.

In an attempt to improve current aircraft waste management processes, Blanca-Alcubilla et al. (2019) performed a detailed characterization of aircraft cabin waste. Their results showed that organic matter (33%), paper waste (28%), and packaging (12%) are the most common waste materials generated in flight. These results allowed the development of further recommendations for the improvement of cabin waste treatment such as inflight waste separation. In addition, a review on food waste LCAs underlined the importance of food waste prevention since most of the food waste impact comes from the food production stage (Scherhaufer et al., 2018). These studies highlight the importance of prioritizing waste prevention instead of focusing only on waste treatment enhancements.

1.5 Research objective and research questions

The objective of the research is to address the identified gap in the literature regarding the quantification of the environmental impact attributed to the life cycle stages of inflight services. The holistic approach of the LCA method will be employed to assess that carbon footprint, as well as the climate performance of measures intending to reduce carbon footprint. The inflight products are divided into four groups according to the type of service they are offering: catering (drinks, food, containers, trays, cutlery, etc.), comfort (blankets, pillows, seat covers, carpets, etc.), entertainment (headphones, in-flight entertainment systems, newspapers, etc.), and hygiene (water, toilet paper, soap). Figure 4 illustrates the LCA research approach of environmental impact quantification for the four service categories.

Figure 4. Research approach.

The project will aim to answer the main research question and the following sub-questions:

How do inflight services and measures intending to reduce their climate impact perform in terms of carbon footprint, and to what extent do they enable sustainability?

a. *How do business-as-usual inflight service products and practices perform in terms of carbon footprint within their life cycle?*
b. *How does the introduction of measures intending to reduce the carbon footprint of inflight services affects the climate performance of the business-as-usual products and practices*?
c. *Can these measures enable environmental sustainability in the aviation industry, and to what extent?*

1.6 Logical strategy

The logical strategy followed in this study begins with a literature review which has already pointed out the research gap. An LCA model will be built and data gathering quantify each process. The LCA model will consist of two business-as-usual (BAU) models as reference scenarios for all grouped products. These two cases will represent a domestic short-haul flight and an international long-haul flight. The system boundary of the assessment will be service-related products within the cabin interior. All research questions will be answered by analyzing the LCA results. First, a business-as-usual case will be analyzed built on practices that have been applied on inflight services for the past years. Then, a selection of four measures that aim to reduce carbon emissions will be assessed. The comparison of all scenarios will reveal environmental impact hotspots and indicate sectors that can be improved. Finally, the sustainability of the applied measures will be assessed and their contribution to the transition to sustainable aviation will be assessed. An overview of the research strategy phases is illustrated in Figure 5.

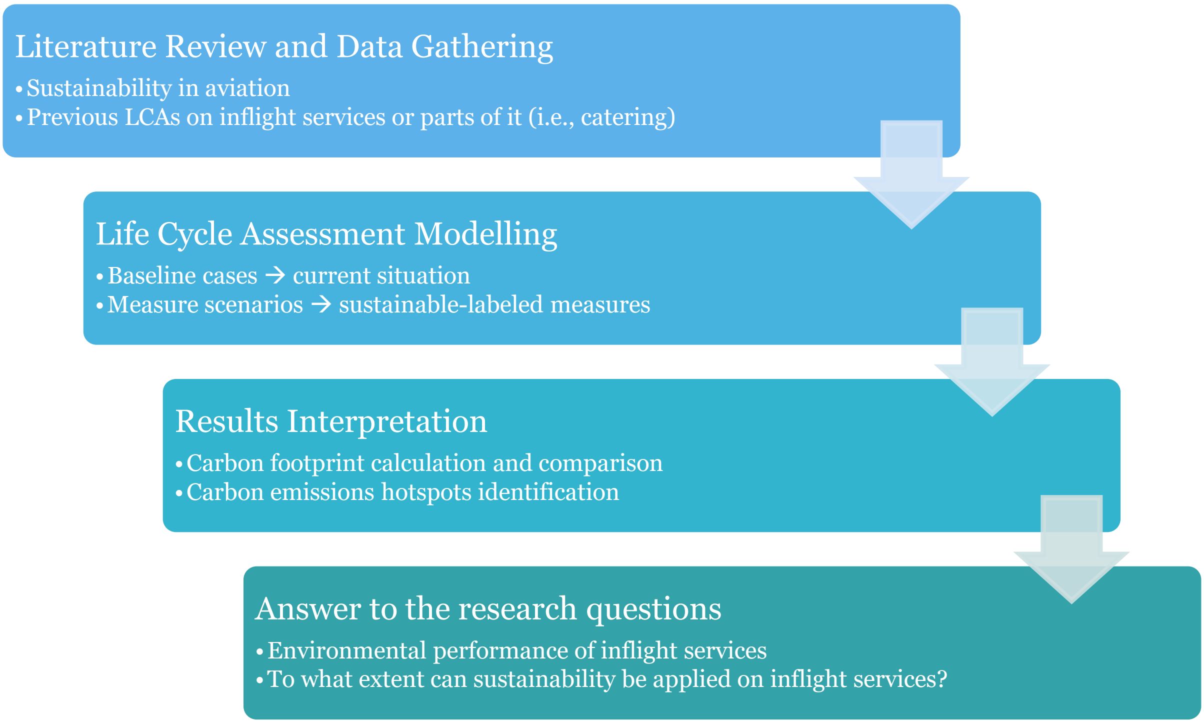

Figure 5. Research process flow

1.7 Relevance

This study proposes the use of the LCA method to assess the carbon footprint of a complex system such as inflight services. A knowledge gap has been identified in the literature and therefore suggests the scientific relevance of this study. The proposed study is relevant to the field of Industrial Ecology (IE) since it analyzes the life cycle stages of inflight services using one of the most popular tools in the IE field, the LCA method.

Airlines present to the public sustainable practices applied to their inflight services as a solution to climate change and a sustainable way to reduce their carbon footprint. The societal relevance of this study lies in the importance of identifying the environmental impacts of inflight services and ways that can improve their performance. The results can be communicated to the public to make informed and conscious decisions about their transportation choices and to airlines to invest in carbon reduction measures.

1.8 Thesis outline

The present thesis consists of an extensive introduction which includes the background information, literature review, problem statement, and methods description. The following chapter includes the detailed LCA report in accordance with the ISO 14040:2006 standards. Discussions of the results and limitations of the study as well as conclusions and recommendations are the chapters that complete this thesis. More details about the LCA modelling are included in the Appendix.

2. Life Cycle Assessment

The LCA method is applied in this study and the chapter structure is following the ISO standards as described in the LCA handbook by Guinee (2002). In this chapter, the LCA steps followed are goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.1 Goal and Scope Definition

In this section, the goal and scope of this study are defined, and the foundations of the study are set in terms of objectives and boundaries.

2.1.1 Goal

The goal of this study is to quantify the climate performance of measures applied to commercial inflight services offered by European airlines that intend to reduce the carbon footprint and compare it to BAU practices that have been the norm for the past years. Through this comparison, the sustainability of these measures will be assessed indicating whether they are indeed less impactful and to what extent sustainability can be applied to commercial aviation. Moreover, environmental impact hotspots will be identified through a contribution analysis. The intended audience of this study is actors in the aviation sector such as airlines and catering facility operators, as well as researchers in the field of circular aviation. LCA is deemed a suitable method to perform this assessment since the environmental impact of each service product is assessed over its entire lifecycle and it does not focus only on the emissions due to fuel combustion. Moreover, the comparative nature of LCA makes it a suitable method given the goal of the study.

The study is being conducted as part of the graduation thesis project for the Industrial Ecology Master’s degree offered by Leiden University and Delft University of Technology. The study is not commissioned by a specific stakeholder and its purpose is solely academic. The supervisors of the thesis are assistant professor Dr. B.R.P. Steubing from Leiden University (CML) and Dr.ir. Bruno Lopes Dos Santos from Delft University of Technology (Faculty of Aerospace Engineering). Finally, the LCA does not aim at a public comparative assertion.

2.1.2 Scope definition

As previously stated, the system boundary of the conducted LCA is service-related products within the aircraft cabin interior. The present analysis has a comparative approach. Two baseline cases are presented as the BAU scenario and each of them is compared to five measure scenarios. The LCA has a change-orientated analysis approach, evaluating alternatives that change the BAU inflight situation i.e., in terms of service material substitution. The approach is cradle-to-grave, including all life stages of the products from production to EOL. Although the aim of the study is set to a detailed sophistication level, due to limited data, extended system boundary, and limited time this was not always possible. Therefore, the detailed sophistication level has not always been consistent throughout all the processes.

Temporal coverage

The temporal coverage of the study is set to the present year (2022) and the data used to build the model should be relevant to 2022. However, this was not always feasible because of some older versions of datasets available in the ecoinvent database. In every case, the most recent available dataset was used with an average deviation of ten years. Since the demand for the products assessed by the study is not expected to change significantly during the time defined by the temporal coverage, the LCA can be considered an attributional LCA.

Geographical coverage

Following the goal of the study, the geographical coverage is set to be the European Union countries. However, many products have complex supply chains that often reach global levels. For most production and EOL processes, the use of datasets from European countries has been prioritized and global alternatives were used only as a second option.

Technological coverage

The technologies covered in the research are well-established in the present time. Background technologies are used to support the modelling of the BAU scenarios. Furthermore, the circular alternatives are also using well-established technologies and materials that are already applied in the market.

Environmental scope

The environmental scope of the analysis focuses on climate change therefore the coverage of the environmental impact of aviation on climate change is assessed. As discussed in the introduction, aviation contributes directly to climate change. Moreover, the time frame of the study contributed to the decision to narrow down the impact categories used for the assessment.

2.1.3 Function, functional unit, alternatives, reference flows

Function and functional unit

The function of inflight services is to provide a service to passengers onboard a flight, therefore the function of the study is the *"provision of inflight services"*.

The functional unit of the study is set as the *"provision of inflight services for a flight per passenger"*. Investigating the environmental impact of service provision per passenger has been chosen aiming to provide an overall personal estimation of each passenger's carbon footprint. The idea behind this choice is to:

1. Calculate individual footprint on each flight aiming for behavioral change
2. Facilitate the calculations and the comparisons between different parameters such as aircraft type.

Scenarios

Baseline cases

The LCA has two baseline cases: a short-haul and a long-haul flight, followed by five measures implemented in the two cases with the intention to reduce their carbon footprint. Since the analysis is not based on airline data, the scenarios were built on average values for a fully booked economy class cabin. By assessing different flight lengths, the change in their environmental behavior can be observed. IATA defines a flight of less than six hours as a short-haul and a flight of six hours and more as a long-haul flight (WRAP, 2017). Both short-haul and long-haul scenarios have been chosen based on the busiest routes and the minimum monthly average distances reported in that range. An overview can be found in Table 1.

The short-haul case represents a domestic flight (within Europe). The minimum monthly average distance reported for 2019 is 1,007km or 540 nautical miles (Eurocontrol, 2021). This is equivalent to a flight between London Heathrow airport and Salzburg airport with a flight duration of approximately 1 hour and 50 minutes. The aircraft type representing this scenario is the Boeing 737-800 (B738) with a maximum capacity of 189 passengers. This aircraft is the most common narrow-bodied aircraft model in terms of sales and completed orders, with 117 airlines having it in their fleet (Boeing, 2022; Staff, 2019). It is also a popular choice for the leading airline based on passenger traffic, Ryanair (Burgueño Salas, 2022). The services provided on a short-haul flight are on a basic level and include catering, comfort, and hygiene. Catering services consist of snacks and drinks, in this case, a sandwich, a coffee, and water. On a comfort level, the services provided are the necessary including the aircraft seat and the carpet. Hygiene services are access to the toilet, water, soap, and tissue. Finally, due to the duration of the flight, entertainment is not applicable. An overview of all the processes involved in this scenario can be found in Appendix 1.

The long-haul case represents an international flight between Europe and the United States of America (USA). Due to a lack of data on the average flight distance for flights between Europe and the USA, the scenario was chosen based on the busiest routes between the two destinations. The busiest route for 2019 was the London Heathrow (LHR) to New York John F. Kennedy airport (JFK) route, based on Eurostat data as reported by Wikipedia (2022a). A flight between LHR and JFK is approximately 5,539 km or 2,991 nautical miles (Flight Distance Calculator, 2022), with a duration of an average of 7 hours and 50 minutes. This scenario is represented by the wide-bodied Boeing 787-800 (B788) aircraft with a maximum capacity of 248 passengers. This aircraft is the second most popular model manufactured by Boeing in terms of sales and completed orders, with 69 airlines having it in their fleet (Boeing, 2022). The services provided on a long-haul flight are more sophisticated and can aim for an enhanced customer experience. Catering includes two full meal services and drinks while blankets and pillows are offered for the passengers' comfort. Entertainment is also provided in the form of an individual touch screen, or inflight entertainment (IFE), and a pair of headphones for every passenger, along with the option of a newspaper. Hygiene is considered a basic need, so it remains the same in both scenarios. An overview of all the processes involved in this scenario can be found in Appendix 2.

Table 1. Baseline cases specifications.

	Baseline Scenarios (Business as Usual)	
	Short haul	Long haul
Flight distance	1,007 km	5,539 km
Flight duration	1h50	7h50
Aircraft type	B738	B788
Aircraft capacity	189 passengers	248 passengers
Service provided	Catering, Comfort, Hygiene	Catering, Comfort, Hygiene, Entertainment

Each parameter mentioned in Table 1 is relevant to the carbon footprint calculation because they affect the emissions. More specifically, emissions are sensitive to parameters such as flight distance and aircraft weight because of their direct connection to fuel demand. Moreover, jet engines have a wide range of technical characteristics based on their model, which results in different emission patterns. Therefore, the aircraft type and flight distance parameters have a key role in the carbon footprint calculation.

Measures

Five alternative measures have been built representing potential sustainable and circular practices for inflight services. These measures are applied to the two baseline flight cases and consist of plastic removal, reduction of food waste, the substitution of heavy material with more lightweight options, carbon offsetting, and a combination of all the above practices.

A1. Less single-use plastic

The reduction and removal of plastic from flights have been popular practices in the past years (Aviation Benefits, 2022). Several airlines have removed a variety of single-use plastic items from their service equipment and have replaced them with other biobased alternatives such as paper packaging and wooden cutlery (Ryanair, n.d.; Etihad Aviation Group, n.d.). Therefore, this is an important circular practice that can be investigated. In this alternative, several plastic service materials are replaced with biobased alternatives, more specifically paper (see Table 2). Furthermore, recycled plastic is used wherever possible.

Table 2. List of the single-use plastic products substituted in A1.

Short-haul		Long-haul	
Discontinued	**Substitution**	**Discontinued**	**Substitution**
Plastic cup	Paper cup	Plastic cup	Paper cup
Coffee cup with lid	Paper cup	Water bottle	Water bottle from recycled PET
Water bottle	Water bottle from recycled PET	Food container lids	Reusable food container lids
Sandwich packaging	100% paper packaging	LDPE cutlery packaging	Cutlery wrapped in napkin

A2. Zero food waste

As discussed in the introduction, airline food waste is an impactful practice for the environment. For this study, 20% of the food and drinks are considered to end up in waste. This is an assumption made following the European food market trends (Food Waste, n.d.). Reducing the amount of discarded food can lower the carbon footprint, and some airlines such as Qantas have already started applying this measure in (Aviation Benefits, 2022). The environmental performance of food waste reduction inflight will be assessed in this study by an alternative measure that assumes zero food waste. In the baseline scenarios, 20% of food waste is expressed as part of the cabin waste that ends up in the landfill. This scenario assumes 0% food waste which implies that a passenger consumes 100% of the provided food inflight and can be expressed as a reduction in cabin waste.

A3. Lightweight equipment

Given the relationship between weight and emissions in aviation, the investigation of a measure that introduces more lightweight equipment could be insightful. Aluminium is a durable and lightweight material used extensively in aircraft fuselage and components manufacturing, while steel is mostly used in the manufacturing of landing gears and engines due to its durability under high temperatures (Sharma & Srinivas, 2020; Thuline, 2021). In the cabin, aluminium and steel can be found in equipment such as meal carts and containers as well as in the seat structures. Carbon fiber is another popular material used extensively in aircraft interior ceilings, flooring, and wall panels due to its high strength and lightweight abilities (Black, 2006; Sharma & Srinivas, 2020). Titanium is a popular replacement for steel due to its lower density and equal durability (Chatterjee & Bhowmik, 2019). It can be found in alloys in the structural components of the aircraft.

This scenario investigates the substitution of seat frame materials such as aluminium, steel, and plastic with lighter but equally durable alternatives, such as carbon fiber and titanium. A typical aircraft seat frame consists of aluminium, steel, and plastic components (Frank & Gneiger, 2017). As reported by the aircraft seat manufacturer Expliseat (2022), titanium and carbon fiber seat frames can become a more lightweight option and reduce seat weight and fuel emissions. In this scenario, the carbon footprint reduction potential of the introduction of a lightweight aircraft seat is assessed.

Table 3. List of the seat frame materials substituted in A3.

Seat frame (short and long-haul flights)			
Discontinued		**Substitution**	
Aluminium	5.7 kg	Titanium	4.1 kg
Steel	1.3 kg		
Plastics	2.2 kg	Carbon fibre	1.3 kg
Total weight	**9.2 kg**	**Total weight**	**5.4 kg**

A4. Carbon offsetting

The fourth scenario is aiming to investigate the overall carbon footprint reduction by carbon offsetting schemes. As discussed in the introduction, the implementation of CORSIA has incentivized airlines to offset their carbon emissions and therefore become carbon neutral. This can be done via various programs, with reforestation being the most popular one. Although carbon offsetting is not a circular application, it is used as a solution to compensate for flight emissions. By planting more trees, in theory, the aircraft carbon emissions are counterbalanced, and carbon gets stored back in natural reserves (i.e., forests), accelerating the, otherwise slow, carbon circle. However, carbon offsetting programs have received criticism (Greenpeace UK, 2020; Greenfield, 2021), and airlines using them as an emissions compensation scheme are being sued for greenwashing ("Environmentalists Sue Dutch Airline KLM for 'Greenwashing', 2022). Further research is needed to quantify whether carbon offsetting via reforestation is beneficial for the environment.

Some European airlines offer passengers the option to offset their emissions via donating to reforestation projects (KLM, 2022; Air France, n.d.; Lufthansa, n.d.). A common methodology used to estimate the total CO_2 emissions calculates the average fuel consumption per passenger for each flight (KLM, 2019). The overall mass used for this calculation includes the mass of the payload (passengers and luggage) and the equipped mass, the mass of the specific equipment necessary for the flight, and the transportation of the payload. Thus, the calculated emissions to be offset are solely based on fuel consumption due to weight and do not include emissions of any other stage of a flight's lifecycle. Consequently, for the calculations of the offset emissions, this scenario only considers CO_2 emissions from fuel consumption due to the equipped mass of service provision activities. These emissions are assumed to be offset by 100%. Other emissions are not included in this scenario. Table 4 contains an overview of the calculated CO_2 emissions per service group (catering, comfort, hygiene, and entertainment) as well as the total emissions that are being offset (expressed as negative emissions). The total offset emissions are then subtracted from the overall carbon footprint to obtain the results of this scenario. More details on the emissions calculations are presented in subsection 2.2.3 and Appendix 11.

Table 4. CO_2 emissions associated with the weight of each service group.

CO_2 emissions (kg)		
	Short-haul flight	Long-haul flight
Catering services	0.88	7.01
Comfort services	5.02	18.41
Hygiene services	1.67	13.03
Entertainment services	-	2.73
Total CO2 emissions	7.57	41.19
Offset CO2 emissions	-7.57	-41.19

A5. Combined scenario

Finally, the fifth alternative will represent a more complex scenario that combines all four of the investigated measures.

Reference flows

Following the description of the two baseline scenarios and the five measures, the reference flows are formed as follows:

Baseline cases:

- **BAU short-haul:** Provision of inflight services for a short-haul flight per passenger
- **BAU long-haul:** Provision of inflight services for a long-haul flight per passenger

Alternative measures:

- **A1 - short-haul:** Provision of inflight services for a short-haul flight per passenger with less single-use plastic
- **A1 - long-haul:** Provision of inflight services for a long-haul flight per passenger with less single-use plastic
- **A2 - short-haul:** Provision of inflight services for a short-haul flight per passenger with 0% food waste
- **A2 - long-haul:** Provision of inflight services for a long-haul flight per passenger with 0% food waste
- **A3 - short-haul:** Provision of inflight services for a short-haul flight per passenger with lightweight materials
- **A3 - long-haul:** Provision of inflight services for a long-haul flight per passenger with lightweight materials
- **A4 - short-haul:** Provision of inflight services for a short-haul flight per passenger with carbon offsetting
- **A4 - long-haul:** Provision of inflight services for a long-haul flight per passenger with carbon offsetting
- **A5 - short-haul:** Provision of inflight services for a short-haul flight per passenger - combined measures
- **A5 - long-haul:** Provision of inflight services for a long-haul flight per passenger – combined measures

2.2 Inventory Analysis

In this section, the product systems for the baseline cases are defined. First, the system boundaries and flowcharts are presented, followed by an overview of the process data involved. Then the section discusses the cut-offs and the absence of multifunctional processes.

2.2.1 System boundaries

Economy-environment system boundary

The system boundaries of this study are set over the entire life cycle of service-related products within the aircraft cabin interior. The life cycle stages included in the analysis are manufacturing, use phase, and EOL. The boundary between the economy and the environment is mostly crossed by the environmental flows created by manufacturing and EOL processes. There is a variety of products and equipment used in inflight service provision, therefore all kinds of emissions are included ranging from emissions from material extraction and chemical used for manufacturing to emissions from waste treatment. Direct emissions from foreground processes were modelled only in two cases: the coffee beans roasting process, due to lack of background processes in the database, and in the case of carbon offsetting alternative, where the avoided impact was modelled as negative carbon dioxide emissions. All other processes were modelled using economic flows.

Cut-off

Due to the complexity of the system, several cut-off choices were made. The number of foreground processes modelled and the absence of direct data from the industry and the time frame of the present study reduced the level of detail of this analysis. More specifically, electricity inputs for most of the production processes were omitted. Due to a lack of data on electricity requirements for product manufacturing, and the number of processes included in the system boundary, these flows were cut off. However, electricity could not be omitted from the whole study. Most material production background processes include electricity. Electricity was also included in a few production processes wherever electricity data were available through other LCA studies (such as in the case of seat cover textile production). Table 5 has an overview of the electricity inputs included and omitted from the production stages of the study. Electricity consumption was however included in processes that do not represent product manufacturing but are describing a service, such as service equipment cleaning. Finally, electricity generated in flight was also omitted due to the complexity of its modelling.

Table 5. Electricity flows included and omitted from the system boundary.

Electricity Flows Omitted	Electricity Flows Included	
All catering products manufacturing processes (except hot meal)	Hot meal production	market for electricity, medium voltage, RER
All comfort products manufacturing processes (except seat cover)		
All hygiene products manufacturing processes	Seat cover production	
All entertainment products manufacturing processes		

The same pattern as the electricity flows can be observed for the flows representing the transportation of products. Transport from the production facilities to the aircraft has been omitted for all products of the study except the transport of the used service and comfort equipment from the aircraft to the equipment washing facilities. This choice is expected to affect the overall result, however, since it has been applied consistently throughout the whole study, it is not expected to alter the relation between other impacts. Finally, grease from the production of the seat cover (wool production) was also cut off.

2.2.2 Flowcharts

The analysis consists of two main flowcharts representing the two BAU cases (Figures 6 and 7). Due to the size of the system and the number of products involved, simplified versions are included in this report. Most products are grouped into four main service categories: catering, comfort, hygiene, and entertainment. Each service category includes sub-categories of grouped products based on their function. An overview can be found in Table 6.

Table 6. Grouped products and services.

	Grouped Services	**Grouped products**
Inflight Service provision	Catering	Service Equipment
		Airline food production
		Drinks production
	Comfort	Seat
		Carpet
		Blankets
		Pillows
	Hygiene	Water
		Soap
		Toilet paper
	Entertainment	IFE
		Headphones
		Newspaper

BAU – Short haul

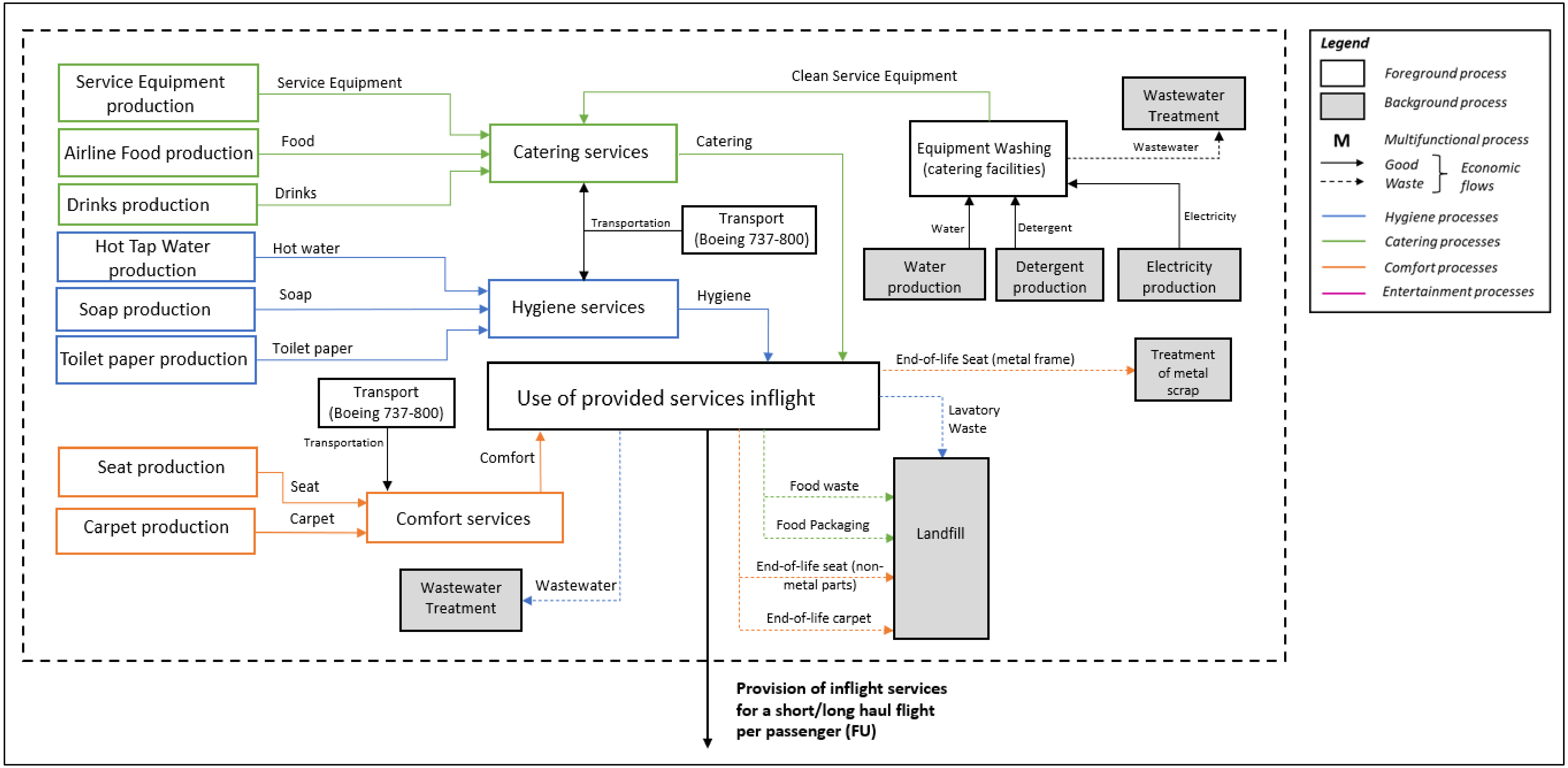

Figure 6. BAU - Short-haul flight flowchart.

BAU – Long-haul

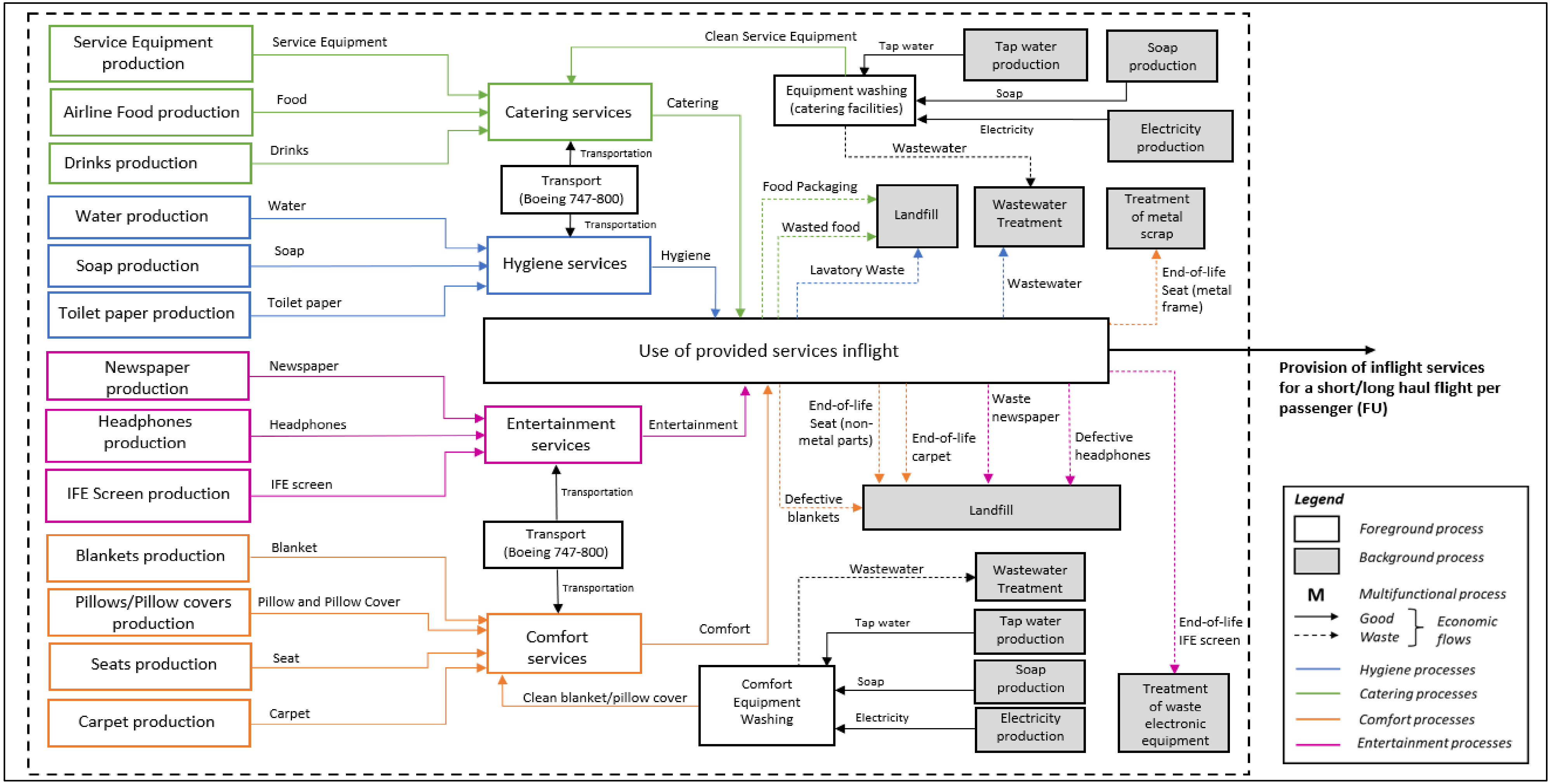

Figure 7. BAU - Long-haul flight flowchart.

2.2.3 Data collection and relating data to unit processes

In this sub-section, each scenario is presented in more detail and data collection is explained. Processes and data are organized in tables. Appendices 1,2 and 13-19 contain unit process data tables with all economic flows for each process mentioned, along with calculations and data sources. The calculations and explanation of proxies are also included in these Appendices. However, due to the large number of processes, this section contains only the processes representing the four main service groups and the respective main process that represents the use of provided services inflight.

Data collection

The main data source of this study is the ecoinvent database (version 3.8). Due to the limited studies available on inflight services LCAs, only a fracture of data was collected from published literature. Most data were sourced from secondary sources which might influence the results. These secondary sources consist of published reports, news articles, and equipment manufacturers' websites. Also, assumptions and proxies were used in some cases to enable the data collection process (see sub-section 3.2.4).

Fuel burn and jet engine emissions calculations

Fuel burn and jet engine emissions calculations involve complicated calculations. This project has approached it in a simplified way. The European Environment Agency (EEA), (2019) published the report 'EMEP/EEA air pollutant emission inventory guidebook' aiming to provide technical guidance to prepare national emission inventories. Under the 'Aviation' chapter, this guidebook includes a 'Master Emissions Calculator' model that has been built on databases from the European region. The model can calculate the fuel burn and emissions of a large variety of aircraft types over a broad range of distances. The emissions consist of CO_2, CO, H_2O, HC, NOx, SOx, and soot. The calculations consider the difference in the consistency of the emissions occurring during the landing/take-off phases (LTO) and climb/cruise/descend flight phases (CCD). ICAO defines an LTO cycle as those activities occurring up to 914.4 meters above ground level and a CCD cycle as activities occurring above 914.4 meters (ICAO, 2011). Both phases are taken into account in the calculations.

The EEA model quantified the emissions released by the flights in both baseline cases. To obtain information on the exact amount of fuel burned and the exact emissions that can be linked to 1 kilogram of products transported over a fixed distance, a simplified approach was followed. An emission factor was calculated for both aircraft types representing the two baseline scenarios by dividing the total fuel weight (FW) by the aircraft take-off weight (TOW) minus the weight of the fuel burned during the flight (FWused). To calculate the *TOW* aircraft specific data were used such as aircraft operating empty weight (OEW), max payload weight (PLW), and total fuel weight (FW) as shown in Equation 1. Full payload was assumed for both cases. The total fuel consumed in both flight scenarios was calculated by the EEA model. To calculate the *FWused,* Equation 2 was employed, where *Mff* represents the total fuel weight fractions over a flight (mission) and can be calculated by Equation 3. A fuel fraction represents the ratio of the weight at the end to the weight at the beginning of a given flight phase. All fuel fractions described in Equation 2 represent each flight phase as illustrated in Figure 8 and have already been calculated with the exemption of the cruise phase fuel fraction ($\frac{W5}{W4}$). This fuel fraction is connected to the flight range and therefore differs for each case. Breguet's range equation (Equation 4) was used for its quantification, where R is the range of the flight, V is the speed of the aircraft, g is gravity, and $\frac{L}{D}$ is the lift-drag ratio.

$$TOW = OEW + PLW + FW \tag{1}$$

$$FWused = (1 - Mff) * TOW \tag{2}$$

$$Mff = \frac{W1}{Wtakeoff} * \frac{W2}{W1} * \frac{W3}{W2} * \frac{W4}{W3} * \frac{W5}{W4} * \frac{W6}{W5} * \frac{W7}{W6} \tag{3}$$

$$R = \left(\frac{V}{g*Cj}\right) cruise * \left(\frac{L}{D}\right) cruise * \ln\left(\frac{W4}{W5}\right) \tag{4}$$

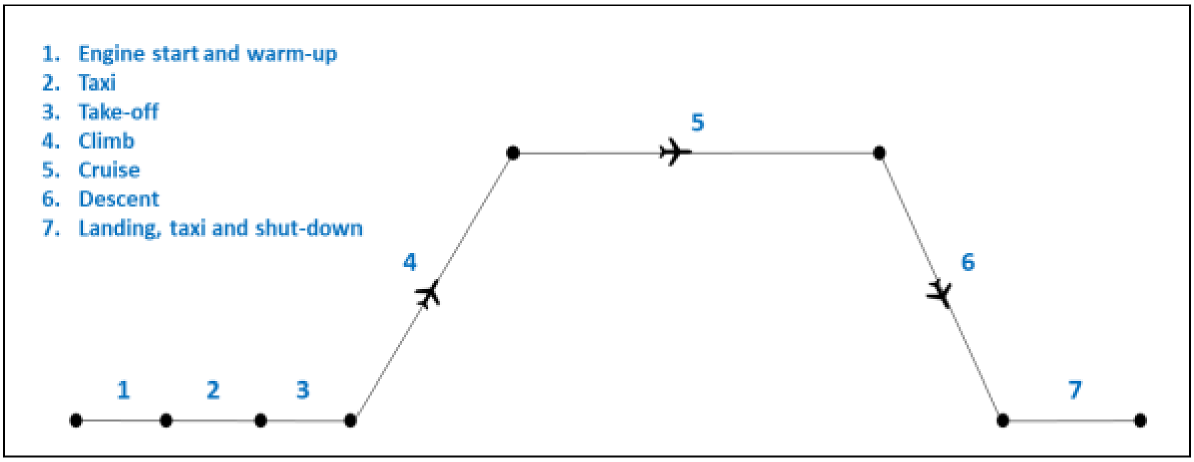

Figure 8. Flight stages for fuel fractures calculations.

Having calculated the *TOW* and *FWused*, the total aircraft weight excluding the used fuel (Wexl) was estimated. By dividing *FW* with *Wexl*, a ratio of fuel per kilogram of product was obtained for each aircraft type. Then using this ratio, and knowing the total weight of each product, an estimation of the total fuel burned per kilogram was made. Finally, knowing the exact weight of each emission type that corresponds to the total fuel burned, the exact emissions per kilogram of product were calculated proportionally. This way transported weight, over a specified distance with a specified aircraft type, and emissions released were related to each other. An overview of the emission factors for each flight scenario can be found in Table 7 and an overview of the detailed calculations can be found in Appendix 11.

Table 7. Emission factors for each flight scenario.

Aircraft type	**Emissions per kilogram transported**							
	Fuel (kg)	**CO_2 (kg)**	**CO (kg)**	**NOx (kg)**	**SOx (kg)**	**H_2O (kg)**	**HC (kg)**	**Soot (PM) (kg)**
B738 (1007 km)	6.60E-02	4.16E-01	7.79E-04	1.82E-03	1.11E-04	1.62E-01	8.76E-05	1.27E-05
B788 (5,539 km)	2.29E-01	1.44E+00	2.39E-03	4.79E-03	3.84E-04	5.63E-01	8.90E-05	4.02E-05

Data and unit processes

There are over eighty unit processes in this study. Tables 8 and 9 contain the weight that is attributed to the service provision processes that are offered to each passenger. Some equipment items, such as meal carts, are used to serve multiple passengers on a flight, therefore the weight that is accounted for each passenger does not represent the total weight of the equipment but just a fracture of it. Other products that are offered to a passenger for personal use, such as food, seat, water for hygiene purposes, etc., are not shared and therefore their full weight is attributed to one passenger. An overview of all the processes, data, assumptions, and calculations, for the BAU cases and measures, can be found in Appendices 1 and 2.

Table 8. Inflight services weight per passenger by service group – short-haul flight.

Short-haul flight				
Inflight service group		Amount	Unit	Details
Catering	Food, drinks & packaging	0.951	kg	Sandwich, coffee, water, and packaging.
	Service Equipment	1.17	kg	Meal cart, galley container, drawers, vacuum flask.
	Total	2.121	kg	
Comfort	Seat	11.5	kg	Seat frame, seat cover, cushion, seat belt
	Carpet	0.567	kg	
	Total	12.067	kg	
Hygiene	Water	4	kg	Sink and toilet water
	Soap	0.002	kg	
	Tissue	0.011	kg	
	Total	4.0134	kg	
Total weight of services per passenger		18.2013	kg	

Table 9. Inflight services weight per passenger by service group – long-haul flight.

Long-haul flight				
Inflight service group		Amount	Unit	Details
Catering	Food, drinks & packaging	1.925	kg	Two full meal services (a hot meal and a cold meal), water, coffee, and packaging.
	Service Equipment	2.939	kg	Meal carts, containers, vacuum flasks, drawers, tableware.
	Total	4.865	kg	
Comfort	Seat	11.3	kg	Seat frame, seat cover, cushion, seat belt.
	Carpet	0.567	kg	
	Blanket	0.5	kg	
	Pillow	0.4	kg	
	Total	12.77	kg	
Hygiene	Water	9	kg	Sink and toilet water.
	Soap	0.006	kg	
	Tissue	0.034	kg	
	Total	9.04	kg	
Entertainment	IFE unit	1.69	kg	Inflight entertainment touch screen.
	Headphones	0.1	kg	Reusable headphones.
	Newspaper	0.105	kg	
	Total	1.895	kg	
Total weight of services per passenger		28.577	kg	

2.2.4 Data quality

Many materials and processes used in this study were not available in the ecoinvent database. The data gap problem was solved with the use of proxy processes available in ecoinvent, with similar functions and estimated environmental impact. Proxies have been used mostly for food products such as watermelon and walnuts. Some other data gaps were solved by adopting assumptions**.** Several assumptions were used in this study, mostly about the life expectancy of products, the material composition of each piece of equipment, the use cycles of equipment before they get retired, and the end-of-life of the products. All proxied products and assumptions are documented in Appendices 1,2 and 13-19.

Another data issue encountered was the geographical coverage of the processes. Production, use, and end-of-life phases occur in Europe for both alternatives and most process datasets. However, some materials can be imported from countries outside Europe such as coffee and sugar. Moreover, whenever European datasets were not available, global datasets were used. This was observed mostly for food production processes, i.e., milk and vegetables, but also for waste treatment methods such as wool textile production. A market mix for Europe was used consistently throughout the study. Finally, in a few cases datasets from Switzerland [CH], Spain [ES], or The Netherlands [NL] were assumed to represent the whole of Europe.

2.2.5 Multi-functionality and allocation

The study does not contain multifunctional processes. Approaching equipment cleaning processes as services was the solution to multifunctional systems. There are two equipment washing processes in this study, catering equipment washing and comfort equipment washing. Both processes could be considered multifunctional since there are two functions present: cleaning the used equipment and providing clean equipment. To avoid allocating these flows, both processes were modeled as services.

2.3 Impact assessment

In the impact assessment section, the environmental impact of all the assessed scenarios is quantified. First, the impact category selection is described. Then the characterization results of all scenarios are presented and the economic flows that are not followed to system boundary are described.

2.3.1 Impact categories

The ReCiPe Midpoint (H) characterization family is used in the present study. The analysis is approached at a midpoint level focusing on the environmental flows and avoiding high uncertainties. The time horizon is one hundred years, following the hierarchist perspective. One impact category is used throughout the whole analysis, the climate change impact category measured in kg CO_2-eq. This choice was made considering the contribution of aviation to climate change (as discussed in the introduction) and the time frame of the study. It would be interesting to investigate other impact categories as part of further research on the topic.

2.3.2 Characterization results and discussion

The characterization results for the baseline scenarios and the five alternatives are presented in Table 10. As expected, the impact of a long-haul flight is four times higher than the impact of the short-haul flight scenario. This can be explained by the highest amount of fuel a long-haul flight consumes in comparison to a short haul-flight. Furthermore, more services are provided on long-haul flights, which increase the overall weight.

As demonstrated in Table 10, alternative measures perform better than the BAU cases however decreasing the amount of single-use plastic (A1) and food waste (A2) does not contribute to a significant impact reduction, less than 1% reduction for both scenarios. On the other hand, the reduction of transported weight by using lightweight materials (A3), results in a 13.81% and 19.1% carbon footprint reduction for the long- and the short-haul flights, respectively. This highlights the importance of lightweight equipment. Finally, the carbon offsetting measure (A4) displays the best results in terms of carbon emissions reduction, 82% for the long-haul flight and 70% for the short-haul flight. This is because of the negative CO_2 emissions considered in the modelling process. The combined measures scenario (A5) entails a summation of the previous measures and represents the maximum impact reduction that can be achieved in this study: approximately 96% for a long-haul flight and 89% for a short-haul flight.

The offsetting measure accounts for most of the impact reduction in A5. This is a significant finding of the study which highlights the importance of lightweight materials in aviation and the potential carbon capture has as a carbon footprint reduction measure. The impact of food waste and plastics as compared to payload seems insignificant. However, it can still reduce the impact, even on the small scale. A graphical representation of the results is illustrated in Figure 9.

Table 10. Characterization results for the use of provided inflight services per passenger.

Impact Category	**ReCiPe Midpoint (H), Climate Change, GWP100**				
Alternatives	Long-haul flight		Short-haul flight		Unit
Baseline scenario – BAU	50.24		10.89		kg CO_2-Eq
A1. Less single-use plastic	50.06	-0.36%	10.84	-0.43%	kg CO_2-Eq
A2. 0% food waste	50.09	-0.30%	10.84	-0.41%	kg CO_2-Eq
A3. Lightweight materials	43.3	-13.81%	8.81	-19.10%	kg CO_2-Eq
A4. Carbon offsetting	9.05	-81.99%	3.32	-69.55%	kg CO_2-Eq
A5. Combined measures	1.79	-96.44%	1.17	-89.22%	kg CO2-Eq

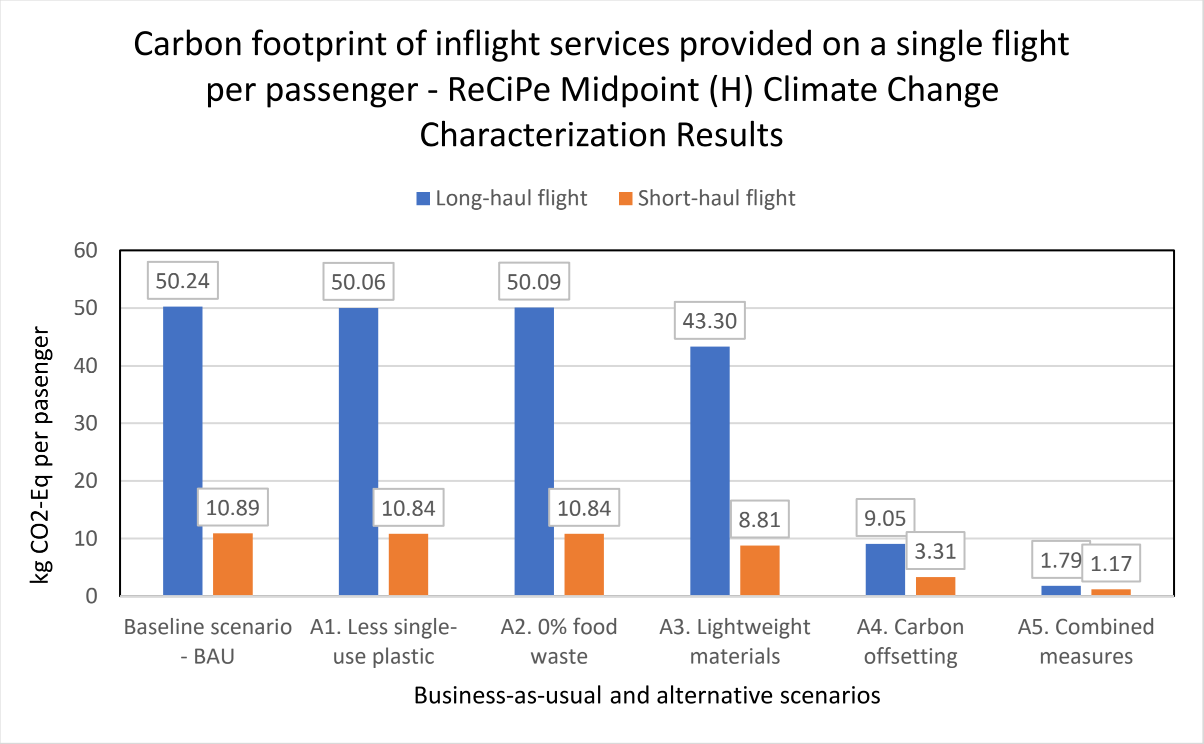

Figure 9. Carbon footprint of inflight services provided on a long-haul and a short-haul flight per passenger and measure scenarios.

To put these results into perspective, the carbon footprint attributed to the transportation of one passenger was calculated. According to Berdowski et al., (2009), the average passenger weighs 88 kilograms and the average luggage weighs 17 kilograms. The overall carbon footprint of an average passenger including one luggage piece was calculated as 43.7 kg CO2-Eq for a short-haul flight and 151.2 kg CO2-Eq for a long-haul flight. These results represent the emissions from the fuel amount required to transport the weight of the passenger and they should not be interpreted as the overall carbon footprint of a passenger. Figure 10 illustrates these results in addition to the inflight services carbon footprint, which represents 20% to 25% percent of the total impact for the short-haul and the long-haul flight respectively.

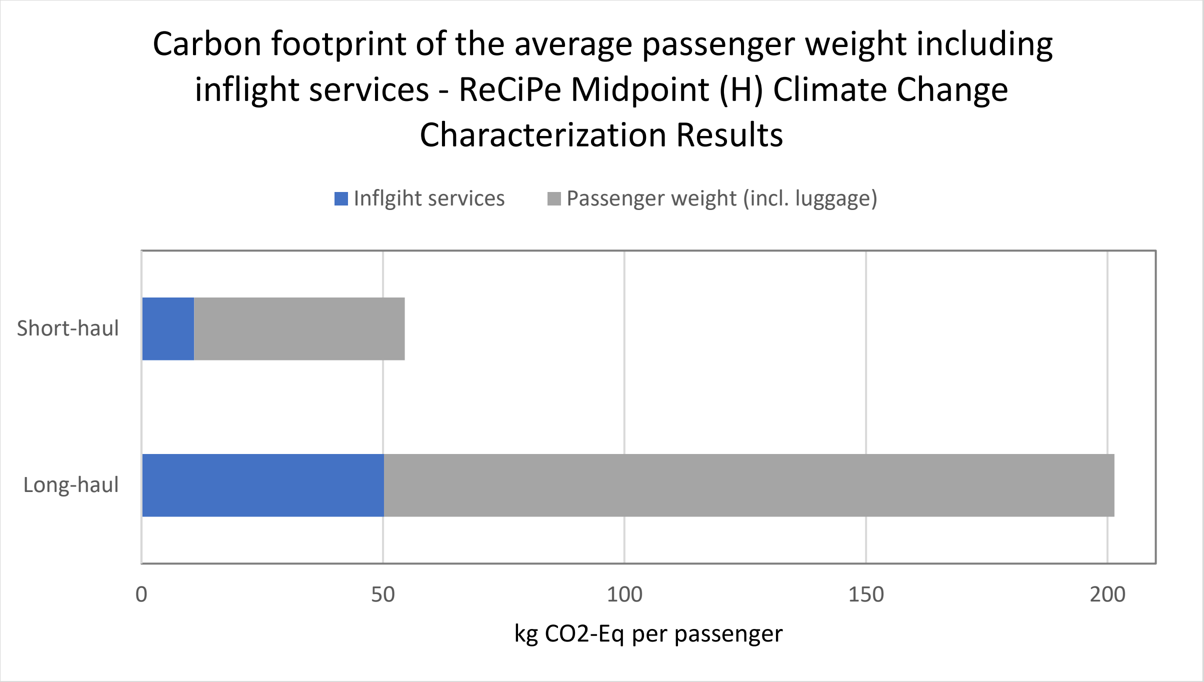

Figure 10. Carbon footprint of the transportation of an average passenger (incl. luggage) including the carbon footprint of provided inflight services.

2.3.3 Economic flows not followed to the system boundary

Despite the effort to make the study as complete as possible, some assumptions had to be followed which limited the scope of the work and require a careful interpretation of the results. Several processes were cut off and not followed by the economy-environment system boundary. An overview of these processes can be found in detail in section 3.2.1.

2.4 Results Interpretation

In this section, the consistency and completeness checks of the study are performed. A contribution analysis is also conducted, and impact hotspots are identified. Finally, the sensitivity of the model is assessed using four different scenarios.

2.4.1 Consistency check

The consistency of the model, data, and assumptions with the goal and scope definition of the study is determined through a consistency check (Guinee, 2002). The goal of the study is to quantify the carbon footprint of emissions reduction measures on commercial inflight services offered by European airlines and compare it to BAU practices that have been the norm for the past years while pointing out their impact hotspots. The study is deemed consistent with its goal and scope in terms of data age and temporal coverage.

However, a few inconsistencies have also been identified. Throughout the modelling process, data gaps have been encountered. The detail level of a few processes such as the 'hot meal production' was relatively higher than other processes such as the 'plastic cup production'. Moreover, a broad range of data sources was used, including scientific publications, news articles, and product manufacturers' websites. These differences in data accuracy and data sources between processes have resulted in inconsistencies. Another identified inconsistency is the difference in geographical representativeness. As described in sub-section 3.2.4, while the geographical coverage has been set to the European market and the models represent European airlines, due to data gaps datasets from other geographical regions had to be used as proxies. Concluding, the study suffers from some inconsistencies that affect the quality of the results.

2.4.2 Completeness check

A completeness check ensures that the data included in the model are available and complete for the interpretation phase (Guinee, 2002). As stated several times throughout this study, data gaps were encountered. As discussed in sub-section 3.2.4, to overcome these gaps, assumptions, proxies, and cut-offs were employed. Appendices 1,2 and 13-19 contain all the assumptions used in this study.

Some of the assumptions used were encountered in other studies, such as the assumption that all inflight waste ends up in landfill and the assumption of the lifespan of several equipment pieces (Blanca Alcubilla, 2021). Where it was not possible to find valid assumptions from literature, logical assumptions were made based on similar cases in the study. An example of this approach is the cleaning of equipment. An assumption was made that the same water and electricity requirements to wash a meal cart apply to all other types of reusable catering equipment proportionally to their volume.

The use of the proxies approach was mostly encountered in food items. The items were proxied with comparable items such as melon production instead of watermelon. Finally, cut-offs were used as a last resort in most cases such as the grease from the wool production in the case of the seat cover production. Moreover, the decisions to cut-off electricity and transport inflows from most production processes were taken to manage the lack of data for most of the processes in a cohesive approach. These modelling decisions affect the completeness of the study. To encounter the completeness issue, data were cross-checked with results in the literature. However, the lack of similar published studies was another obstacle to this effort.

Overall, the model faces some completeness and consistency issues. This can be explained by the absence of a real-life case study. However, the nature of the study leans more towards providing an indication of the sustainability level of circular inflight service practices and an identification of impact hotspots. Consequently, the results should be interpreted more as a guide pointing in the direction of a successful implementation of circularity in aviation. Therefore, the results should not be viewed as definitive.

3.4.3 Contribution analyses

Two contribution analyses were performed to identify the environmental impact hotspots of the models: the contribution of each service product group to the overall flight impact and the contribution of processes to the overall flight impact. An overview of the calculations can be found in Appendix 9.

Contribution of grouped service products

Focusing on the baseline cases, Table 11 and Figure 11 contain an overview of the share of each service group over the total climate change impact of both cases. It can be observed that the largest contributor for both cases is the comfort services, 37% for the long-haul and 47% for the short-haul flights. These results are in line with the services weights reported in Tables 8 and 9, where comfort services are the heaviest among the other service groups. On the contrary, the second largest contributing service group for both cases is catering even though hygiene services are overall heavier. This pattern could be explained by other emission-intensive processes involved in the life cycle of catering services besides the transportation one. A process contribution analysis will investigate this pattern in the next part.

The third highest contributing service group is the hygiene services provision due to the amount of water and wastewater carried by the aircraft. For the long-haul flight, hygiene services score relatively close to catering and comfort services (26%) while for the short-haul flight it is significantly less (16%). The frequency of toilet usage increases as the flight becomes longer, therefore this is an expected result. Entertainment services are only provided in the long-haul case and their contribution to the overall impact is relatively small (6%) which can be explained by their small weight factor. Lastly, the small percentage expressed as ‘rest’ represents the impact of the transport of the waste flows from the aircraft to the landfill. As can be observed in Figures 6 and 7, the waste flows have not been attributed to any of the grouped services. On the contrary, they are modeled as outflows from the ‘use of inflight services’ process and therefore are labeled as ‘rest’.

Table 11. Characterization results for the baseline scenarios per service category.

	ReCiPe Midpoint (H), Climate Change, GWP100				
	Long-haul		**Short-haul**		**Unit**
Use of provided services inflight	50.24		10.89		kg CO_2-Eq
	Char. Result	Share	Char. Result	Share	
Catering Services	15.27	30%	3.71	34%	kg CO_2-Eq
Comfort Services	18.53	37%	5.06	47%	kg CO_2-Eq
Hygiene Services	13.09	26%	1.69	16%	kg CO_2-Eq
Entertainment Services	2.87	6%	-	0%	kg CO_2-Eq
Rest	0.49	1%	0.42	4%	kg CO_2-Eq

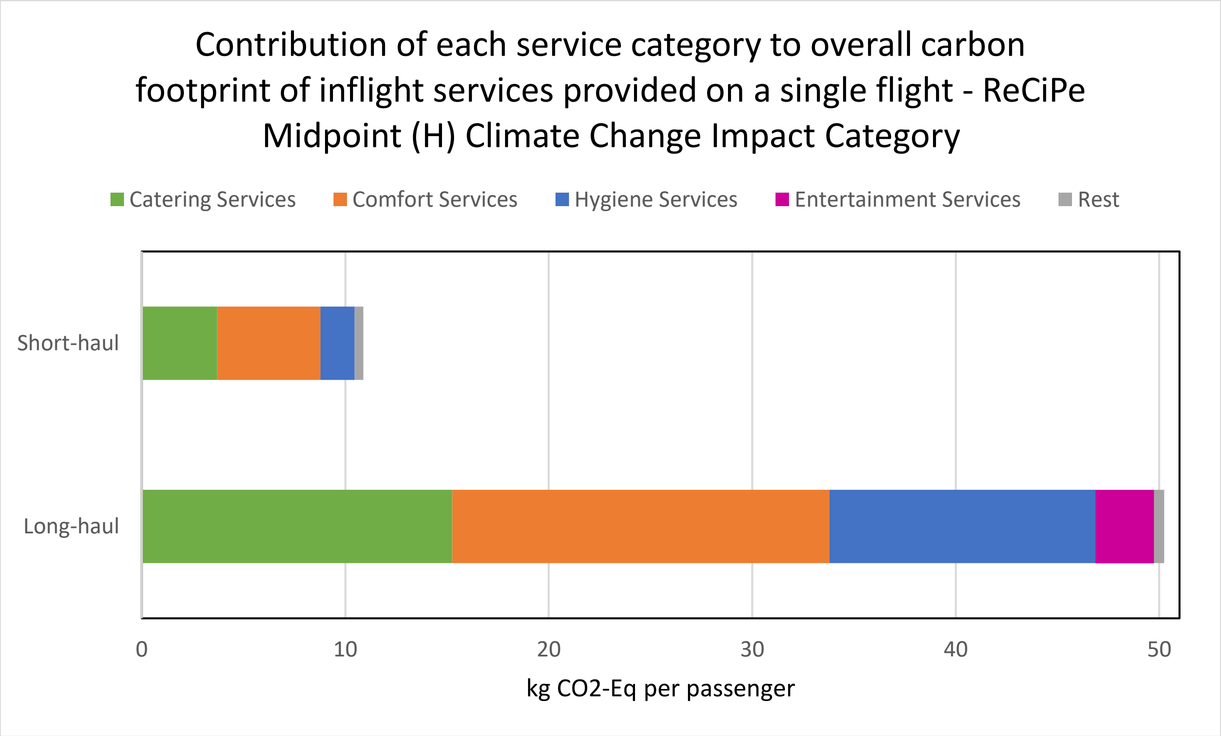

Figure 11. Contribution of each service category to the overall carbon footprint of inflight services provided on a single flight - Characterization results for the baseline scenarios per passenger.

Process contribution to the overall impact

The eight highest contributing processes to climate change are illustrated in Figures 12 and 13 for the short-haul and long-haul cases respectively including the studied carbon footprint reduction measures. The results are included in Tables 12 and 13. In alignment with Figure 11, the most contributing processes are the transportation of comfort, catering, hygiene, and entertainment related products and equipment. This result is directly related to the fuel needed to transport the weight and it has also been observed and discussed in a similar study (Blanca-Alcubilla et al., 2020). Although the aircraft transport processes are by far the highest contributors to the carbon footprint of inflight services per passenger, responsible for approximately 70% in the short-haul case and 80% in the long-haul case, other processes contribute to that impact, and are worth investigating.

More specifically, an interesting observation is the presence of different contributors for each case. More specifically, EOL treatment is the fourth highest contributor for the short-haul scenario, while for the long-haul the fifth place (since entertainment services have the fourth place) belongs to cow milk production. This difference can be explained by the single-use service equipment used in short flights which increases the amount of waste generated onboard. However, measures A1 and A2 still have the EOL treatment as their fourth highest contributor despite the single-use plastic substitution and the reduction of wasted food. Therefore, attention should be drawn to the overall single-use service equipment and packaging reduction and not only the plastic ones. On the other hand, on a long-haul flight, two full meals are served and thus the consumption of food is relatively higher. Moreover, all meals contain dairy products and none of the measures studied introduce vegan options, thus the milk production process remains the fourth highest contributor to all measures.

In the short-haul case, the fifth and sixth highest contributors are electricity production for use in the service equipment cleaning facilities and transport by lorry for the transportation of the used service equipment from the aircraft to the cleaning facilities as well as the waste transportation from the aircraft to landfill. The same processes are in the sixth and seventh place in the long-haul case top contributors list. Although these two processes do not happen onboard, they are still part of the services' life-cycle and thus are considered part of the analysis. This is an interesting example of why the LCA approach is necessary for environmental impact assessments.

The last two processes on the top eight highest contributor list for the short-haul flight are milk production and heat and power co-generation. The food served on the short-haul flight also contains dairy products, and the heat and power-cogeneration process is also related to the electricity production for use in the service equipment cleaning facilities. In the long-haul case, the last contributing process on the list is soybean production which serves as animal fodder in the cow milk production process. This highlights the importance of the dietary choices onboard and how that impact increases with the increase of the flight duration. It would be expected that the contribution of food-related processes would decrease with the application of the A2 measure. However, due to the modelling choices, that does not reflect in the analysis. This point should be considered in the interpretation of the results. Finally, carbon offsetting is identified as a negative impact contributor. This result is related to the modelling approach which expresses the emissions reduction as negative values.

Table 12. Contribution analysis results for the short-haul flight case.

Short-haul flight - Top 8 contributors to inflight services provision carbon footprint							
Process name	**BAU**	**A1**	**A2**	**A3**	**A4**	**A5**	**Unit**
Rest	2.306	2.282	2.305	2.307	2.414	2.391	kg CO2-Eq
Transport Short-haul Comfort	5.018	5.018	5.018	2.939	5.018	2.939	kg CO2-Eq
Transport Short-haul Hygiene	1.669	1.669	1.669	1.669	1.669	1.669	kg CO2-Eq
Transport Short-haul Catering	0.882	0.883	0.882	0.882	0.882	0.883	kg CO2-Eq
Product EOL treatment - Landfill	0.313	0.289	0.272	0.313	0.313	0.273	kg CO2-Eq
Electricity production, lignite (equipment cleaning)	0.230	0.230	0.230	0.230	0.230	0.230	kg CO2-Eq
Transport, lorry - waste and used equipment	0.195	0.195	0.194	0.195	0.195	0.194	kg CO2-Eq
Milk production, cow (catering)	0.164	0.164	0.164	0.164	0.164	0.164	kg CO2-Eq
Heat and power co-generation, hard coal (equipment cleaning)	0.109	0.109	0.109	0.108	-	-	kg CO2-Eq
Carbon offsetting via reforestation	-	-	-	-	-7.571	-7.571	kg CO2-Eq

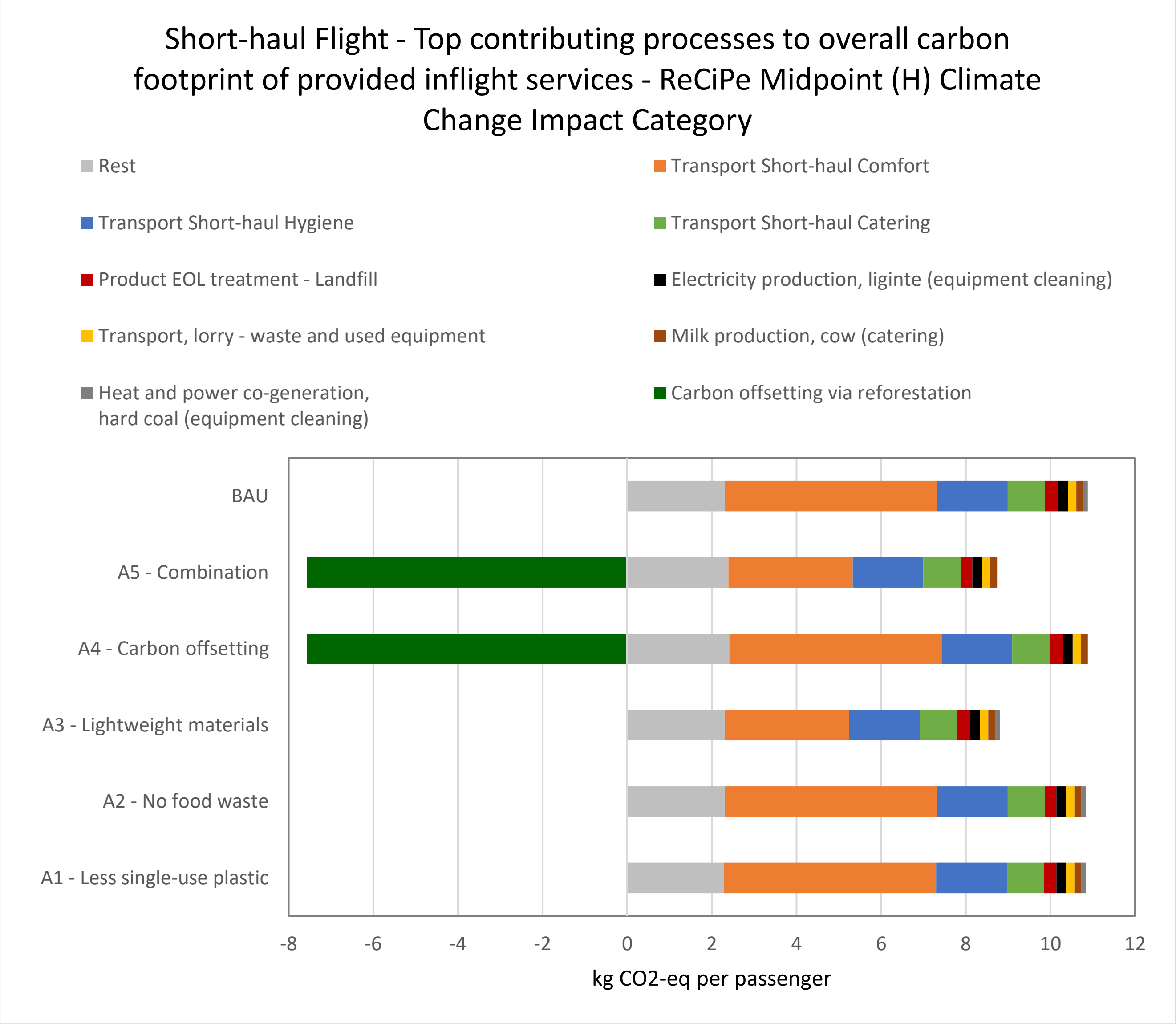

Figure 12. Contribution analysis results for the short-haul flight case.

Table 13. Contribution analysis results for the long-haul flight case.

Long-haul flight - Top 8 contributors to inflight services provision carbon footprint							
name	**BAU**	**A1**	**A2**	**A3**	**A4**	**A5**	**unit**
Rest	7.180	7.002	7.031	7.170	7.502	7.171	
Transport Long-haul comfort	18.399	18.399	18.399	11.472	18.399	11.472	kg CO2-Eq
Transport Long-haul hygiene	13.018	13.018	13.018	13.018	13.018	13.018	kg CO2-Eq
Transport Long-haul catering	7.005	7.005	7.005	7.005	7.005	7.005	kg CO2-Eq
Transport Long-haul entertainment	2.729	2.729	2.729	2.729	2.729	2.729	kg CO2-Eq
Milk production, cow (catering)	0.688	0.688	0.688	0.688	0.688	0.688	kg CO2-Eq
Electricity production, lignite (equipment cleaning)	0.503	0.503	0.503	0.503	0.503	0.502	kg CO2-Eq
Transport, lorry (waste and used equipment)	0.397	0.396	0.393	0.397	0.397	0.392	kg CO2-Eq
Soybean production (cow milk production)	0.322	0.322	0.322	0.321	-	-	kg CO2-Eq
Carbon offsetting via reforestation	-	-	-	-	-41.191	-41.191	kg CO2-Eq

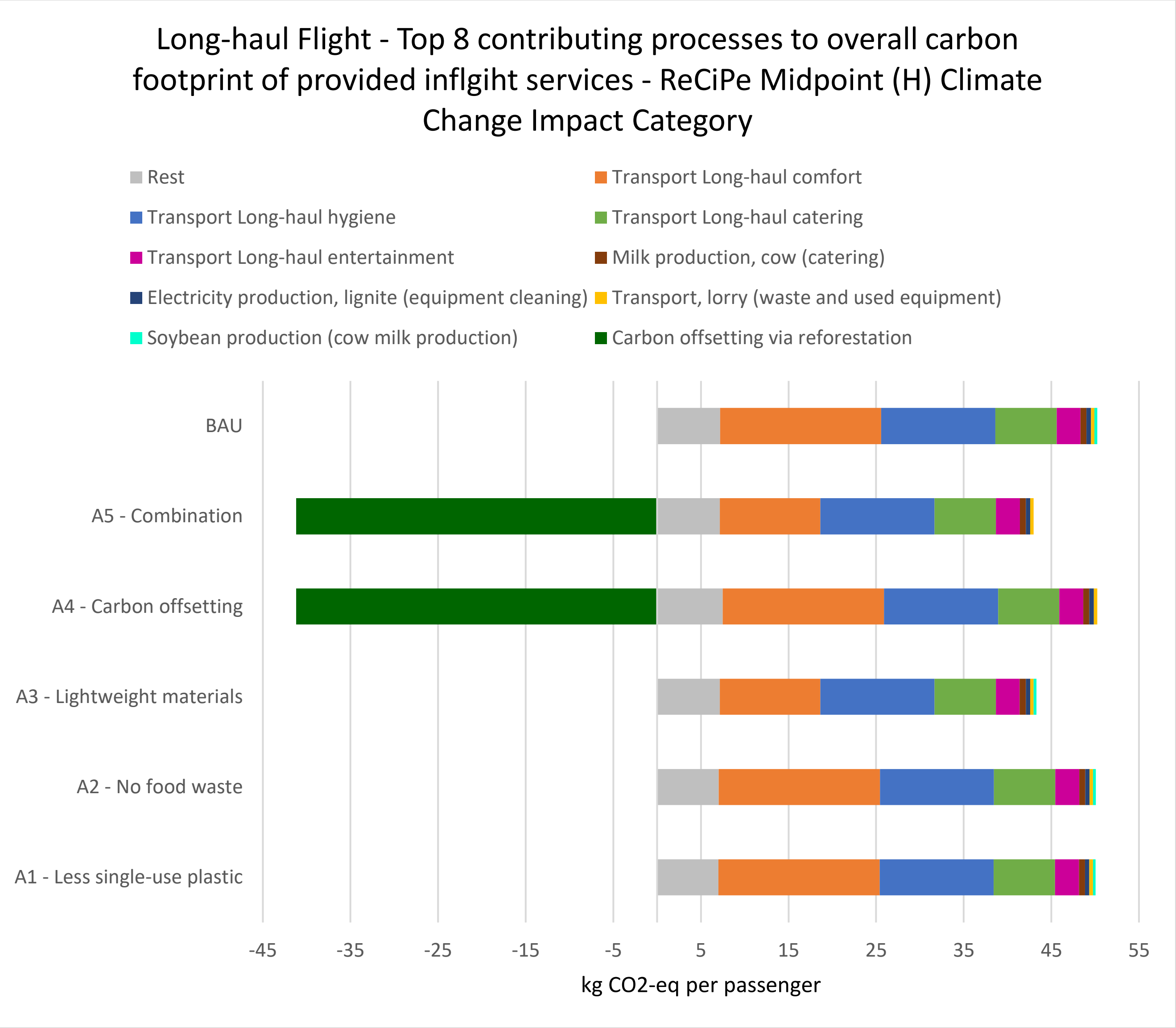

Figure 13. Contribution analysis results for the long-haul flight case.

2.4.4 Sensitivity analysis

To ensure the analysis is robust enough for decisions making, a sensitivity analysis on variations of process data, modelling choices, assumptions, and other variables was performed (Guinee, 2002). Based on the results of the contribution analysis, specific hotspots have been identified. As discussed in sub-section 2.4.3, these include emissions from fuel burn associated with the payload, emissions from electricity and transportation for equipment cleaning, and emissions related to agriculture and dairy products offered onboard. Based on these results, four sensitivity analyses were performed: sensitivity to flight distance, sensitivity to renewable electricity for equipment cleaning, sensitivity to a smaller distance between the airport and the landfill, and sensitivity to different EOL technology. It is important to mention that an interesting sensitivity analysis would be on transporting equipment and waste from the aircraft to the respective contractor with electric vehicles. However, the database does not include the dataset for electric vehicles yet and therefore a sensitivity analysis was not possible. An overview of the calculations can be found in Appendices 10 and 12.

Sensitivity Analysis 1: flight distance

In this sensitivity analysis, two scenarios with alternative flight distances were tested for each BAU scenario (Table 14). Two scenarios were developed: a 1,586 km flight of around 2h30 hours (London to Lisbon) and a flight of 8,700 km with an approximate flight time of 11 hours (London to Los Angeles). All scenarios were recovered from the Flight Distance Calculator website (2022).

Table 14. Sensitivity scenario 1 modelling *information.*

	Sensitivity Analysis 1 – Flight distance	
	Short haul	Long haul
Flight distance (km)	1,586 km	8,700 km
Flight duration	2h30	11h
Aircraft type	B738	B788
Aircraft capacity	189 passengers	248 passengers
Service provided	Catering, Comfort, Hygiene	Catering, Comfort, Hygiene, Entertainment

The results of this sensitivity analysis showed that the impact increases and decreases according to the flight distance (Figure 14). The 8,700 km flight had an impact of 67.4 kg CO_2-Eq which is 34% higher than the baseline. Similarly, the 1,586 km flight had an impact increase of 25% with a result of 13.7 kg CO_2-Eq. It can be observed that although the difference in distance between the short-haul flight baseline and sensitivity scenarios is only 579 km, the impact change is almost the same as the one for the long-haul scenario. On the other hand, the difference in distance between baseline and sensitivity scenarios for the long-haul flight is much higher (3200 km). Therefore, it can be concluded that the model is more sensitive to distances that range in the short-haul level.

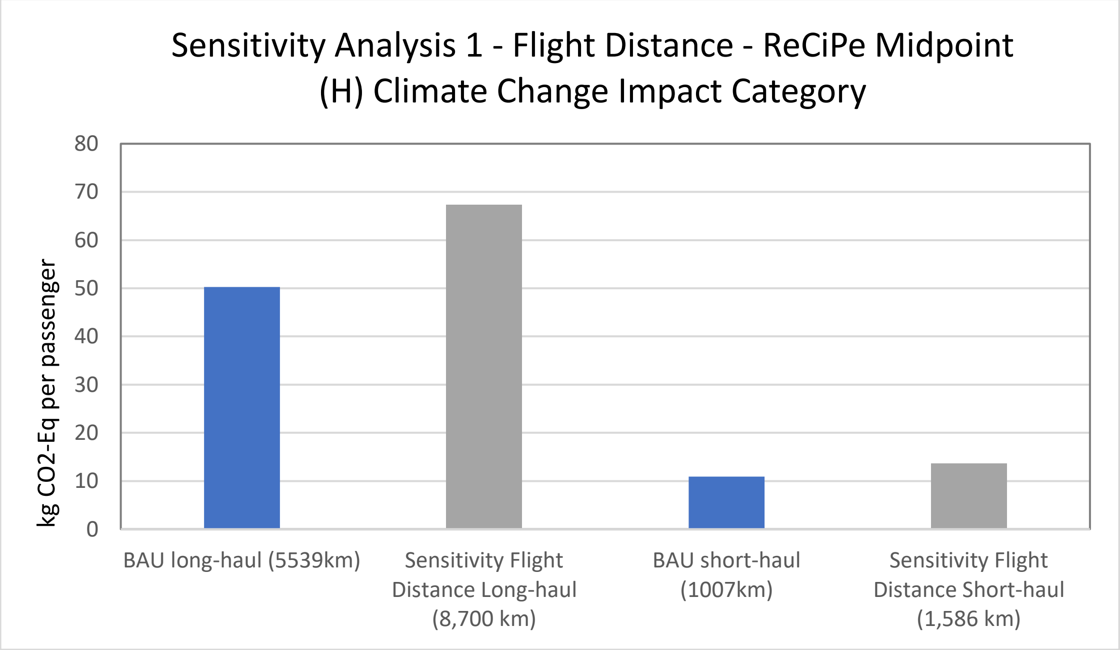

Figure 14. Sensitivity analysis results – flight distance.

Sensitivity Analysis 2: renewable electricity grid

In this sensitivity analysis, the European electricity market which has been used consistently throughout this study as the electricity source is replaced with renewable electricity via wind power. According to (Eurostat, 2022), wind power contributed 14.7% of the total net electricity generation in Europe. Therefore, onshore wind turbines were chosen to substitute the electricity source of this scenario. The processes substituted were electricity for equipment washing. The dataset used was retrieved from ecoinvent and represents the electricity production via onshore wind turbines of 1-3 megawatt. Since there is no dataset available representing the average of Europe, the dataset representing the Netherlands was chosen.

The results of the sensitivity showed a small reduction in the impact for both scenarios, as illustrated in Figure 15. The carbon footprint of the long-haul flight was reduced by 7% and the carbon footprint of the short-haul flight was reduced by 15%. These results show that the short-haul scenario is again more sensitive to changes.

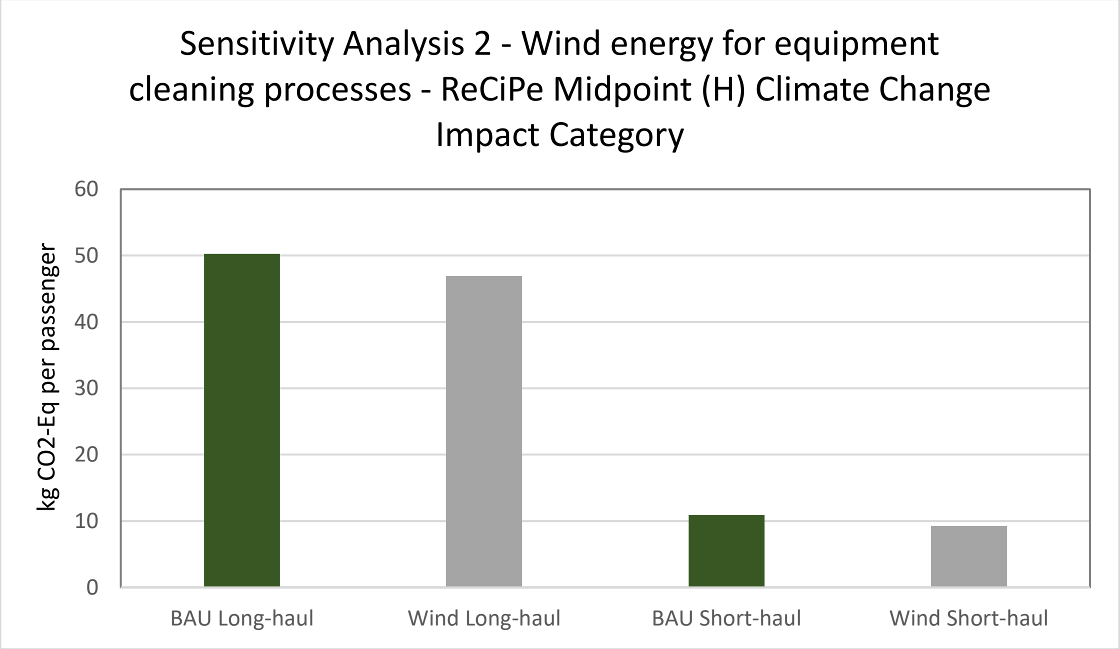

Figure 15. Sensitivity analysis results – renewable electricity for equipment cleaning processes.

Sensitivity Analysis 3: on-ground equipment transport distance

For the baseline scenarios, a distance of 40.3 km between the airport and the landfill has been assumed based on the data reported by Blanca-Alcubilla et al. (2020). In this part of the analysis, a distance of 20 km was assumed to investigate the sensitivity of the model to the transportation distance on-ground. As observed in Figure 16, the change in the distance between the aircraft and the landfill does not change the climate change impact significantly. Again, the short-haul flight model is more sensitive with a decrease in carbon footprint by 0.7%, while the carbon footprint of the long-haul model decreased by 0.1%.

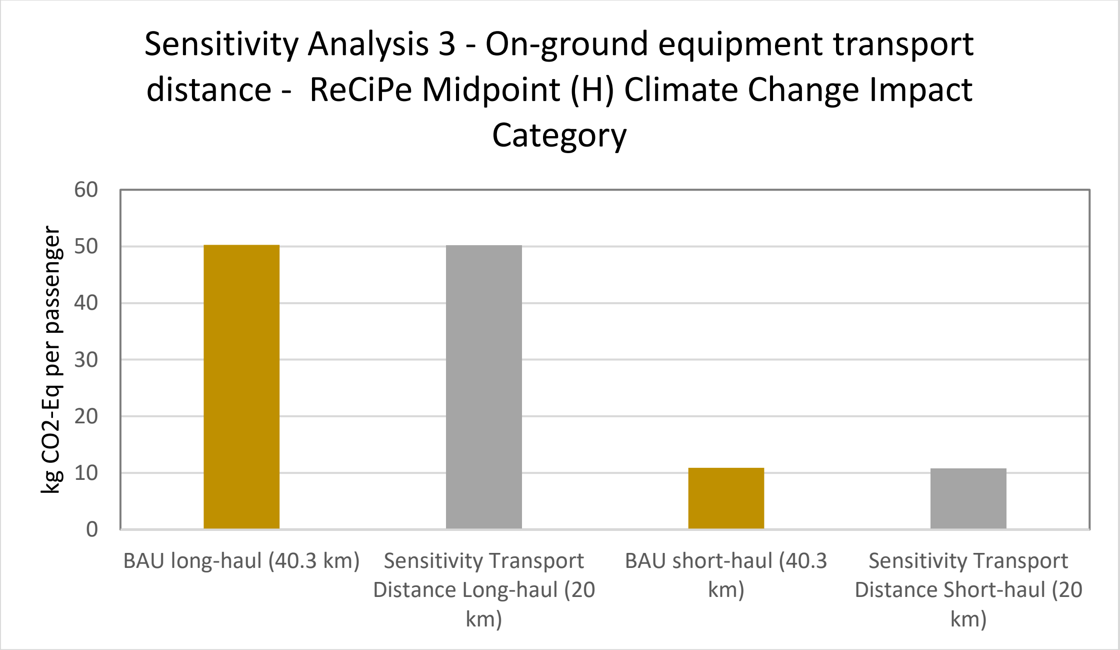

Figure 16. Sensitivity analysis results – on-ground equipment transport distance.

Sensitivity Analysis 4: EOL treatment

The final sensitivity scenario was built by substituting the current EOL treatment method (landfill) with another option, incineration. As discussed in the introduction, European legislation does not allow incineration as an EOL treatment method for international cabin waste. However, this option was chosen as an alternative waste treatment method in theory, and it does not represent a real-life scenario. The results as shown in Figure 17, indicated minimum to no change between the scenarios. More specifically, the long-haul incineration scenario displayed a small increase in the carbon footprint by 0.1%. The short-haul incineration scenario increased the carbon footprint by 0.2%, confirming again that it is a more sensitive model.

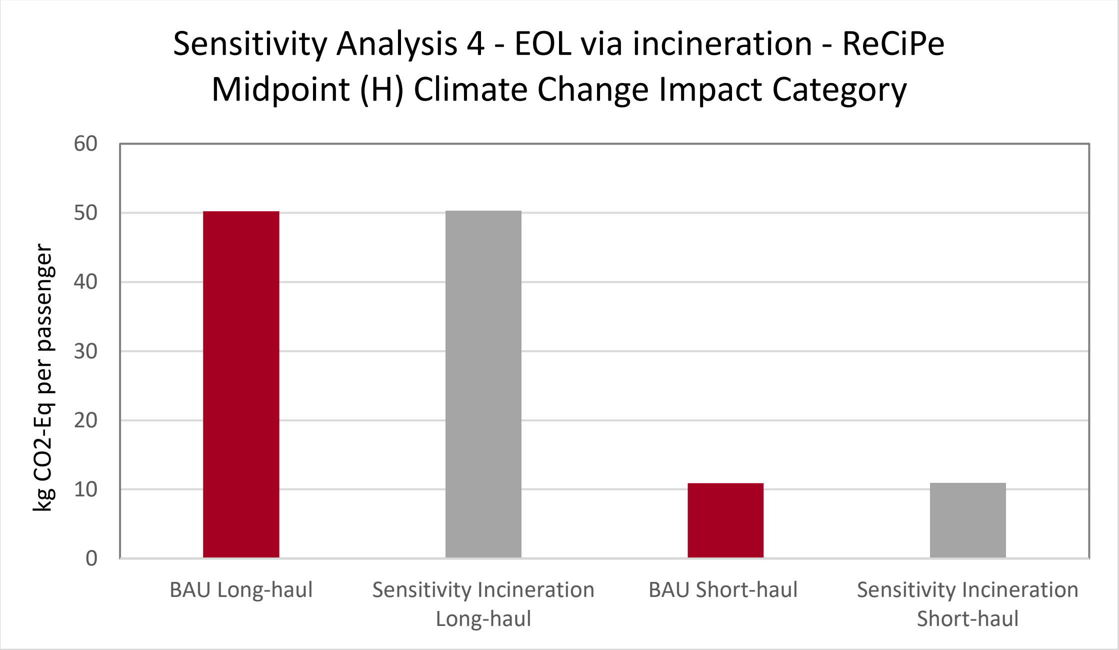

Figure 17. Sensitivity analysis results – EOL treatment/incineration.

3. Discussion, Limitations and Recommendations

3.1 Modelling choices and limitations

The present study investigates the carbon footprint of inflight services and to what extent sustainable and circular applications have a positive impact on the environment. The difficulty of obtaining data led to the construction of a model based on average technologies and values, simplifications, and assumptions. As reported in the consistency (2.4.1) and completeness (2.4.2) sub-sections, the study aims to provide stakeholders in the field of aviation a basic guide on which areas to improve to get one step closer to achieving ICAO's global aspirational goals for sustainable growth in aviation.

The two BAU cases and the carbon emissions reduction measures were built based on estimations and data availability. Especially the choice of circular practices investigated was done considering the modelling part of the assessment and the available datasets. Some measures potentially have a more positive impact than the ones investigated, such as the separation of cabin waste onboard and then transportation to different recycling facilities. Such a measure would be very interesting to assess, however modelling and data collection would be more time-consuming since it entails a broad system boundary. Similarly, another interesting alternative to investigate would be substituting current materials with more sustainable but newly introduced to the market materials, such as bioplastics. This alternative would limit the study in terms of technological coverage and data sourcing.

The assessed measures were modeled in a simplified way. The simplified model limits the in-depth investigation of each alternative and results in model limitations. In the case of food waste reduction, only the impact related to reduced waste from avoiding food waste was taken into account. The environmental impacts related to agriculture that could be avoided by not wasting food were not included in the study. This is a limitation that needs to be considered when interpreting the results.

Another limitation of the model was the choice to omit electricity requirements for product manufacturing and their transportation from the production facilities to the aircraft. This decision automatically excludes the impact from possibly energy-intensive products or products that are transported for a long distance. If the study was modeled in more detail, the results could deviate from the current ones. Nonetheless, it is expected that the trends observed in this study, i.e., high impact from transporting weight, would remain the same.

The decision to calculate the environmental impact attributed to each passenger was taken in an attempt to set the base for more detailed calculations. Airlines calculate the carbon footprint of a flight by focusing on the fuel burn associated with transported weight (KLM, 2022). This approach excludes other impacts associated with the passengers such as impact from food consumption. Calculating the impact per passenger can help airlines create an individual flight impact indicator that can be communicated to the passengers upon the booking of a flight. This information can serve as the basis of behavioral change and influence the decision of the passenger. For example, a passenger will be able to be informed of the number of emissions associated with the inflight meal before booking a flight and will have the option to decline that meal. This way, the production of the meal and the related emissions will be avoided.

Finally, the decision to only include climate change as an impact category in the analysis has limited the potential of the thesis. Aviation's impact on climate change is evident and it has been extensively investigated. Nevertheless, its impact on other impact categories could also lead to interesting results, especially regarding the impact of material flows. This is a limitation in the design of the study and could be investigated in further research.

3.2 Results discussion

The assessment of the sustainability of inflight services and impact reduction measures has resulted in interesting findings. Although all measures reduce the carbon footprint, the best performing ones are carbon offsetting and the use of lightweight materials. The magnitude of the impact reduction by these alternatives points to the direction of research on lightweight materials and carbon capture technologies. Furthermore, the results reveal that reducing plastic and food waste has a negligible impact on carbon footprint reduction. It is necessary to mention that these findings represent the climate change impact category. The results could differ for other impact categories such as land use and eutrophication for the impact of food and fossil depletion for the impact of plastics.

The results of the carbon offsetting alternative represent another interesting discussion point. It has been assumed that a passenger can offset the carbon emitted due to fuel burnt by transporting all the service materials that are used to serve that passenger. This is assumed to be done through donations to reforestation programs. However, several limitations arise from this approach. First, the emissions associated with any other life cycle stage of the services are not included in the offset emissions. As discussed in sub-section 2.1.3, airlines estimate passengers' carbon footprint through fuel requirements due to the mass of the payload and the equipment. In their calculations, they include other life cycle stages for the fuel but not for the equipment. Although aviation fuel is the primary source of carbon emissions and offsetting it can theoretically lower a passenger's carbon footprint, the flight cannot be considered carbon neutral because emissions from subsequent stages are not offset.

Another limitation of the carbon offsetting approach is that aircraft emissions have an immediate effect on climate change, however planting trees and carbon capture by biomass can take years (Greenpeace UK, 2021). Moreover, the extreme weather conditions due to climate change may harm the plantations before they can remove the expected carbon from the atmosphere. Finally, as revealed in a study conducted by Greenpeace (Clarke, 2021), although reforestation projects are beneficial to the local environment and population, the way their carbon savings are quantified and commercialized as carbon credits is based on vast assumptions and overestimated predictions. As reported in the same study, this creates “phantom” carbon credits that are not tied to realistic impact calculations. Therefore, the solution is questionable, and the results of this study should be interpreted critically. Nevertheless, the results suggest that carbon capture is indeed effective and if applied transparently and with immediate effect, it could lead to positive results. Further study is advised on other carbon capture methods that can be applied to aviation.

Following the goal of the study, indeed carbon footprint hotspots were identified which can be translated into actions in further studies. As anticipated, fuel emissions were the number one contributor. The electricity and transportation used for the equipment cleaning process is an important hotspot throughout the whole study. The important part of this finding is that both processes are not dependent on aviation and therefore are easier to adjust. As discussed in the sensitivity analysis, renewables are already part of the European electricity mix and the possibility of fully renewable-powered catering facilities in the near future is very high. Similarly, electric-powered vehicles are also already on the market and therefore the transportation of equipment and waste could switch to electric vehicles in the near future. Unfortunately, datasets for such vehicles were not available at the moment this study was performed and therefore the impact reduction evaluation due to this implementation was not possible.

The present analysis is conducted on a passenger level and the carbon footprint results may appear negligible. To put results into context, the carbon footprint of a passenger was extrapolated to the European market level. The total carbon emissions in the EU for 2019 were estimated at 152 megatons (Graver et al., 2020) and 1,146.44 million passengers were carried by air in the European Union (Eurostat, 2019). Assuming that half of these passengers flew on domestic flights and half on international, the annual emissions attributed to inflight services are estimated as 35 megatons of CO_2-Eq which represents 23% of the total emissions in the EU. Using the carbon footprint reduction rates from Table 10, the reduced emissions are quantified as approximately 0.13 megatons CO_2-Eq for the single-use plastic reduction measure, 0.11 megatons CO_2-Eq for the food waste reduction measure, 5.2 megatons CO_2-Eq for the lightweight materials measure and 27.9 megatons CO_2-Eq for the carbon offset measure. The calculations of these values can be found in Appendix 8. This extrapolation is subjective since it is based on vast assumptions, and it would require a more detailed analysis with different flight distances, cabin options (business and first class), and specific inflight services data. Nevertheless, this estimation is a rough indication of the impact contribution of inflight services to climate change and it is not negligible. The annual emissions reduced by the lowest performing measure (decreasing single-use plastics onboard) are nearly comparable to the annual production-based emissions of a small country like Lichtenstein, as reported in Wikipedia (2022b). It would therefore be beneficial to invest in measures that reduce this carbon footprint.

3.3 Recommendations

As derived from the contribution analysis of this study, the most impactful stages of inflight services provision are the fuel emissions due to transported weight, electricity used in the service equipment cleaning process, transport of the equipment from the aircraft to the equipment cleaning facilities, transport of the waste from the aircraft to landfill, food choices and EOL waste treatment. Sustainable and circular measures can be applied to these identified impact hotspots and enable environmental sustainability.

More specifically, to reduce the impact of carbon emissions, materials substitutions can be applied throughout the whole aircraft. It has been shown in this study that lightweight materials can reduce the emissions associated with fuel burn, therefore further reductions in the weight of the services could be achieved. Apart from renewable energy solutions, another suggestion for the reduction of electricity use could be investing in cleaning equipment that consumes less energy. Similarly, the obvious solution to the transportation hot spot could be to switch to electric vehicles or vehicles powered by alternative fuels. However, this solution should be further investigated. The inflight food hotspot can be dealt with by substituting animal products with plant-based alternatives while the leftovers can be separated onboard and used for compost. Finally, a circular approach to waste treatment is necessary. Ideally, all equipment should be reusable, however, that might affect the impact via an increase in transported weight and electricity consumption for equipment cleaning. As a secondary solution, waste separation should take place onboard to avoid unnecessary transport, while the maximum levels of recycling and composting should be achieved.

For future research, this study recommends investigating measures with possibly greater magnitude such as the substitution of current materials with lighter materials (different composites) or materials that are newly introduced to the market (i.e., bioplastics). Moreover, it would be interesting to explore how the introduction of electric vehicles and vegan meal options could affect the carbon footprint. Modelling recommendations were also identified. Besides obtaining data directly from the industry, including electricity and transportation for each service product and equipment item could improve the accuracy of the study. Furthermore, enhancing the food waste carbon footprint estimation could also improve the quality of the results. The inclusion of inflight services offered in other cabins, such as business class, in the analysis would also improve its accuracy. Finally, including more impact categories in the analysis is recommended for a holistic approach.

4. Conclusions

In this thesis, several inflight service practices were assessed in terms of their carbon footprint using the LCA method to answer the research question: "*How do inflight services and measures intending to reduce their climate impact, perform in terms of carbon footprint, and to what extent do they enable sustainability?"*. To answer this question, three sub-questions were first answered.

a) How do business-as-usual inflight service products and practices perform in terms of carbon footprint within their life cycle?

The climate performance of two BAU cases, namely a long-haul and a short-haul flight was investigated in terms of their carbon footprint. The cases were built on average values. The analysis showed that the inflight services offered to a passenger on a long-haul flight of 7 hours and 50 minutes are responsible for emitting 50.24 kg CO_2-Eq. Accordingly, the inflight services offered to a passenger on a short-haul flight of 1 hour and 50 minutes are responsible for emitting 10.89 kg CO_2-Eq. The transportation process was identified as the highest contributor in both cases. Other top contributing processes were food-related processes and electricity production for cleaning facilities.

b) *How does the introduction of measures intending to reduce the carbon footprint of inflight services affects the climate performance of the business-as-usual products and practices*?

Five measures were assessed based on sustainable and circular service practices, namely less single-use plastic, no food waste, lightweight materials, carbon offsetting, and a combination of the previous four. Reduction of single-use plastic and food waste performed worse in terms of carbon footprint reduction (approximately 0.4%) while the lightweight materials measure resulted in an approximately 13.8% and 19% impact reduction for the long-haul and the short-haul flight respectively. Finally, the carbon offsetting measure displays the best performance by reducing the impact by 81.9% for the long-haul and by 69.5% for the short-haul flight. The results of this assessment are strongly dependent on the data and modelling options. Additional research is required to investigate the impact of these alternatives on other impact categories representing different environmental problems.

c) Can these measures enable environmental sustainability in the aviation industry, and to what extent?

The carbon footprint reduction measures, as modeled in this study, are indeed reducing the climate impact calculated for the baseline scenarios with a reduction of up to 96% as observed in the results. Therefore, it can be assumed that they enable environmental sustainability in the aviation industry. However, there are a few issues with that statement. Firstly, this study only investigates carbon footprint and does not include other potential environmental problems. Secondly, some important circular measures such as waste sorting onboard and recycling are not included in the study. Finally, the most successful measure, carbon offsetting via reforestation, is a questionable practice and the title of most sustainable measure does not represent the reality. Further research on this alternative should be performed since carbon capture via other methods could be a useful and immediate solution.

Considering the results and the previous sub-questions, the main research question can be answered: *How do inflight services, and measures intending to reduce their climate impact perform in terms of carbon footprint, and to what extent do they enable sustainability?*

The applied inflight service carbon footprint reduction measures performed better than the business-as-usual inflight service practices, achieving their purpose. Their climate performance varies depending on the measures and the emissions source it targets achieving emissions reduction rates of up to 96%. Practices that target weight reduction have a better climate change impact reduction potential than practices that target food waste. This thesis can serve as a guide for actions that can take place immediately and reduce the impact of aviation in the short term. Although the reduction might be minor compared to the overall impact of an aircraft, circular actions in the inflight sector can be enforced immediately. They may mark the start of a change in the high-emitting aviation industry, and they may begin to reduce the impact until innovative technologies and breakthrough solutions become available.

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6. Appendix

Please find all related calculations and relevant information in the Excel file.