sustainability

MDPI

Article

Method to Model the Environmental Impacts of Aircraft Cabin Configurations during the Operational Phase

Dennis Keiser [1,*], Michael Arenz [2], Michael Freitag [1,2] and Matthias Reiß [3]

[1] BIBA—Bremer Institut für Produktion und Logistik GmbH, Hochschulring 20, 28359 Bremen, Germany
[2] Faculty of Production Engineering, University of Bremen, Badgasteiner Straße 1, 28359 Bremen, Germany
[3] Airbus Operations GmbH, Kreetslag 10, 21129 Hamburg, Germany
* Correspondence: ked@biba.uni-bremen.de; Tel.: +49-421-218-50183

Abstract: The entire aircraft industry is facing major challenges due to the formulated targets to reduce environmental emissions. For decision-makers, it is therefore of great importance to be able to compare the environmental impact of aircrafts. This includes the impact assessment of different aircraft-cabin configurations. Based on this motivation, this paper proposes a dynamic method for calculating those environmental impacts. To ensure a straightforward application, the method allows for the cabin configuration with the main cabin components. In addition, a specific mission profile can be defined and is considered in the calculations. The method follows the standardized life-cycle assessment framework. The first application of the method showed that there were large differences in the environmental impacts depending on the cabin configuration and that airlines can contribute to the achievement of sustainability goals with optimized cabin layouts.

Keywords: aviation; sustainability; cabin configuration; environmental assessment; life-cycle assessment

check for updates

Citation: Keiser, D.; Arenz, M.; Freitag, M.; Reiß, M. Method to Model the Environmental Impacts of Aircraft Cabin Configurations during the Operational Phase. *Sustainability* **2023**, *15*, 5477. https://doi.org/10.3390/su15065477

Academic Editor: Gilberto Santos

Received: 22 February 2023
Revised: 14 March 2023
Accepted: 16 March 2023
Published: 20 March 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

CO_2 emissions caused by the aviation industry were approximately 2.8–3.5% of global emissions from 2016 to 2018 [1,2]. A large proportion of these emissions are attributable to the operational phase of the aircraft, during which fuel is burned to generate energy [3–5]. Due to increasing societal pressure as well as industry-wide goals to reduce emissions, it is of great importance for manufacturers as well as airlines to be able to quickly and transparently calculate the environmental impacts of their aircraft and its subsystems for the different life-cycle phases of aircraft [6]. The aircraft cabin and its operating processes are a particular focus for manufacturers and airlines when it comes to reducing emissions [7]. This is primarily due to the high proportion of weight in a typical commercial flight [8]. In addition, possible optimizations and changes in the layout of the cabin can be implemented in existing fleets and thus quickly realize fuel savings for individual aircraft types as well as the entire cabin [8,9]. The basis for decision-makers in these strategic decisions is a transparent and rapid method for quantifying the environmental impacts of different cabin alternatives, which ensures potential investments and thus helps achieve sustainability goals [10–12].

Based on this motivation, this paper proposes a method for determining the environmental impacts of aircraft cabins for the operational phase. This enables the user to compare different layouts. The methodological basis for this is the life-cycle assessment (LCA) framework, which is recognized in science and in practice [13,14]. In Section 2, we therefore present the state of the art of LCA and compare existing methods for assessing environmental impacts in the aviation industry. In Section 3, we first introduce the established requirements for the methodology as well as the conceptual framework, and then build on this to present the method along the steps of the LCA framework. The paper concludes with an application of the developed method, a discussion of the results, and a summary and derivation of further research needs.

2. Related Work

2.1. Life-Cycle Assessment

Growing environmental pollution and high resource consumption were increasingly discussed in society in the 1960s [15]. As a result, the need for a scientific and transparent method to assess the environmental impacts of products, processes, and services increased [16]. The result was the LCA method, whose beginnings can be found in the 1960s [13]. The LCA method for products and services was developed to investigate the environmental impact of emissions and resource consumption resulting from the production, use, and disposal of products [17] and is now one of the most widely recognized methods to investigate environmental impacts [18]. The preparation of LCA studies is standardized according to ISO 14040 and ISO 14044 and is divided into four phases [14,19]: goal and scope definition, inventory analysis, impact assessment, and interpretation. In the first phase, the objective and the scope of the study are defined. In this step, the product system is to be investigated and the system boundaries are defined [17]. In addition, the functional unit is described, which describes the function of the investigated product to which the results relate [20]. The second step, the preparation of a life-cycle inventory, focuses on the necessary data collection based on the system boundaries [21]. Using the collected data, an input–output model is created [22]. In the context of LCA, inputs describe resource withdrawals from the environment and outputs are emissions into the environment [23]. In the third phase, an impact assessment is performed [13]. For this purpose, different impact categories can be used [24]. In the last phase, the findings are summarized and presented. Depending on the objective, this final step also serves to formulate conclusions and recommendations [12]. This overarching framework, on which every LCA is based, is shown in Figure 1.

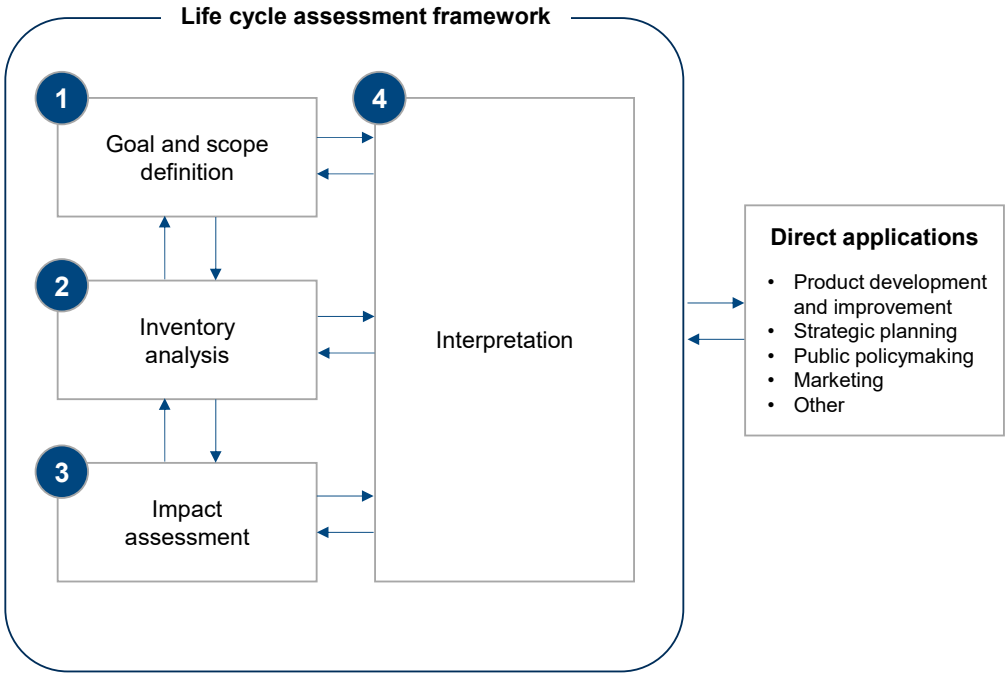


Figure 1. General life-cycle assessment framework [14].

Depending on the use case and the objective of the study, the user has methodological degrees of freedom within this framework for the implementation and presentation of results. For example, it is possible to dispense with modeling the entire life cycle and to perform studies only for specific life-cycle phases of products [17,25]. These gate-to-gate studies are performed mostly due to a poor data situation and hace already been applied in various studies in the context of the aviation industry [26–30]. In this case, only individual phases of the life cycle of the aircraft are modeled.

2.2. LCA-Related Methods in Aviation

Based on the topicality of aviation emissions, novel, fully comprehensive methods for LCAs of commercial aircraft have been developed in recent years [5,31,32]. The goal of these methods is to model the life cycle of aircrafts using a variety of parameters. As a result, such methods can represent environmental impacts with multidimensional environmental indicators. Users and addressees of this first type of method are experts in science and practice. The method developed by Johanning [5] for integrating LCA into preliminary aircraft design follows a fully cradle-to-grave modeling approach and thus poses challenges to the user, especially in terms of data acquisition. Johanning takes into account all subsystems of the aircraft and enables a simplified parameterization of the aircraft cabin. The method was applied to the balancing of a design for turboprop aircraft. Further methods exist for the comparison of different fuel types as well as propulsion types [33]. Among others, a dynamic method for the comparison of conventional kerosene with hydrogen was presented by Scholz [34]. Another method was developed by Caers, with the aim of taking into account aerodynamic influences as well as engine utilization [35].

In addition to experts from the industry, there is also an increasing interest among passengers in the environmental impact caused by their own flights [36,37]. In line with this demand, simplified methods and publicly available calculators for calculating emissions from flights have been developed by various institutions and submissions [38–43]. These calculators are used to calculate the emissions of individual air travel and use simplified calculation methods. This second type of method presents the results in such a way that no expert knowledge is required and only a few user inputs are necessary for parameterization.

Finally, a third type of method and study should be mentioned that models the emissions of the entire aviation industry [2] but is not analyzed further in this paper and not described in the following table. Within these studies, global flight emissions are modelled. In Table 1, the identified and relevant methods are compared using so-called Harvey balls. Here, a discrete scale with five expressions was chosen, as it provides sufficient differentiation while maintaining assessment robustness [44]. The comparison was carried out in three dimensions: First, input parameters such as aircraft type and emissions profile were considered. Second, the system boundaries and methodological characteristics were determined. Third, the results were presented.

It becomes apparent that the analyzed emission calculators pursue a one-dimensional presentation of results. The focus is on the representation of the emitted CO_2, which is only one midpoint indicator within the full LCA framework. In contrast, the scientifically developed methods use multidimensional environmental indicators for the presentation of results with a full set of midpoint and endpoint indicators. Furthermore, none of the methods focuses on a detailed examination of the aircraft cabin. The user of the methods is therefore not able to configure different cabin elements and the layout of the cabin specifically. This is exactly where the developed method comes in and enables a life-cycle assessment of the aircraft cabin based on flexible inputs. The method presented in the following sections thus closes the research gap identified here and contributes to increasing the transparency of life-cycle assessments in the aviation industry. The necessary data for modeling are presented in the following section.

Table 1. Comparison of different methods and calculators for aircraft emissions.

		Variable Input Parameter		System Boundaries and Method		Boundaries and Metrics	
Legend ○ **Characteristic Not Present** ◔ **Characteristic Very Low** ◑ **Characteristic Low** ◕ **Characteristic High** ● **Characteristic Very High**		**Aircraft Type**	**Mission Profile**	**Cabin Configuration**	**Consideration Height-Dependent Effect**	**Fuel Production**	**Presentation of Results**
Method and Source	**Description**						
[5]	Full LCA method included in preliminary aircraft design	●	◑	◔	●	●	Env. Ind.*
[34]	Comparison of conventional kerosene with hydrogen	◔	◑	◔	●	○	CO_2 eq.
[35]	Considers aerodynamic influences as well as the engine utilization	◑	◑	◔	●	○	CO_2 eq.
[38]	Carbon-emissions calculator	◑	●	○	○	○	CO_2 eq.
[39]	Emissions calculator for passengers	●	●	○	○	○	CO_2 eq.
[40]	Emissions calculator for passengers	◑	●	○	◔	◑	CO_2 eq.
[42]	Emissions calculator according to different flight phases	●	●	○	○	○	CO_2 eq.
[41]	Emissions calculator for passengers	●	●	○	○	○	CO_2 eq.
[43]	Emissions calculator for passengers	●	●	○	○	○	CO_2 eq.

* Full set of environmental indicators (midpoint and endpoint).

2.3. Aviation-Specific Databases and Data Sources

In order to develop a method that can calculate the environmental impact of different cabin configurations, a wide variety of data is required. The data can be categorized into three areas: First, the best possible database is required for the fuel-consumption values of the aircraft to be investigated. A good database along the typical flight phases of commercial aircraft increases the accuracy and robustness of the results. According to the subdivision of the flight phase into landing and takeoff phase (LTO phase) and climb, cruise, and descent phase (CCD phase) shown in Appendix A, various publicly accessible as well as access-restricted databases are available. The European Environment Agency (EMEP/EEA) air-pollutant-emission inventory guidebook contains LTO- and CCD-phase consumption data for all current aircraft types and is publicly available [42]. As another database, the Aircraft Engine Emission database of the International Civil Aviation Organization (ICAO) can be used as a data source for fuel consumption [45]. The database is directly supported by data from the engine manufacturers and is constantly updated. A third data source, which is restricted in access, is operated by Eurocontrol [46]. The Base of Aircraft Data (BADA) provides data on the performance of over 1000 aircraft types and is used by various researchers [47].

Second, in order to model the environmental impact of specific aircraft consumption, databases are needed to quantify the environmental impact of the fuel-combustion process in aviation. Four data sources have been identified for this purpose. First, emission factors for the combustion of kerosene and other energy sources are provided by the British government, the United States Environmental Protection Agency (US EPA), and the German Federal Environmental Agency [48–50]. Second, the ICAO database, which has already been introduced, provides emission factors in addition to consumption values

for hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) [45]. This data source, in conjunction with the data provided by the German Federal Environment Agency, offers a good database for this second data area.

In addition to the direct environmental impacts caused by the combustion of the fuel, emissions are also caused by the production of the fuel [4]. Third, therefore, databases quantifying the emission factors of fuel production are necessary. The European Commission and the National Energy Technology Laboratory, under the U.S. Department of Energy, offer corresponding data. [51,52]. Table 2 shows the databases and data sources presented and also shows which of the data sources are used in the methodology presented here.

Table 2. Overview of identified aviation-specific and -related databases and sources for environmental-impact modelling.

Data Type	Database	Description	Source	Used in the Developed Method
Aircraft-specific fuel-burn consumption values	Air-pollutant-emission inventory guidebook 2019 (EMEP/EEA)	The EMEP/EEA air-pollutant-emission inventory guidebook 2019 contains consumption values for the LTO and CCD phases of various aircraft types.	[42]	Yes
	ICAO 2021	The ICAO Aircraft Engine Emission Database contains fuel-consumption values for common aircraft engines, which are specified by engine for the LTO phase.	[45]	Yes
	BADA	BADA is the international reference for aircraft-performance modelling for the purposes of trajectory prediction and simulation.	[46]	No
Environmental-emissions fuel burn	UK Government greenhouse-gas reporting—Conversion Factors for Company Reporting	Databases with emission factors for burning kerosene and other energy sources such as liquefied petroleum gas and coal.	[48]	No
	German Federal Environment Agency: Revision of the aviation-emissions inventory		[49]	Yes
	EPA—Emission Factors for Greenhouse Gas Inventories		[50]	No
	ICAO 2021	The ICAO Aircraft Engine Emission database contains fuel-consumption values for the LTO phase as well as the environmental impact of fuel combustion.	[45]	Yes
Environmental-emissions fuel production (kerosene)	European Platform on life-cycle assessment. European Commission. Life Cycle Inventory Data—Unit Process: Petroleum Based Kerosene Jet Fuel Energy Conversion Facility. National Energy Technology Laboratory, under the U.S. Department of Energy	Databases with emission factors for the production of kerosene.	[51]	Yes
			[52]	Yes
Aircraft-specific design characteristics	EASA 2022	Database of EASA with certifications of aircraft types including different versions, which are flown in the European area. Contains data on engine, dimensions, mass (MFW, MTOW, MZFW, MLW), and permitted cabin seating configurations in relation to the number of seats.	[53]	No, but could be used for further extension of method (see Conclusions)
	Airbus aircraft characteristics	Aircraft characteristics from the manufacturers describing dimensions, permitted seating configurations in the cabin, engine, and mass specifications (MFW, MTOW, MZFW, MLW).	[54]	
	Boeing airplane characteristics for airport planning		[55]	

Finally, a fourth category of data sources is listed in Table 2, which is not applied in the context of the method but is highly relevant for later extensions of the method. The aircraft-specific design characteristics published by the aircraft manufacturers [54,55] as well as EASA [53] are of great importance for cabin development and preliminary studies. The research agenda proposed for this purpose is presented by the authors at the end of the paper.

3. Requirements and Conceptual Framework

For the development of the method presented here, multidimensional requirements were defined and considered by the authors as a basis for further development. A two-stage approach was chosen to determine the requirements: First, requirements were conditioned by the application context: the aircraft cabin. The aircraft cabin considered in the paper and the further conceptual framework considered the main cabin components that are relevant for branding and the operational processes (see Section 4.1) Examples for these components are the seats or the galleys. In order to reduce the application complexity of the method, constructional topics of the cabin were not considered. Based on the design-thinking method [56], initial requirements for the method to be developed were established through understanding, observation, and synthesis in different workshops. Secondly, further requirements were established by analyzing the methods related in Section 2.2, the literature, and relevant standards. In total, 12 requirements were established in two dimensions:

- Conceptual requirements based on aircraft cabin;
- Methodological requirements based on the life-cycle assessment method.

Table 3 lists, explains, and justifies all the requirements that have been established.

Table 3. Defined requirements for the method.

Type	Definition	Description and Justification
Conceptual requirements based on aircraft cabin	Independence from aircraft program and manufacturer	The method shall be applicable to all common wide-body aircraft in the current fleets, which ensures broad applicability.
	Possibility of dynamic input of flight profile	Since different flight profiles have an impact on the environmental impact over the life cycle, they have to be considered as dynamic parameters (e.g., flight duration).
	Possibility to configure multi-class cabin layout	Due to the diversity of classes in different airlines it is necessary to cover this diversity.
	Calculation of proportional environmental impacts for cabin and its subsystems	Due to the use case, the method must be able to output the cabin's environmental impact and that of the entire aircraft.
	Possibility to configure the aircraft cabin	The cabin differs depending on the airline. Therefore, the method must offer the possibility to flexibly configure different cabins.
	Possibility to perform the method without LCA software	In order to quickly compare different cabin configurations, the method must be applicable independently of external software.
	Simplification of the aircraft cabin to main components	The method should be applicable without complex data collection; therefore, main components of the cabin are considered and an appropriate level of detail is chosen.
Methodological requirements based on LCA method	Consideration of established LCA standards	As an internationally established standard, ISO 14044 must be taken into account; this leads to further methodological validation.
	Possibility to choose different functional units	Depending on the level of consideration, the method should offer the possibility of different functional units.
	Impact assessment by means of a scientifically recognized method	To ensure the comparability of the results, a widely used and scientifically recognized method for impact assessment must be used.
	Exclusive use of publicly available data sources	The databases listed in Section 2.3 and other data sources form the data basis. Data not publicly available for the implementation of the method are not used.
	Focus of the method on the operational phase	To ensure the applicability of the method, only the operational phase is considered. High expenses for data collection are thus prevented.

Based on these requirements, Figure 2 shows the conceptual framework of the developed method. Due to the significantly high share of the operational phase, up to 99% of the environmental impact during the life cycle of aircraft [3,4], the method presented here provides for a gate-to-gate approach and does not pursue a full life-cycle modeling. Gate-to-gate approaches enable the balancing of individual phases and can be used to reduce application complexity [22]. Furthermore, they can fulfill the established requirements regarding applicability.

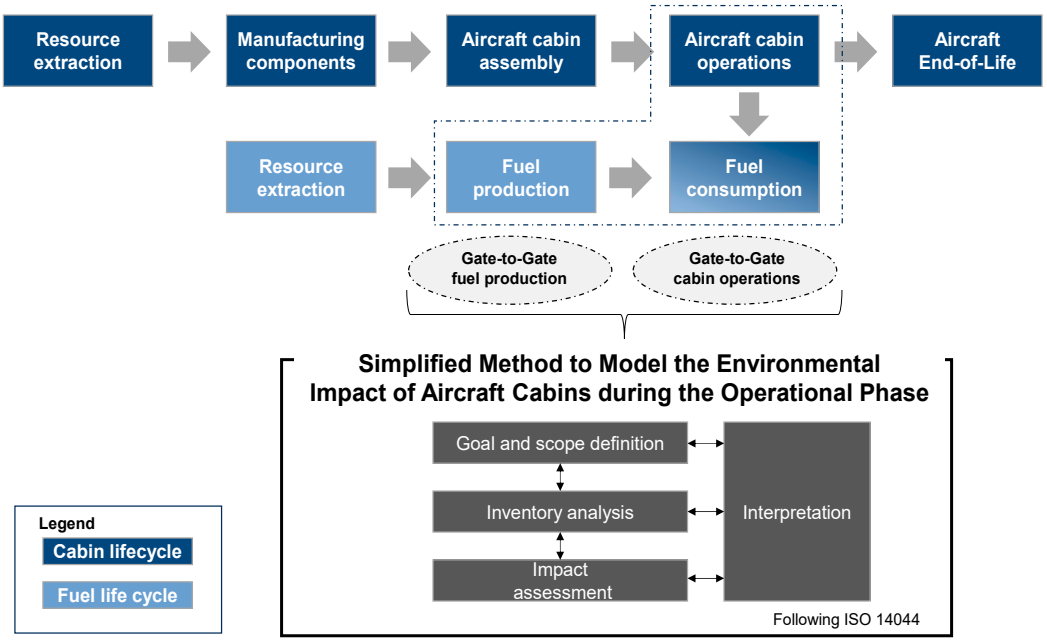


Figure 2. Conceptual framework for the developed method [14].

Within the operational phase of aircraft cabins, however, other environmentally effective processes take place in addition to the production and consumption of fuel. These include maintenance and repair as well as passenger service [57,58]. These secondary processes are not considered further in the method presented here. With the aim to consider as much of the environmental impacts as possible and at the same time to ensure the applicability of the method, the system boundaries are defined as follows: First, fuel consumption during the operational phase is considered, and second, fuel production is considered. The reason for this is that fuel consumption (fuel burn) and production together cause up to 99% of the environmental impact for the entire life cycle of aircraft [3,4]. The method does not take into account the production of cabin components or the recycling processes with regard to the usage of cutoff rules, which makes it possible to exclude processes with very low environmental impacts. However, the modular structure of the method allows the user to add these phases if required.

4. Methodology

The developed method is structured along the four phases of ISO 14044 [19]. Figure 3 shows the structure of the method and depicts the process steps within the individual phases. The requirements listed in Section 3 as well as the necessary data sources and databases from Section 2.3 were taken into account. The detailed presentation of the method follows along the process flow.

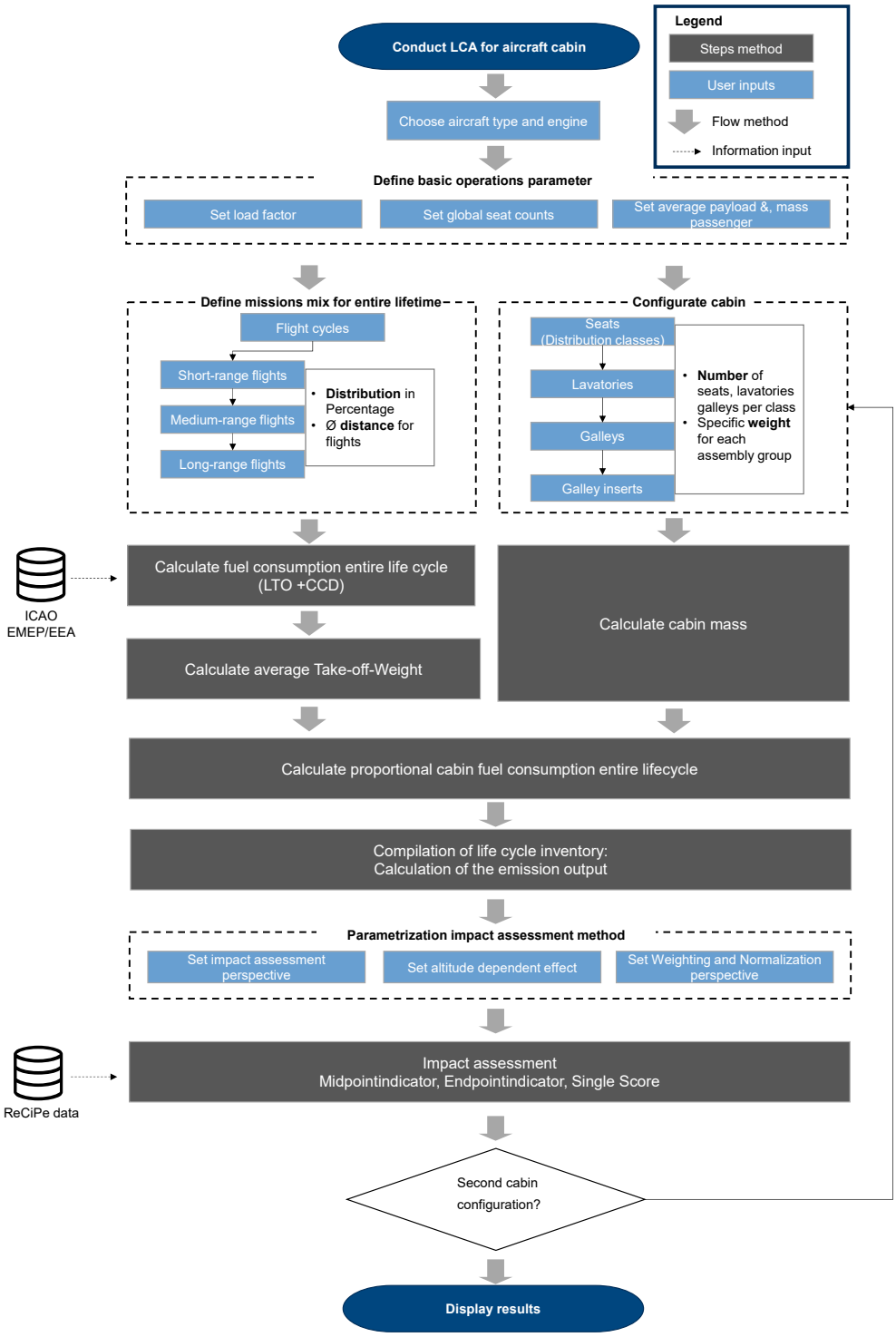


Figure 3. Overview with process flow of the developed method.

4.1. Goal and Scope Definition

In the first step of the method, the target and the investigation framework are defined. The aim of the method is to investigate the environmental impact of an aircraft and its cabin within the framework of a gate-to-gate LCA. Here, the object of consideration is the aircraft cabin with various layout alternatives. During the cabin configuration, individual components of the Air Transport Association of America (ATA) Chapter 25, "Equipment/Furnishings," are selected, which are used as a standard for the technical structuring of commercial aircraft [59]. ATA 25 particularly considers those components

and assemblies that are perceived by the passenger and directly influence the branding and operational processes of the airline [60,61]. Examples are the seats, galleys, and lavatory components. According to the established requirements, the following cabin components are thus considered:

- Passenger seats;
- Aircraft lavatories;
- Galley modules;
- Galley equipment.

In addition to the technical delimitation of the object under consideration, the first step of an LCA also involves defining the system boundaries in terms of the life phases to be considered. This was already done in Section 3 by means of the conceptual framework established, and the method accordingly considers only the operating phase of the aircraft. Within the operational phase, maintenance, servicing, and passenger service are not considered due to the low environmental impact measured against the entire operational phase and the insufficient data basis. Finally, the developed method allows for the selection of a functional unit, which can be distinguished between two functional units:

- Environmental impact per lifetime cabin (Fct. 1);
- Environmental impact per passenger-kilometer cabin (Fct. 2).

The fuel consumption of an aircraft is approximately linear to the transported mass and can therefore be approximated [62,63]. Therefore, Fct. 1 is used to quantify the fuel consumption and environmental impact of the aircraft cabin. Fct. 2 is a common reference for fuel consumption in aviation [59]. Hence, Fct. 2 is particularly suitable for comparisons with other LCAs in the aviation industry. The impact-assessment method applied is the scientifically widely used [33] ReCiPe 2016 method [24], which is also used in the aviation industry. This offers different environmental indicators for the presentation of the results and thus ensures a multidimensional presentation of the results.

4.2. Life-Cycle Inventory

Once the objective and scope of the study have been defined, the life-cycle inventory is drawn up. The basis of the life-cycle inventory is the fuel consumed on the basis of the mission profile and the defined aircraft parameters. The following section describes the basis for the calculation.

4.2.1. Definition and Introduction of Basic Parameters

In order to set up the life-cycle inventory for the operational phase as shown in Figure 3, it is first necessary to determine the specific takeoff weight (ms_{TOW}). The takeoff weight of a commercial aircraft differs depending on the mission profile but is always composed of the following components [64]:

- Operating empty weight (m_{OEW});
- Passenger and baggage weight ($m_{PAX,total}$);
- Payload ($m_{payload}$);
- Fuel weight including cab fuel ($m_{fuel,total}$);
- Reserve fuel weight ($m_{fuel,reserve}$).

The operating empty weight (m_{OEW}) is specific to each aircraft series, and variations within aircraft programs may be possible depending on the equipment characteristics [60]. Appendix B shows typical m_{OEW} for the Airbus A320–200 and the Airbus A350–900, which were used in the application of the method. For the calculation of $m_{PAX,total}$, further basic parameters have to be introduced first: First, the so-called load factor (p_{pax}) has to be considered, which describes the average passenger-load factor. The ICAO publishes the global passenger-load factor on a monthly basis; for example, the studies for May 2022 resulted in a load factor of 79.1% [65]. On the other hand, the specific seat layout has to be integrated with regard to the total number of seats (n_{seat}). Airline data can be used for this purpose. As an example, a typical A350–900 cabin layout is mentioned here, which

consists of 293 seats in total [66]. This results in the following relationship for the number of passengers (n_{PAX}):

$$n_{PAX} = p_{pax} \cdot n_{seat} \quad (1)$$

Using n_{PAX}, the average passenger weight (m_{PAX}), which includes baggage, is multiplied to calculate $m_{PAX,total}$. As a reference for m_{PAX}, 105 kg can be assumed as an average value [67].

$$m_{PAX,total} = n_{PAX} \cdot m_{PAX} \quad (2)$$

The payload ($m_{payload}$) is considered as an individual parameter. By means of calculating the fuel weight ($m_{fuel,total}$) as well as the reserve fuel ($m_{fuel,reserve}$), Formula (3) can be used to calculate the specific takeoff weight (ms_{TOW}):

$$ms_{TOW} = m_{OEW} + m_{payload} + m_{PAX,total} + m_{fuel,total} + m_{fuel,reserve} \quad (3)$$

For the plausibility check of ms_{TOW}, the maximum takeoff weight (m_{TOW}) published by the aircraft manufacturers can be used. If this value is exceeded, non-permissible entries are made. The calculation of the necessary fuel masses ($m_{fuel,total}$, $m_{fuel,reserve}$) depends on the mission profile and is presented in the following section.

4.2.2. Calculation of Fuel Consumption and Mass

To calculate the total fuel mass of an aircraft ($m_{fuel,total}$), different phases of the flight have to be considered. On the one hand, the takeoff and landing cycle (LTO) and, on the other hand, the so-called climb–cruise–descent (CCD) phase, are taken into account. This results in the following formula relationship for $m_{fuel,total}$:

$$m_{fuel,total} = m_{fuel,LTO} + m_{fuel,CCD} \quad (4)$$

The ICAO Aircraft Engine Emissions Database [45] can be used to calculate $m_{fuel,LTO}$. The database lists consumption values for all common commercial aviation engines and, in conjunction with EMEP/EEA 2019 [42], provides a good data basis. Appendices C and D provide excerpts of the required data sets. Also considered in $m_{fuel,LTO}$ are the times adopted as standard by ICAO and presented in the following Table 4.

Table 4. Times of the individual operational phases of the ICAO LTO cycle [59].

Taxiing (t_{Idle})	Takeoff (t_{TO})	Climb (t_{CO})	Approach (t_{App})
26.0 min	0.7 min	2.2 min	4.0 min

Thus, for $m_{fuel,LTO}$ the following formula relationship can be formulated. The variables ff_{Idle}, ff_{TO}, ff_{CO}, ff_{App} describe the fuel flow for the different phases (see Appendix C).

$$m_{fuel,LTO} = \left(t_{Idle} \cdot ff_{Idle} + t_{TO} \cdot ff_{TO} + t_{CO} \cdot ff_{CO} + t_{App} \cdot ff_{App}\right) \cdot n_{Engines} \quad (5)$$

To calculate the total fuel mass of the LTO phases in relation to the entire life cycle of an aircraft ($m_{fuel,LTO,Life}$), the number of flight cycles (n_{Cycles}) is calculated using Formula (7). For this purpose, the flight hours for short-, medium-, and long-haul flights ($t_{Range,S,M,L}$) are first calculated using Formula (6). The user of this method has the possibility to define the distribution of the mission profile by means of $p_{Range,S,M,L}$. The total flight hours (t_{Life}) are further set by the user. For this purpose, reference values of 60,000 flight hours can be used [68].

$$t_{Range,S,M,L} = t_{Life} \cdot p_{Range,S,M,L} \quad (6)$$

Using $t_{Range,S,M,L}$ as well as the formula for interpolating the flight times ($tinerpol_{S,M,L}$) shown in Appendix E, the number of flight cycles can be calculated:

$$n_{Cycles} = \frac{t_{Range,S}}{tinerpol_{Short}} + \frac{t_{Range,M}}{tinerpol_{Mid}} + \frac{t_{Range,L}}{tinerpol_{Long}} \tag{7}$$

Finally, the total fuel mass $m_{fuel,LTO,Life}$ is calculated by multiplication:

$$m_{fuel,LTO,Life} = m_{fuel,LTO} \cdot n_{Zyklus} \tag{8}$$

Due to the necessary degrees of freedom in the input of the flight routes, a further interpolation is necessary for the calculation of the fuel consumption during the CCD phase ($m_{fuel,CCD,S,M,L}$). Here, the consumption values of the EMEP database (Appendix D) are used and manipulated according to the user inputs by means of Formula (9). Depending on the selected flight distance ($l_{flight(S,M,L)}$), the next-smallest or -largest value must be taken from the EMEP database for $m_{fuel,CCD(1)}$ and $m_{fuel,CCD(2)}$. For $l_{flight(1)}$ and $l_{flight(2)}$, the procedure is carried out analogously. The necessary data for two typical commercial aircraft can be found in Appendix D.

$$m_{fuel,CCD,S,M,L} = m_{fuel,CCD(1)} + \frac{\left(m_{fuel,CCD(2)} - m_{fuel,CCD(1)}\right)}{\left(l_{flight(2)} - l_{flight(1)}\right)} \cdot \left(l_{flight(2)} - l_{flight(S,M,L)}\right) \tag{9}$$

Within the scope of the interpolation, $l_{flug(S,M,L)}$ is calculated over the defined short, medium, and long distance, as well as the reference values from the EMEP/EEP database for the consumed fuel within the cruise phase ($m_{fuel,CCD}$) for the associated flight distance l_{flug}.

For the calculation of $m_{fuel,CCD,S,M,L}$ related to the entire life cycle of an aircraft $\left(m_{fuel,CCD,Life}\right)$, there is a dependency on the mission profile, which is characterized by the number of short-, medium-, and long-distance flights. The partial sums from Formulas (7) and (9) describe these and by multiplication and addition, and the total fuel consumption of the CCD phase ($m_{fuel,CCD,Life}$) can be calculated depending on the mission profile. $m_{FuelCCD,S,M,L}$ here represents the fuel consumption for short-, medium-, and long-range flights. $n_{Life,S,M,L}$ is the number of aircraft cycles.

$$m_{fuel,CCD,Life} = m_{FuelCCD,S} \cdot n_{Life,S} + m_{FuelCCD,M} \cdot n_{Life,M} + m_{FuelCCD,L} \cdot n_{Life,L} \tag{10}$$

Finally, the total fuel mass for the life cycle ($m_{fuel,Life}$) is calculated by addition:

$$m_{fuel,Life} = m_{fuel,LTO,Life} + m_{fuel,CCD,Life} \tag{11}$$

The average reserve fuel ($m_{fuel,reserve}$) corresponds to the amount of fuel required for 30 min of cruise flight and is calculated using $m_{fuel,Life}$ and the associated total flight time $\left(t_{Life}\right)$ [59]:

$$m_{fuel,Reserve} = \frac{m_{fuel,Life}}{t_{Life}} \cdot 0.5\ \text{h} \tag{12}$$

Unlike $m_{fuel,total}$, $m_{fuel,Reserve}$ is not considered in the impact assessment because $m_{fuel,Reserve}$ is not consumed in regular operation. The mass consideration is nevertheless necessary to relate the consumption values to Fct. 1. Finally, for the following impact estimate, the average aircraft mass ($m_{averageAC}$) must be calculated using Formula (13):

$$m_{averageAC} = m_{OEW} + m_{payload} + m_{PAX,total} + \frac{m_{fuel,total}}{2} + m_{fuel,reserve} \tag{13}$$

Here, m_{AC} is calculated analogously to the calculation of ms_{TOW}, with the difference that $m_{fuel,total}$ is included at half due to the consumption during the flight. Due to the fuel consumption during the aircraft, half of this can be assumed as a simplification.

4.2.3. Calculation of the Cabin Mass

The calculation of the cabin mass is based on the four areas of the cabin defined in Section 4.1. The cabin configuration is individually selected by the user of the method, and finally, based on the configuration process, the total mass of the cabin (m_{Cabin}) can be calculated by adding up the partial masses:

$$m_{Cabin} = m_{Seats} + m_{Lav} + m_{Gall} + m_{GallIn} \quad (14)$$

4.2.4. Relation of Fuel Mass to Functional Units

Using the calculated fuel quantity for the entire life cycle ($m_{fuel,Life}$) and the ratio of the average aircraft mass m_{AC} and the calculated cabin mass (m_{Cabin}), the fuel is allocated to the configured cabin. Formula (15) can be used to calculate the proportional fuel consumption of the cabin $\left(m_{fuel,Life,Cabin}\right)$:

$$m_{fuel,Life,Cabin} = m_{fuel,Life} \cdot \frac{m_{Cabin}}{m_{AC}} \quad (15)$$

With $m_{fuel,Life,Kabine}$ Fct. 1, environmental impact per lifetime cabin can be modeled. For the modeling of Fct. 2, environmental impact per passenger-kilometer cabin, a final conversion of $m_{fuel,Life,Cabin}$ is necessary:

$$m_{fuel,PKM,Cabin} = \frac{m_{fuel,Life,Cabin}}{l_{flight,total} \cdot n_{PAX}} \quad (16)$$

Here, the flight distance over the life cycle ($l_{flight,total}$) is described by the following formula:

$$l_{flight,total} = l_{flight,S} \cdot n_{Life,S} + l_{flight,M} \cdot n_{Life,M} + l_{flight,L} \cdot n_{Life,L} \quad (17)$$

The user of the method can use $l_{flight,S}$, $l_{flight,M}$, $l_{flight,L}$ here to freely select the length of short-, medium-, and long-haul flights in kilometers depending on the airline's operating scenario.

4.2.5. Life-Cycle Inventory: Calculation of the Emission Output

To calculate the outgoing emissions, the calculated fuel consumption from the last two process steps is used to prepare the life-cycle inventory. Emissions factors (EF) ($EF_{fuel(x)}$) are used to calculate the emissions ($m_{out(x)}$), which depend on the fuel and emission product (x) [49]:

$$m_{out(x)} = m_{\text{fuel}} \cdot EF_{\text{fuel}(x)} \quad (18)$$

Within the framework of the method developed here, the emissions from the combustion and production of fuel are taken into account. The EF of the LTO and cruise phase differ from each other [49]. For the LTO phase, the engine-specific EF of the ICAO Aircraft Engine Emissions database and the factors published by the German Federal Environmental Agency are applied [45,49]. For the cruise phase, the factors of the German Federal Environmental Agency are also applied as shown in Table 5.

Table 5. Emissions factors for kerosene combustion during the LTO and CCD phases [45,49].

	CO_2	CH_4	N_2O	SO_2	H_2O	NO_x	HC	CO	NH_3	NMVOC	TSP
EF-LTO [g/kg]	3160	0.13	0.09	0.2	1237	Engine-specific ICAO data (Appendix F)			0.172	0.9	0.09
EF-CCD [g/kg]	3150	0	0.1	0.2	1237	16.5	1.0	13.5	0.172	13.5	0.2

In addition to the emissions resulting from the combustion of fuel, the emissions for fuel production are also taken into account. For this purpose, EFs for fuel production are used. The EFs for the production of kerosene are shown in the following Table 6. The most relevant emission factors are taken into account, which in total are responsible for more than 99% of the environmental impact caused by the production of kerosene [51,52].

Table 6. Emission factors for the production of kerosene [51,52].

	CO_2	CH_4	SO_2	NH_3	Oil	Gas
Kerosene [g/kg]	239	0.293	0.319	0.0026	1110	57.9

The life-cycle inventory results $m_{out,GES(x)}$ are calculated by summing all occurring emissions:

$$m_{out,fueltotal(x)} = m_{out,burn(x)} + m_{out,production(x)} \quad (19)$$

4.3. Impact Assessment

In the impact assessment, the established life-cycle inventory results are further used and environmental indicators are calculated. For the impact estimation, the ReCiPe 2016 method is used within the contribution. The ReCiPe 2016 method was co-developed by the Dutch National Institute for Public Health and the Environment (RIVM) and is well suited as a recognized method of impact estimation of emissions [24,69]. In the following, the parameterization of the impact estimation is presented first.

4.3.1. Parameterization of the Impact Assessment

For the ReCiPe 2016 impact-estimation method, the perspective, region, and weighting factors are selected. The following impact estimation perspectives are offered by ReCiPe [24]:

- Individualistic—short time horizon of 20 years;
- Hierarchic—time horizon of 100 years (standard);
- Egalitarian—time horizon of 1000 years and longer.

The "hierarchical" perspective with a medium-term time horizon is the most widely used in science [17,18] and is therefore used in the context of the method presented here. For the region, the value "World" was chosen due to the globalized air traffic. For the weighting, in addition to the mentioned perspectives, an average weighting is provided by ReCiPe 2016 as a recommended standard [24].

In addition, the user can decide whether the altitude dependence is considered by the Schwartz 2009 method [70]. The environmental impact of aviation-induced cloudiness (AIC) and nitrogen oxides depends on atmospheric conditions such as air pressure, temperature, and humidity. Since these atmospheric conditions depend on flight altitude, the environmental effect of an aircraft is altitude dependent. Consideration of the Schwartz altitude-dependent effect can be optionally selected by the user of the method as part of the following impact assessment. Depending on the objective of the study, the height-dependent effect is considered by other authors [5,71]. Appendix H shows and describes in more detail how the environmental impacts diverge depending on the altitude of the aircraft.

4.3.2. Calculation of the Midpoint Indicators

First, the life-cycle inventory results are assigned (classified) to the corresponding impact categories. For this purpose, the characterization factors (CF) are considered, which are used to convert a substance into the corresponding impact indicator. In Appendix G, the substances and characterization factors required here are taken from the ReCiPe method [72] and listed. Using CF, the result of a midpoint category ($MP_{i,Total(x,PW)}$) is calculated:

$$MP_{i,Total(x,PW)} = \sum_{x=1}^{n} m_{out,total(x)} \cdot CF_{(x,PW)} \quad (20)$$

For this purpose, all substances assigned to a midpoint category (MP) are related to the common impact indicator with the associated CF of the selected perspective for impact assessment (for example CO_2 equivalent mass for the climate-change category). In [70], sustained global-temperature-change potentials (SGTP) are used as an alternative to

global-warming potential (GWP), which the Intergovernmental Panel on Climate Change (IPCC) defined by the midpoint indicator increase in infrared radiation [17,70]. The SGTP was introduced in 2005 as an alternative to the GWP and provides comparable results [73]. By normalizing the radiative force to the reference substance CO_2, the CF of the height-dependent effects are described [70]:

$$CF_{(x,PW,h)} = \frac{STGP_{(x,PW)} \cdot s_{(x,h)}}{STGP_{CO_2(PW)}} \quad (21)$$

The height-dependent weighting factors $s_{(x,h)}$ for the calculation of CF were taken from Scholz 2020 [34] and can be found in Appendix H. In addition, the calculation of all further substances and the AIC using the method presented by Schwartz is presented in Appendix H.

4.3.3. Calculation of the Endpoint Indicators and the Single Score

The calculation of the 18 MP is followed by the calculation of the endpoint indicators (EPs). The EPs quantify the damage to the three endpoint categories $EP_{(j,PW)}$:

$$EP_{(j,PW)} = \sum_{i=1}^{18} MP_{(i)} \cdot MTE_{(j,PW)} \quad (22)$$

For calculation, all MPs for the PW acting on EPs are related to EPs with the mid-to-endpoint factors ($MTE_{(j,PW)}$). The mid-to-endpoint indicators required for this purpose are listed in Appendix I, divided into the endpoint indicators of human health, ecosystem, and resource use [74]. Here, the endpoint categories can be interpreted as follows [69]:

- Human health (DALY)—life lost in years;
- Ecosystem (species)—life forms lost to extinction in one year;
- Resource availability (USD)—increase in cost in USD.

To be able to compare the EPs with each other, the reference to the same unit in a single score is normalized and weighted:

$$S_{(j,WT,PW)} = \sum_{i=1}^{18} \frac{EP_{(i)} \cdot W_{(j,WT)}}{NF_{(j,PW)}} \quad (23)$$

The single score $S_{(j,WT,PW)}$, which is calculated by the weighting factors ($W_{(j,WT)}$) and normalization factors ($NF_{(j,WT)}$), is used as a reference to determine the proportion of each midpoint and endpoint category in the total environmental impact. Here, $W_{(j,WT)}$ depends on the selected weighting perspective (WP), which is set by default with the parameter of "average", as recommended by RIVM [75]. Appendix J conclusively lists all necessary normalization and weighting factors [75,76].

4.4. Evaluation and Interpretation

The final step of the LCA framework consists of the evaluation and interpretation of the results [14]. Within the scope of the evaluation, the results of the impact assessment are examined and clearly presented. First, the incoming and outgoing substances are considered via the life-cycle inventory results. For this purpose, the results per lifetime (Fct. 1) and per passenger-kilometer cabin (Fct. 2) are evaluated via the functional units. By relating the midpoint and endpoint indicators to the single scores, the share of the respective category in the total environmental impact is determined. This makes the categories comparable with each other and a statement can be made regarding the ecological efficiency of a cabin configuration. When comparing cabin configurations, it is important to change only the cabin configuration and not to change any other parameters. This ensures comparability.

5. Results and Discussion

Within the scope of the research work, the developed method was implemented in a spreadsheet program so that a simple application was possible. According to the defined parameters, the user can select the parameters shown in Figure 4. The parameters set for the calculation performed are noted in parentheses.

Aircraft	Basic operations parameter	Mission mix entire life cycle	Cabin configuration
• Aircraft type *(A350-900)* • Engine type *(Trent XWB-84)*	• Load factor *(79.1 %)* • Number of passenger seats *(Cabin A: 293; Cabin B: 303)* • Average Payload *(5000 kg)* • *Mass passenger (105 kg)*	• Short-haul flights *(25 %; 1500 km)* • Medium-haul flights *(50 %; 3000 km)* • Long-haul flights *(25 %; 9000 km)*	• Seats • Lavatories • Galleys • Galley inserts

Figure 4. Variable parameters for users. In brackets we show the parameters used for the following results. Cabin configuration is shown in Table 7.

Table 7. Defined cabin layout for application of the method.

Components	Mass (kg)	Quantity Cabin A	Quantity Cabin B
First-class seats	50	0	0
Business-class seats	27	48	40
Premium economy-class seats	17	21	0
Economy-class seats	10	216	255
First-class lavatories	150	0	0
Business-class lavatories	150	2	2
Premium economy-class lavatories	100	0	0
Economy-class lavatories	100	6	5
Galley modules (all classes)	100	9	7
Standard units (all galleys)	3	45	35
Coffee machines (all galleys)	7	27	21
Kettles (all galleys)	6	9	7
Trolleys—full size (all galleys)	17	36	28
Trolleys—half size (all galleys)	11	36	28

Based on the selected parameters, the spreadsheet program automatically accesses the necessary databases, and the results are calculated and presented for Functional Unit 1 and Functional Unit 2. For the application of the method, an Airbus A350–900 was chosen as the reference aircraft since it is considered to be one of the most modern wide-body civil aircraft. In addition, the cabin components shown in Table 7 were defined.

Compared to cabin B, cabin A has an additional passenger class due to the premium-economy class. Overall, cabin A has 285 passenger seats, which is 10 seats less than cabin B. This is due to the higher weighting of business class and an additional premium economy class, which takes up more space. In addition to the space taken up, the mass of the higher-class components is greater, which means that cabin A weighs 6999 kg, about 800 kg more than cabin B. The higher mass of cabin A results in additional fuel consumption of 1 million kg over the entire life cycle, as shown in the life-cycle inventory results in Table 8.

Table 8. Results of the inventory analysis for cabin A and cabin B.

Input (kg)	Cabin A (Fuel Lifetime)	Cabin B (Fuel Lifetime)
m_{Fuel}	1.92E + 07	1.71E + 07
Output	(Emissions Lifetime)	(Emissions Lifetime)
m_{CO2}	6.52E + 07	5.78E + 07
m_{N2O}	1.90E + 03	1.69E + 03
m_{SO2}	9.99E + 03	8.86E + 03
m_{H2O}	2.38E + 07	2.11E + 07
m_{NOX}	3.65E + 05	3.24E + 05
m_{HC}	5.41E + 03	4.80E + 03
m_{CO}	4.71E + 04	4.17E + 04
m_{NH3}	3.35E + 03	2.97E + 03
m_{NMVOC}	1.90E + 04	1.69E + 04
m_{TSP}	3.59E + 03	3.19E + 03
m_{CH4}	5.94E + 03	5.27E + 03
$m_{Öl}$	2.14E + 07	1.90E + 07
m_{Gas}	1.11E + 06	9.88E + 05

Due to the linear relationship between the amount of fuel consumed and the calculation of the initial materials with the emission factors, the emitted masses for each emission product for cabin configuration B were about 11% lower. Analogous to the higher emission values, quantifying the environmental impact by evaluating the midpoint and endpoint indicators showed the negative impact of the increased fuel consumption on the environment. Table 9 shows the midpoint and endpoint indicators calculated from the life-cycle inventory results using the 2016 ReCiPe method. The midpoint and endpoint categories were not comparable to each other due to the different units. However, by calculating the dimensionless single scores, the individual single scores could be compared with each other.

Table 9. Midpoint indicators, endpoints, and single scores for cabin A and cabin B.

Midpoint Indicator	Unit	Cabin A (Lifetime)	Cabin B (Lifetime)
Climate change	kg CO_2 eq.	1.86E + 08	1.65E + 08
Ozone depletion	kg CFC11 eq.	2.09E + 01	1.85E + 01
Ionizing radiation	kBq Co-60 to air eq.	0.00E + 00	0.00E + 00
Particulate-matter formation	kg PM2.5-eq.	4.39E + 04	3.89E + 04
Photochemical ozone formation (human)	kg NOx-eq.	3.70E + 05	3.28E + 05
Photochemical ozone formation (land)	kg NOx-eq.	3.67E + 05	3.25E + 05
Toxicity (carcinogenic)	1,4-DCB eq.	9.31E + 02	8.25E + 02
Toxicity (non-carcinogenic)	1,4-DCB eq.	4.24E + 03	3.76E + 03
Toxicity (land)	1,4-DCB eq.	1.62E + 02	1.44E + 02
Toxicity (fresh water)	1,4-DCB eq.	8.33E − 02	7.39E − 02
Toxicity (seawater)	1,4-DCB eq.	2.10E + 00	1.86E + 00
Water consumption	m3 H20 consumed	0.00E + 00	0.00E + 00
Acidification	kg SO2-eq	1.48E + 05	1.31E + 05
Land use and transformation	m2·annual crop eq.	0.00E + 00	0.00E + 00
Freshwater eutrophication	kg P-eq. to freshwater	0.00E + 00	0.00E + 00
Seawater eutrophication	kg N-eq. to marine water	1.40E + 04	1.24E + 04
Mineral consumption	kg Cu-eq.	0.00E + 00	0.00E + 00
Consumption of raw fossil materials	kg oil-eq.	2.22E + 07	1.97E + 07
Endpoint Indicator	Unit	Cabin A (Lifetime)	Cabin B (Lifetime)
Human health	DALY	2.00E + 02	1.78E + 02
Ecosystem	species	5.52E − 01	4.90E − 01
Resource availability	USD	9.96E + 06	8.83E + 06
Total Single Score	Points	5.46E + 07	4.84E + 07

By relating the individual environmental impacts to the total single score, it was possible to determine the share of the environmental impact of the individual midpoint and endpoint categories in the total environmental impact. The seven midpoint categories shown in Figure 5 accounted for a total of over 99% of the environmental impact. The category of climate change had the largest share of the environmental impact, with 47.36%.

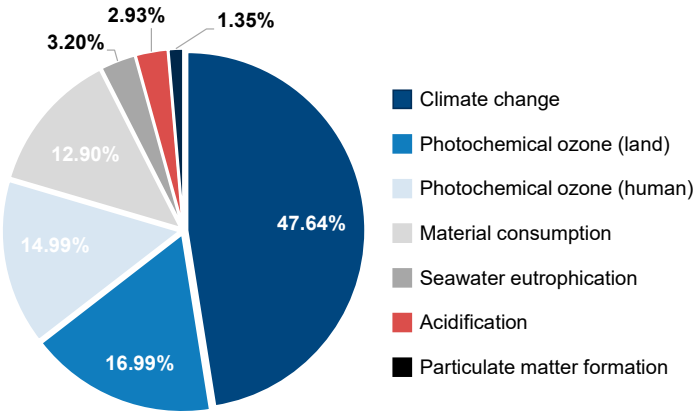


Figure 5. Share of midpoint indicators on single score.

Figure 6 below shows the share of the environmental impact of the endpoint categories in the total environmental impact. The quantification of the environmental damage was thereby divided into human health, ecosystem, and resource availability according to the ReCiPe 2016 method. The largest damage occurred to the ecosystem with 54.7% and to human health with 32.40%. The relevant midpoint categories of climate change and photochemical ozone formation (human and ecosystem) were responsible for this circumstance, which cause damage to human health and the ecosystem.

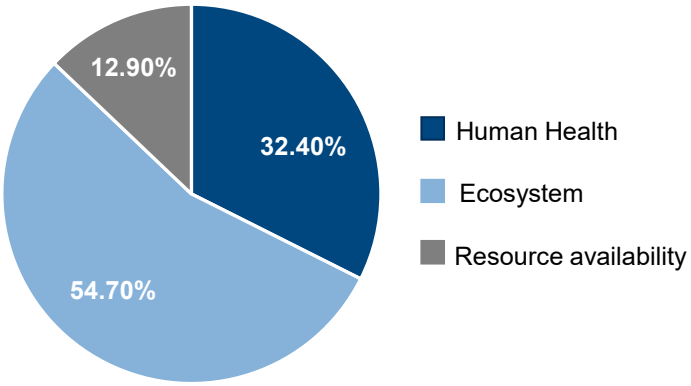


Figure 6. Share of endpoint indicators on single score.

6. Conclusions and Outlook

This paper presents a method for calculating the environmental impacts of aircraft cabins. The basis of the developed method is the four-phase LCA procedure. The method allows the user to carry out a parameterization on the basis of which different publicly available data sources are used. Thus, it is possible to choose between all common aircraft and engine types and furthermore to select the mission profile according to the real operational scenario. Subsequently, a cabin layout can be defined. This covers the major areas of the cabin, seats, lavatories, and galleys. On the basis of the subsequent life-cycle inventory, an impact assessment of the environmental effects is made possible by means of the ReCiPe method. Finally, different cabin layouts can be compared and analyzed with regard to their LCA.

The first application of the method shows that different cabin configurations have a direct and non-negligible impact on the LCA when compared directly and that, in

particular, the functional unit of passenger kilometers over the entire life cycle is suitable as a functional unit for comparison. Despite the first successful application, there is a need for further validation and research to close the following limitations: Firstly, sensitivity studies will be pursued in future research work. The aim here is, among others, to investigate the effects of different mission profiles and engine types. Secondly, for operationalization in practice, it is necessary to develop process models for integrating the method into decision-making processes at aircraft manufacturers and airlines. In addition to the cabin development and design, the focus is on the cabin-customization process as an interface between manufacturer and airline. One of the limitations is also that we applied a gate-to-gate approach and excluded the production phase of the cabin components. For a comprehensive cradle-to-grave approach, we will work on the integration of the supplier to close data gaps and enable a full environmental assessment. Another field of application could be also the environmental assessment of new cabin-operation concepts [77].

Author Contributions: Conceptualization, D.K., M.A. and M.R.; methodology, D.K.; validation, D.K. and M.A.; formal analysis, M.A.; investigation, D.K. and M.A.; resources, M.A.; data curation, M.A.; writing—original draft preparation, D.K. and M.A.; writing—review and editing, D.K., M.A. and M.F.; visualization, M.A.; supervision, D.K. and M.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviations

AIC	Aviation-induced cloudiness
ATA	Air Transport Association of America
BDL	Federal Association of the German Air Transport Industry
CCD	Climb–cruise–descent phases
CF	Characterization factor
DIN	German Institute for Standardization
EASA	European Union Aviation Safety Agency
EEA	European Environment Agency
EF	Endpoint factor
EMEP	European Monitoring and Evaluation Programme
EP	Endpoint indicator
GWP	Global-warming potential
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life-cycle assessment
LTO	Landing and takeoff cycle
MFW	Maximum fuel weight
MLW	Maximum landing weight
MP	Midpoint factor
MTE	Mid-to-Endpoint factor
MTOW	Maximum takeoff weight
MZFW	Maximum zero-fuel weight
NF	Normalization factor

OEW	Operating empty weight
PAX	Passenger
PKM	Passenger kilometer
PW	Perspective impact assessment
RIVM	Dutch National Institute for Public Health and the Environment
SAF	Sustainable aviation fuel
STGP	Global-temperature-change potential
W	Weighting factor
WP	Weighting perspective
Symbols	
$h_{flight(1)}$	Interpolation variable 1: lower value, cruising altitude
$h_{flight(2)}$	Interpolation variable 2: upper value, cruising altitude
$h_{flight(S,M,L)}$	Cruising altitude of short-, medium-, and long-distance flights
$CF_{(x,PW)}$	Characterization factors per substance x
$EF_{\text{fuel}(x)}$	Emission factor for fuel of substance x
$EP_{(j,PW)}$	Result per endpoint indicator
$MP_{i,Total(x,PW)}$	Result per midpoint indicator
$MTE_{(j,PW)}$	Mid-to-endpoint conversion factors
$NF_{(j,PW)}$	Endpoint-normalization factors
$S_{(j,WT,PW)}$	Single score depending on weighting factor, perspective, endpoint indicators
$W_{(j,WT)}$	Weighting factors
ff_{App}	Fuel flow approach time
ff_{CO}	Fuel flow climb time
ff_{Idle}	Fuel flow taxi time
ff_{TO}	Fuel flow takeoff time
$l_{flight,total}$	Total flight distance in life cycle
$l_{flight(1)}$	Interpolation variable 1: lower value, flight distance
$l_{flight(2)}$	Interpolation variable 2: upper value, flight distance
$l_{flight,L}$	Defined length long-haul
$l_{flight,M}$	Defined length medium-haul
$l_{flight,S}$	Defined length short-haul
l_{flight}	Flight distance
m_{fuel}	Weight of fuel
$m_{averageAC}$	Average weight of aircraft
m_{Cabin}	Weight of cabin
$m_{FuelCCD,L}$	Weight of fuel for cruising long-haul over entire life cycle
$m_{FuelCCD,M}$	Weight of fuel for cruising medium-haul over entire life cycle
$m_{FuelCCD,S}$	Weight of fuel for cruising short-haul over entire life cycle
m_{Gall}	Weight of galleys
m_{GallIn}	Weight of galley interior
m_{Lav}	Weight of aircraft lavatories
m_{OEW}	Operating empty weight
$m_{PAX,total}$	Total passenger weight
m_{PAX}	Average weight per passenger including baggage
m_{Seats}	Weight of passenger seats
$m_{fuel,CCD(1)}$	Interpolation variable 1: lower value, weight of fuel
$m_{fuel,CCD(2)}$	Interpolation variable 2: upper value, weight of fuel
$m_{fuel,CCD,Life}$	Weight of fuel for cruise flight over entire life cycle
$m_{fuel,CCD,S,M,L}$	Weight of fuel for short-, medium- and long-haul, including takeoff and landing cycle
$m_{fuel,CCD}$	Weight of fuel for cruise flight
$m_{fuel,LTO,Life}$	Weight of fuel for takeoff and landing cycle over total life cycle
$m_{fuel,LTO}$	Weight of fuel for takeoff and landing cycle
$m_{fuel,Life}$	Weight of fuel for entire life cycle
$m_{fuel,reserve}$	Weight of reserve fuel
$m_{fuel,total}$	Weight of fuel

$m_{fuel,Life,Cabin}$	Weight of fuel related to cabin over life cycle
$m_{fuel,PKM,Cabin}$	Weight of fuel related to cabin passenger kilometers
$m_{out(x)}$	Output emissions of substance x
$m_{out,burn(x)}$	Output emissions fuel combustion
$m_{out,fueltotal(x)}$	Output emissions total
$m_{out,production(x)}$	Outgoing emissions fuel production
$m_{payload}$	Payload
ms_{TOW}	Specific takeoff weight
$n_{Engines}$	Number of engines
$n_{Life,L}$	Number of long-haul flight cycles over total life cycle
$n_{Life,M}$	Number of medium-haul flight cycles over total life cycle
$n_{Life,S}$	Number of short-haul flight cycles over total life cycle
n_{PAX}	Number of passengers
n_{Cycles}	Number of flight cycles
n_{seat}	Number of seats
$p_{Range,S,M,L}$	Distribution of short-, medium-, and long-haul flights
p_{pax}	Load factor
$s_{Substance(1)}$	Interpolation variable 1: lower value, weighting-factor substance
$s_{Substance(2)}$	Interpolation variable 2: upper value, weighting-factor substance
$s_{Substance(h)}$	Altitude-dependent weighting factors
t_{App}	Approach time
t_{CO}	Climb time
t_{Idle}	Taxiing time
t_{Life}	Total flight hours over aircraft life cycle
$t_{Range(1)}$	Interpolation variable 1: lower value, duration flight
$t_{Range(2)}$	Interpolation variable 2: upper value, duration flight
$t_{Range,L}$	Long-haul flight hours over aircraft life cycle
$t_{Range,M}$	Medium-haul flight hours over aircraft life cycle
$t_{Range,S,M,L}$	Short-, medium-, and long-haul flight hours over aircraft life cycle
$t_{Range,S,M,L}$	Interpolated flight hours of short-, medium-, and long-haul flights
$t_{Range,S}$	Short-haul flight hours over aircraft life cycle
t_{TO}	Takeoff time
$tinerpol_{Long}$	Interpolated flight time of long-haul flight
$tinerpol_{Mid}$	Interpolated flight time of medium-haul flight
$tinerpol_{Short}$	Interpolated flight time of short-haul flight
$STGP$	Sustained global-temperature-change potential

Appendix A

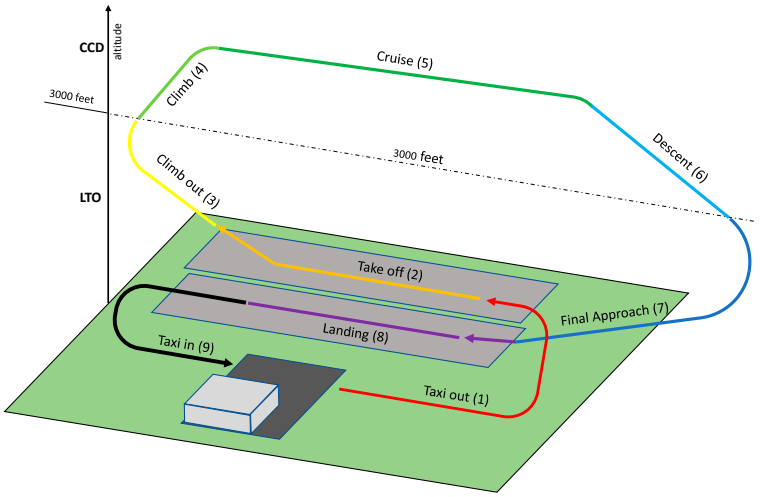


Figure A1. Landing–takeoff (LTO) and climb–cruise–descent (CCD) phase [78].

Appendix B

Table A1. Aircraft characteristics of A350–900 and A320–200.

Type	A350–900	A320–200	Source
Example operating empty weight	115.7 t		[79]
Maximum takeoff weight	268,900 kg	73,500 kg	[80,81]
Number of engines	2	2	[80,81]
Engine type	Trent XWB-84	PW1124G1-JM	[80,81]

Appendix C

Table A2. Consumption values of the engine types used here from ICAO database in kg/s [45].

Engine Type	Fuel Flow T/O(ff_{TO})	Fuel Flow C/O(ff_{CO})	Fuel Flow App(ff_{App})	Fuel Flow Idle(ff_{Idle})
Trent XWB-84	2.819	2.306	0.801	0.291
PW1124G1-JM	0.710	0.600	0.210	0.080

Appendix D

Table A3. Distance, altitude, duration, and typical fuel consumption for A320 and A350 [42].

Distance (NM)	A320			A350		
	Most Frequently Observed Cruising Altitude (100 Feet)	Duration (hh:mm:ss)	Fuel Consumption (kg)	Most Frequently Observed Cruising Altitude (100 Feet)	Duration (hh:mm:ss)	Fuel Consumption (kg)
125	180	00:21:37	931.92	180	00:21:56	1786.52
200	270	00:31:18	1356.45	240	00:31:55	2692.42
250	280	00:37:44	1647.38	280	00:37:51	3226.65
500	320	01:10:49	2946.00	360	01:08:34	5713.71
750	360	01:45:05	4124.49	400	01:39:48	8071.12
1000	380	02:18:37	5273.37	400	02:10:56	10,641.24
1500	380	03:25:45	7768.61	420	03:13:15	15,553.61
2000	380	04:32:47	10,483.84	420	04:15:41	20,705.44
2500	380	05:39:50	12,914.24	440	05:17:56	25,537.04
3000	380	06:46:01	15,846.86	440	06:20:25	30,705.60
3500				440	07:22:39	35,715.75
4000				440	08:25:09	40,920.82
4500				440	09:27:24	45,933.32
5000				440	10:30:01	51,380.03
5500				440	11:32:17	56,391.88

Appendix E

Formula (A1): interpolation of the duration of a short-, medium-, and long-haul flight—for this purpose, the data of the EMEP database from Appendix D are used according to the mission profile.

$$t_{Range,S,M,L} = t_{Range(1)} + \frac{\left(t_{Range(2)} - t_{Range(1)}\right)}{\left(l_{fight(2)} - l_{flight(1)}\right)} \cdot \left(l_{flight(2)} - l_{flight(S,M,L)}\right) \quad \text{(A1)}$$

Appendix F

Table A4. Specific emission factors for two engine types for the LTO phase [45].

		EF—Taxi	EF—Takeoff	EF—Climb	EF—Approach
Trent XWB-84	HC	0.94	0	0	0
	CO	20.56	0.39	0.39	1.2
	NO_x	4.73	45.48	34.53	11.46
PW1124G1-JM	HC	0.55	0.1	0.1	0.02
	CO	29.78	0.26	0.38	6.39
	NO_x	4.72	16.47	13.85	8.92

Appendix G

Table A5. Characterization factors for the calculation of endpoint indicators—hierarchical [72].

Midpoint Indicator	Unit	Assigned Substances (Hierarchical Characterization Factor)
Climate change	kg CO_2eq.	CO_2 (1), N_2O (298), H_2O*, NO_X* (*), CH_4 (34)
Ozone depletion	kg CFC11eq.	N_2O (0.011)
Ionizing radiation	kBq Co-60 to air eq.	-
Particulate-matter formation	kg PM2.5 eq.	SO_2 (0.29), NO_X (0.11), NH_3 (0.24)
Photochemical ozone formation (ecosystem)	kg NOx-eq.	NO_x (1), HC (0.26)
Photochemical ozone formation (human health)	kg NOx eq.	NOX (1), HC (0.16), NMVOC (0.18)
Acidification	1,4-DCB eq.	SO_2 (1), NO_X (0.36), NH_3 (1.96)
Freshwater eutrophication	1,4-DCB eq.	-
Seawater eutrophication	1,4-DCB eq.	NO_X (0.0384), NH_3 (0.104)
Toxicity (carcinogenic)	1,4-DCB eq.	HC (0.17)
Toxicity (non-carcinogenic)	1,4-DCB eq.	HC (0.78)
Toxicity (land)	m^3 H_20 consumed	HC (0.03)
Toxicity (freshwater)	kg SO_2 eq.	HC (0.0000154)
Toxicity (seawater)	m^2·annual crop eq.	HC (0.000388)
Land use and transformation	kg P eq. to freshwater	-
Water consumption	kg N eq. to marine water	-
Mineral consumption	kg Cu eq.	-
Consumption of raw fossil materials	kg oil eq.	Crude (1), gas (0.71)

* Consideration by means of Schwartz.

Appendix H

As described in Section 4.3. the SGTPs are comparable to GWP and are therefore suitable for integration into the ReCiPe 2016 method, which uses GWP as a characterization model for MP climate change [24,73]. The SGTP for calculating CF are taken from [70] for the hierarchical perspective and listed in Table A6 below:

Table A6. SGTPs for the hierarchical perspective [70].

Substance (x)	Unit	$SGTP_{(x,100)}$
CO_2	K/kg CO_2	3.58E − 14
O_3 (short time)	K/kg NO_X	7.97E − 12
CH_4	K/kg NO_X	−3.9E − 12
O_3 (long time)	K/kg NO_X	−9.14E − 13
Contrails	K/km	1.37E − 13
Cirrus clouds	K/km	4.12E − 13

SGTPs for AIC effects per H_2O re calculated over the distance flown in 2018 and total water emissions emitted [2]:

- $SGTP_{(contrails,100)} = 1.78E - 14[K/kgH_2O]$
- $SGTP_{(circusclouds,100)} = 5.36E - 14[K/kgH_2O]$

Using the STGP per kg of water emitted and the relationship in Formula (A2), the CF for the AIC effects is calculated:

$$CF_{(AIC,100,h)} = \frac{SGTP_{(Kond.,100)} \cdot s_{Kond(h)}}{SGTP_{(CO_2,100)}} + \frac{SGTP_{(Zirr.,100)} \cdot s_{Zirr(h)}}{SGTP_{(CO_2,100)}} \quad \text{(A2)}$$

For the height-dependent effects, the increase in O_3 and decrease in CH_4 as a consequence of NO_X emissions are responsible for the height-dependent NO_X effects; therefore, the STGPs of these substances are used vgl. [82], (p. 24). When O_3 interacts with NO_X there is a warming effect for short-lived O_3 and a cooling effect for long-lived O_3. Although at ground level a cooling effect due to the decrease in CH_4 predominates, at usual cruising altitudes of passenger aircraft the warming effect as a result of O_3 increasing due to NO_X emissions is dominant. Despite the O_3 increase, the amount of O_3 in the atmosphere is reduced because by reducing the residence time of CH_4 and the amount of O_3 in the atmosphere is reduced overall. The following Formula (A3) describes, considering short- and long-lived O_3 effects, the calculation of CF for NO_X emissions:

$$CF_{(NOX,100,h)} = \frac{SGTP_{(O3kurzlebig,100)} \cdot s_{O3kurzlebig(h)}}{SGTP_{(CO_2,100)}} + \frac{SGTP_{CH4,100} \cdot s_{CH4(h)}}{SGTP_{(CO_2,100)}} + \frac{SGTP_{(O3langlebig,100)} \cdot s_{O3langlebig(h)}}{SGTP_{(CO_2,100)}} \quad \text{(A3)}$$

The height-dependent weighting factors $s_{(x,h)}$ for the calculation of CF were taken from Scholz 2020 and are listed in Table A8 based on [34].

Table A7. Forcing factors depending on altitude for AIC, O_3, and CH_4, and O_3 [34].

AIC		O_3 (S)		CH_4 and O_3 (L)	
Forcing Factors	**Altitude (ft)**	**Forcing Factors**	**Altitude (ft)**	**Forcing Factors**	**Altitude (ft)**
0.02845	17,470	0.46942	17,502	0.86771	17,470
0.00000	19,548	0.55761	19,484	0.92461	19,484
0.00000	21,530	0.62020	21,498	0.95590	21,498
0.17354	23,511	0.71124	23,480	0.96159	23,543
0.39545	25,525	0.71124	25,525	0.94452	25,525
0.79943	27,507	0.81366	27,507	0.92745	27,539
1.25178	29,457	0.93030	29,521	0.92745	29,521
1.70982	31,598	1.00996	31,502	0.94168	31,534
2.10526	33,548	1.13229	33,484	0.97582	33,516
1.82077	35,530	1.42816	35,562	1.14083	35,562
1.53343	37,543	1.62447	37,575	1.21479	37,543
0.96728	39,557	1.80370	39,589	1.20341	39,589
0.79374	41,539	1.93172	41,539	1.20341	41,571

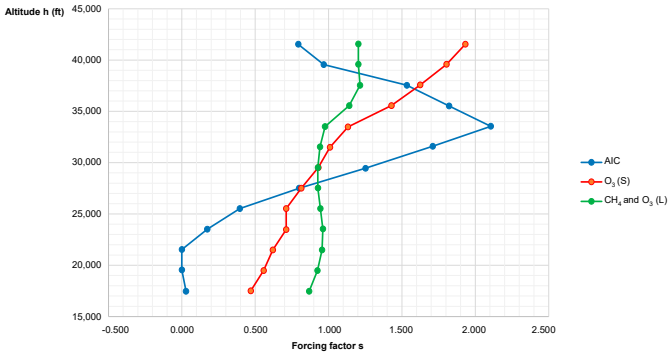


Figure A2. Radiative forcing-factor data [34,70].

Figure A2 shows the graphical representation of the weighting factors from Table A8. Since data are not available for all flight altitudes, the calculation is performed by means of

interpolation from the existing data basis. Using the following Formula (A4), the weighting factors are determined by interpolation according to the Schwartz 2009 method as a function of the flight altitude h_{flug}:

$$s_{Substance(h)} = s_{Substance(1)} + \frac{\left(s_{Substance(2)} - s_{Substance(1)}\right)}{\left(h_{flight(2)} - h_{flight(1)}\right)} \cdot \left(h_{flight(2)} - h_{flight(S,M,L)}\right) \quad \text{(A4)}$$

Appendix I

Table A8. Mid- to endpoint factors—hierarchical [74].

Midpoint Indicator	Unit	Characterization Factor (Hierarchical)
Human Health		
Climate change (human health)	DALY/kg CO_2 eq.	9.28E − 07
Ozone depletion (human health)	DALY/kg CFC11 eq.	5.31E − 04
Ionizing radiation (human health)	DALY/kBq Co-60 to air eq.	8.50E − 09
Particulate-matter formation (human health)	DALY/kg PM2.5 eq.	6.29E − 04
Photochemical ozone formation (human health)	DALY/kg NOx eq.	9.10E − 07
Toxicity (carcinogenic)	DALY/kg 1,4-DCB emitted to urban air eq.	3.32E − 06
Toxicity (non-carcinogenic)	DALY/kg 1,4-DCB emitted to urban air eq.	2.28E − 07
Water consumption (human health)	1,4-DCB eq.	2.22E − 06
Ecosystem		
Climate change (ecosystem land)	Species·year/kg CO_2 eq.	2.80E − 09
Photochemical ozone formation (ecosystem land)	Species·year/kg NOx eq.	1.29E − 07
Acidification (ecosystem land)	Species·year/kg SO_2 eq.	2.12E − 07
Toxicity (ecosystem land)	Species·year/kg 1,4-DBC emitted to industrial soil eq.	1.14E − 11
Water consumption (ecosystem land)	Species·year/m^3 consumed	1.35E − 08
Land use and transformation (ecosystem land)	Species/m^2·annual crop eq.	8.88E − 09
Climate change (ecosystem freshwater)	Species·year/kg CO_2 eq.	1.45E − 14
Eutrophication (ecosystem freshwater)	Species·year/kg P to freshwater eq.	6.71E − 07
Toxicity (ecosystem freshwater)	Species·year/kg 1,4-DBC emitted to freshwater eq.	6.95E − 10
Water consumption	Species·year/m^3 consumed	6.04E − 13
Sea toxicity (ecosystem saltwater)	Species·year/kg 1,4-DBC emitted to sea water eq.	1.05E − 10
Eutrophication (ecosystem saltwater)	Species·year/kg N to marine water eq	1.70E − 09
Resource Availability		
Mineral consumption	Species·year/kg 1,4-DBC emitted to sea water eq.	1.05E − 10
Consumption of raw fossil materials	Species·year/kg N to marine water eq.	1.70E − 09

Appendix J

Table A9. Normalization factors of endpoint indicators [76].

Midpoint Indicator	Unit	Perspective		
		Individualistic	Hierarchical	Egalitarian
Human Health				
Climate change (human health)	DALY/kg CO_2 eq.	8.73E − 04	7.42E − 03	7.25E − 02
Ozone depletion (human health)	DALY/kg CFC11 eq.	1.55E − 05	3.19E − 05	9.44E − 05
Ionizing radiation (human health)	DALY/kBq Co-60 to air eq.	3.19E − 06	4.08E − 06	9.78E − 06
Particulate-matter formation (human health)	DALY/kg PM2.5 eq.	1.00E − 02	1.61E − 02	1.61E − 02
Photochemical ozone formation (human health)	DALY/kg NOx eq.	1.80E − 05	1.80E − 05	1.80E − 05
Toxicity (carcinogenic)	DALY/kg 1,4-DCB emitted to urban air eq.	3.29E − 06	3.42E − 05	9.80E − 04
Toxicity (non-carcinogenic)	DALY/kg 1,4-DCB emitted to urban air eq.	3.39E − 07	2.08E − 04	1.48E − 02
Water consumption (human health)	1,4-DCB eq.	1.96E − 04	1.96E − 04	2.91E − 04
Ecosystem				
Climate change (ecosystem land)	Species·year/kg CO_2 eq.	5.72E − 06	2.24E − 05	1.45E − 04
Photochemical ozone formation (ecosystem land)	Species·year/kg NOx eq.	2.24E − 06	2.24E − 06	2.24E − 06
Acidification (ecosystem land)	Species·year/kg SO_2 eq.	8.42E − 06	8.42E − 06	8.42E − 06
Toxicity (ecosystem land)	Species·year/kg 1,4-DBC emitted to industrial soil eq.	3.62E − 04	8.19E − 04	8.82E − 04
Water consumption (ecosystem land)	Species·year/m^3 consumed	0.00E + 00	3.48E − 06	3.48E − 06
Land use and transformation (ecosystem land)	Species/ (m^2·annual crop eq.)	6.23E − 04	6.23E − 04	6.23E − 04
Climate change (ecosystem freshwater)	Species·year/kg CO_2 eq.	1.56E − 10	6.11E − 10	3.95E − 09
Eutrophication (ecosystem freshwater)	Species·year/kg P to freshwater eq.	4.90E − 07	4.90E − 07	4.90E − 07
Toxicity (ecosystem saltwater)	Species·year/kg 1,4-DBC emitted to freshwater eq.	8.74E − 09	1.75E − 08	2.02E − 07
Water consumption	Species·year/m^3 consumed	6.16E − 10	6.16E − 10	6.16E − 10
Sea toxicity (ecosystem saltwater)	Species·year/kg 1,4-DBC emitted to sea water eq.	9.24E − 10	4.56E − 09	2.59E − 04
Eutrophication (ecosystem saltwater)	Species·year/kg N to marine water eq.	6.12E − 09	6.12E − 09	6.12E − 09
Resource Availability				
Mineral consumption	Species·year/kg 1,4-DBC emitted to sea water eq.	3.08E + 04	2.77E + 04	2.77E + 04
Consumption of raw fossil materials	Species·year/kg N to marine water eq.	2.91E + 02	2.91E + 02	2.91E + 02

Table A10. Weighting factors of endpoint indicators [75].

	Human Health	Ecosystem	Resource Availability
Average Value	**400**	**400**	**200**
Individualist	250	550	200
Hierarchist	400	300	300
Egalitarian	500	300	200

References

1. Federal Association of the German Air Transport Industry e. V. (BDL). *Klimaschutz im Luftverkehr—Analyse der Instrumente zur CO_2-Reduktion*; Federal Association of the German Air Transport Industry: Berlin, Germany, 2019.
2. Lee, D.S.; Fahey, D.W.; Skowron, A.; Allen, M.R.; Burkhardt, U.; Chen, Q.; Doherty, S.J.; Freeman, S.; Forster, P.M.; Fuglestvedt, J.; et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* **2021**, *244*, 117834. [CrossRef] [PubMed]
3. Howe, S.; Kolios, A.J.; Brennan, F.P. Environmental life cycle assessment of commercial passenger jet airliners. *Transp. Res. Part D Transp. Environ.* **2013**, *19*, 34–41. [CrossRef]
4. Krieg, H.; Ilg, R.; Brethauer, L.; Loske, F. Environmental impact assessment of aircraft operation: A key for greening the aviation sector. *Aerotec. Missili Spaz.* **2012**, *91*, 73–78.
5. Johanning, A. *Methodik zur Ökobilanzierung im Flugzeugvorentwurf*; Technische Universität München: München, Germany, 2017.
6. International Air Transport Association (IATA). *Aircraft Technology Roadmap to 2050*; IATA: Geneva, Switzerland, 2019.
7. Hall, A.; Mayer, T.; Wuggetzer, I.; Childs, P.R.N. Future aircraft cabins and design thinking: Optimisation vs. win-win scenarios. *Propuls. Power Res.* **2013**, *2*, 85–95. [CrossRef]
8. Tsai, W.H.; Chang, Y.C.; Lin, S.J.; Chen, H.C.; Chu, P.Y. A green approach to the weight reduction of aircraft cabins. *J. Air Transp. Manag.* **2014**, *40*, 65–77. [CrossRef]
9. Mortensen, R.; Pupkes, B.; Keiser, D.; Reiß, M.; Freitag, M. Inflight catering services—A comparison of central and decentral galleys inside the aircraft cabin, a concept-based approach. *Transp. Res. Procedia* **2022**, *65*, 34–43.
10. International Civil Aviation Organization (ICAO). *Introduction to the ICAO Basket of Measures to Mitigate Climate Change*; ICAO: Montreal, QC, Canada, 2019.
11. Dong, Y.; Miraglia, S.; Manzo, S.; Georgiadis, S.; Sørup, H.J.D.; Boriani, E.; Hald, T.; Thöns, S.; Hauschild, M.Z. Environmental sustainable decision making—The need and obstacles for integration of LCA into decision analysis. *Environ. Sci. Policy* **2018**, *87*, 33–44. [CrossRef]
12. Pryshlakivsky, J.; Searcy, C. Life Cycle Assessment as a decision-making tool: Practitioner and managerial considerations. *J. Clean. Prod.* **2021**, *309*, 127344. [CrossRef]
13. Hauschild, M.Z. Introduction to LCA Methodology. In *Life Cycle Assessment*; Springer International Publishing: Cham, Switzerland, 2018; pp. 59–66. ISBN 9783319564753.
14. *DIN EN ISO 14040*; Environmental Management-Life Cycle Assessment-Principles and Framework. VDI Zentrum Ressourceneffizienz: Berlin, Germany, 2009.
15. Björn, A.; Owsianiak, M.; Molin, C.; Hauschld, Z.M. LCA History. In *Life Cycle Assessment—Theory and Practice*; Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., Eds.; Springer: Cham, Switzerland, 2018; pp. 17–30. ISBN 9781315778730.
16. Jolliet, O.; Saade-Sbeih, M.; Shaked, S.; Jolliet, A.; Crettaz, P. *Environmental Life Cycle Assessment*; CRC Press: Boca Raton, FL, USA, 2015; ISBN 9781439887707.
17. Frischknecht, R. *Lehrbuch der Ökobilanzierung*; Springer Spektrum: Berlin, Germany, 2020; ISBN 9783662547625.
18. European Commission. *ILCD-Handbook-General-Guide-for-LCA—Detailed Guidance*; European Commission: Luxembourg, 2010.
19. *DIN EN ISO 14044*; Umweltmanagement—Ökobilanz—Anforderungen Anleitungen. VDI Zentrum Ressourceneffizienz: Berlin, Germany, 2006.
20. Lüdemann, L.; Sumpf, J.; Golder, M. Ökobilanzergebnisse von Stetigförderern—Einfluss von funktioneller Einheit, Untersuchungsrahmen und Datenqualität. In Proceedings of the 17th Fachkolloquium der WGTL, Chemnitz, Germany, 20–21 September 2021; pp. 116–130.
21. Farjana, S.H.; Mahmud, P.M.A.; Huda, N. An introduction to life cycle assessment. In *Life Cycle Assessment for Sustainable Mining*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 12.
22. Kaltschmitt, M. *Umweltbewertung für Ingenieure*; Springer: Berlin, Germany, 2015; ISBN 9783642369889.
23. Weißenberger, M. *Lebenszyklusbasierte Analyse der Ökologischen Eigenschaften von Niedrigstenergiewohngebäuden unter Besonderer Berücksichtigung der Gebäudetechnik*; Technische Universität München: München, Germany, 2016.
24. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
25. Bong, P.X.H.; Malek, M.A.; Mardi, N.H.; Hanafiah, M.M. Cradle-to-gate water-related impacts on production of traditional food products in Malaysia. *Sustainability* **2020**, *12*, 5274. [CrossRef]

26. Barke, A.; Bley, T.; Thies, C.; Weckenborg, C.; Spengler, T.S. Are Sustainable Aviation Fuels a Viable Option for Decarbonizing Air Transport in Europe? An Environmental and Economic Sustainability Assessment. *Appl. Sci.* **2022**, *12*, 597. [CrossRef]
27. Fricke, K.; Gierlings, S.; Ganser, P.; Seimann, M.; Bergs, T. A cradle to gate approach for life-cycle-assessment of blisk manufacturing. In Proceedings of the ASME Turbo Expo 2021, Online, 7–11 June 2021; pp. 1–10. [CrossRef]
28. Dong, S.; Xian, G.; Yi, X.S. Life cycle assessment of ramie fiber used for FRPs. *Aerospace* **2018**, *5*, 81. [CrossRef]
29. Meng, F.; McKechnie, J.; Turner, T.A.; Pickering, S.J. Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres. *Compos. Part A Appl. Sci. Manuf.* **2017**, *100*, 206–214. [CrossRef]
30. Al-Lami, A.; Hilmer, P.; Sinapius, M. Eco-efficiency assessment of manufacturing carbon fiber reinforced polymers (CFRP) in aerospace industry. *Aerosp. Sci. Technol.* **2018**, *79*, 669–678. [CrossRef]
31. Johanning, A.; Scholz, D. *A First Step towards the Integration of Life Cycle Assessment into Conceptual Aircraft Design*; Deutsche Gesellschaft für Luft-und Raumfahrt-Lilienthal-Oberth: Bonn, Germany, 2013; pp. 1–16.
32. Fabre, A.; Planès, T.; Delbecq, S.; Pommier-Budinger, V.; Lafforgue, G. Life cycle assessment models for overall aircraft design. In Proceedings of the AIAA SCITECH 2022 Forum, San Diego, CA, USA, 3–7 January 2022; pp. 1–20. [CrossRef]
33. Melo, S.P.; Barke, A.; Cerdas, F.; Thies, C.; Mennenga, M.; Spengler, T.S.; Herrmann, C. Sustainability assessment and engineering of emerging aircraft technologies-challenges, methods and tools. *Sustainability* **2020**, *12*, 5663. [CrossRef]
34. Scholz, D. *Calculation of the Emission Characteristics of Aircraft Kerosene and Hydrogen Propulsion*; Harvard Dataverse: Cambridge, MA, USA, 2020; Version 4. [CrossRef]
35. Caers, B. *Conditions for Passenger Aircraft Minimum Fuel Consumption, Direct Operating Costs and Environmental Impact*; HAW: Hamburg, Germany, 2019.
36. Gössling, S.; Hanna, P.; Higham, J.; Cohen, S.; Hopkins, D. Can we fly less? Evaluating the 'necessity' of air travel. *J. Air Transp. Manag.* **2019**, *81*, 101722. [CrossRef]
37. Baumeister, S. Mitigating the Climate Change Impacts of Aviation through Behavioural Change. *Transp. Res. Procedia* **2020**, *48*, 2006–2017. [CrossRef]
38. International Civil Aviation Organization (ICAO). *ICAO Carbon Emissions Calculator*; ICAO: Montreal, QC, Canada, 2018.
39. EUROCONTROL. *Small Emitters Tool (SET)—2021*; EUROCONTROL: Brussels, Belgium, 2021.
40. Myclimate. Der Myclimate Flugrechner. 2019. Available online: https://www.myclimate.org/fileadmin/user_upload/myclimate_-_home/01_Information/01_About_myclimate/09_Calculation_principles/Documents/myclimate-Flugrechner-Grundlagen_DE.pdf (accessed on 15 December 2022).
41. Atmosfair gGmbH. Atmosfair Flug-Emissionsrechner. 2016. Available online: https://www.atmosfair.de/wp-content/uploads/flug-emissionsrechner-dokumentation-berechnungsmethode-1.pdf (accessed on 15 December 2022).
42. European Environment Agency (EMEP/EEP). *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019*; EMEP/EEA: Copenhagen, Denmark, 2019.
43. International Air Transport Association (IATA). *IATA CO2 Connect Calculator International Air Transport Association (IATA)*; IATA: Montreal, QC, Canada, 2022.
44. Dawes, J. Do Data Characteristics Change According to the Number of Scale Points Used? An Experiment Using 5-Point, 7-Point and 10-Point Scales. *Int. J. Mark. Res.* **2008**, *50*, 61–104. [CrossRef]
45. International Civil Aviation Organization (ICAO). *ICAO Aircraft Engine Emissions Databank*; EASA: Cologne, Germany, 2021.
46. European Organisation for the Safety of Air Navigation (Eurocontrol). *Base of Aircraft Data (BADA)*; Eurocontrol: Brussels, Belgium, 2022.
47. Nuic, A.; Poles, D.; Mouillet, V. BADA: An advanced aircraft performance model for present and future ATM systems. *Int. J. Adapt. Control Signal Process.* **2010**, *24*, 850–866. [CrossRef]
48. UK Government. *UK Government GHG Conversion Factors for Company Reporting Department for Business, Energy & Industrial Strategy*; Department for Environment Food & Rural Affairs: London, UK, 2021.
49. Graichen, J.; Gores, S.; Herold, A. *Überarbeitung des Emissionsinventars des Flugverkehrs*; Öko-Institut: Berlin, Germany, 2010.
50. U.S. Environmental Protection Agency (EPA). Emission Factors for Greenhouse Gas Inventories. 2018. Available online: https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf (accessed on 5 December 2022).
51. European Commission. European Commission European Platform on Life Cycle Assessment. 2018. Available online: https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml (accessed on 9 July 2022).
52. National Energy Technology Labatoratory (NETL). *NETL Life Cycle Inventory Data—Unit Process: Petroleum Based Kerosene Jet Fuel Energy Conversion Facility 2005*; U.S. Department of Energy, National Energy Technology Laboratory: Washington, DC, USA, 2005.
53. European Union Aviation Safety Agency (EASA). Type Certificate Data Sheets (TCDS). EASA Document Library. 2022. Available online: https://www.easa.europa.eu/document-library/type-certificates?search=737&year=&year_to= (accessed on 20 March 2022).
54. Airbus Group. *Aircraft Charateristics*; Airbus: Leiden, The Netherlands, 2022.
55. Boeing. *Airplane Characteristics for Airport Planning*; Boeing: Chicago, IL, USA, 2022.
56. Schallmo, D.R.A.; Lang, K. *Design Thinking Erfolgreich Anwenden*; Springer Fachmedien: Wiesbaden, Germany, 2020; ISBN 978-3-658-28324-7.
57. Rolinck, M.; Gellrich, S.; Bode, C.; Mennenga, M.; Cerdas, F.; Friedrichs, J.; Herrmann, C. A Concept for Blockchain-Based LCA and its Application in the Context of Aircraft MRO. *Procedia CIRP* **2021**, *98*, 394–399. [CrossRef]

58. Schmidt, M.; Plötner, K.O.; Pornet, C.; Isikveren, A.T.; Hornung, M. *Contributions of Cabin Related and Ground Operation Technologies Towards Flightpath 2050*; Deutsche Gesellschaft für Luft-und Raumfahrt-Lilienthal-Oberth: Bonn, Germany, 2013; pp. 1–9.
59. Mensen, H. *Handbuch der Luftfahrt*, 2nd ed.; Springer: Berlin/Heidelberg, Germany, 2013; ISBN 9783642344015.
60. Oehme, G. Fulfil Customer Order Process: Customization of Commercial Aircraft. In *Supply Chain Integration Challenges in Commercial Aerospace*; Richter, K., Walther, J., Eds.; Springer Nature: Cham, Switzerland, 2017; pp. 91–104. ISBN 9783319461540.
61. Ackert, S. Commercial Aspects of Aircraft Customization. 2013. Available online: http://www.aircraftmonitor.com/uploads/1/5/9/9/15993320/commercial_aspects_of_aircraft_customization___v1.pdf (accessed on 5 December 2022).
62. Steinegger, R. *Fuel Economy for Aircraft Operation as a Function of Weight and Distance*; ZHAW Zürcher Hochschule für Angewandte Wissenschaften: Zürich, Switzerland, 2017.
63. Marinus, B.G.; Hauglustaine, A. Data-driven modeling of fuel consumption for turboprop-powered civil airliners. *Energies* **2020**, *13*, 1695. [CrossRef]
64. *DIN 9020-1:1983-10*; Aerospace, Mass Breakdown for Aircraft Heavier than Air, Main Mass Groups and Terms of Mass, Survey. Beuth: Berlin, Germany, 1983.
65. International Civil Aviation Organization (ICAO). *Jul 2022: Air Transport Monthly Monitor*; ICAO: Montreal, QC, Canada, 2022.
66. Deutsche Lufthansa AG. Airbus A350-900 Sitzpläne. lufthansa.com. 2022. Available online: https://www.lufthansa.com/de/de/35a (accessed on 26 June 2022).
67. Berdowski, Z.; Van den Broek-Serlé, F.N.; Jetten, J.T.; Kawabatta, Y.; Schoemaker, J.T.; Versteegh, R. *Survey on Standard Weights of Passengers and Baggage*; EASA: Cologne, Germany, 2009.
68. Pfingstl, S.; Steinweg, D.; Zimmermann, M.; Hornung, M. On the Potential of Extending Aircraft Service Time Using Load Monitoring. *J. Aircr.* **2022**, *59*, 377–385. [CrossRef]
69. Goedkoop, M.; Huijbregts, M. *ReCiPe 2008: A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level*; VROM: Amsterdam, The Netherlands, 2013.
70. Schwartz, E.; Kroo, I.M. Aircraft design: Trading cost and climate impact. In Proceedings of the 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, Orlando, FL, USA, 6–8 January 2009; Volume 47, p. 16. [CrossRef]
71. Koch, A.; Lührs, B.; Dahlmann, K.; Linke, F.; Grewe, V.; Litz, M.; Plohr, M.; Nagel, B.; Gollnick, V.; Schumann, U. Climate impact assessment of varying cruise flight altitudes applying the CATS simulation approach. In Proceedings of the 3rd CEAS Air&Space Conference and 21st AIDAA Congress, Venice, Italy, 24–28 October 2011; p. 12.
72. National Institute for Public Health and the Environment Ministry of Health; Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.D.M.; Hollander, A.; Van Zelm, R. ReCiPe 2016: Characterisation Factors. Provided Data Set by RVIM. 2017. Available online: https://www.rivm.nl/en/life-cycle-assessment-lca/downloads (accessed on 5 January 2023).
73. Shine, K.P.; Fuglestvedt, J.S.; Hailemariam, K.; Stuber, N. Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. *Clim. Change* **2005**, *68*, 281–302. [CrossRef]
74. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.D.M.; Hollander, A.; Van Zelm, R. National Institute for Public Health and the Environment Ministry of Health, ReCiPe 2016: Mid-to-Endpoint Factors. 2017. Available online: https://www.rivm.nl/en/life-cycle-assessment-lca/downloads (accessed on 5 January 2023).
75. National Institute for Public Health and the Environment Ministry of Health; Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.D.M.; Hollander, A.; Van Zelm, R. ReCiPe 2008: Weighting Factors. 2014. Available online: https://www.rivm.nl/en/life-cycle-assessment-lca/downloads (accessed on 5 January 2023).
76. National Institute for Public Health and the Environment Ministry of Health; Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.D.M.; Hollander, A.; Van Zelm, R. ReCiPe 2016: Normalization Factors. 2017. Available online: https://www.rivm.nl/en/life-cycle-assessment-lca/downloads (accessed on 5 January 2023).
77. Mortensen Ernits, R.; Reiß, M.; Bauer, M.; Becker, A.; Freitag, M. Individualisation of Inflight Catering Meals—An Automation Concept for Integrating Pre-Ordered Meals during the Flight for All Passengers. *Aerospace* **2022**, *9*, 736. [CrossRef]
78. European Organisation for the Safety of Air Navigation (EURONCTROL). *EUROCONTROL Method for Estimating Aviation Fuel Burnt and Emissions*; Eurocontrol: Brussels, Belgium, 2016.
79. FLugzeug-Lexikon.de FLugzeug-Lexikon.de. Available online: https://www.flugzeug-lexikon.de/ILA_2010/Verkehrsflugzeuge/Airbus_A350/airbus_a350.html (accessed on 5 January 2023).
80. AIRBUS, S.A.S. *A320 Aircraft Characteristics Airport and Maintenance Planning*; AIRBUS: Blagnac, France, 2020.
81. AIRBUS, S.A.S. *A350 Aircraft Characteristics Airport and Maintenance Planning*; AIRBUS: Blagnac, France, 2016.
82. Niklaß, M.; Dahlmann, K.; Grewe, V.; Maertens, S.; Plohr, M.; Scheelhaase, J.; Schwieger, J.; Brodmann, U.; Kurzböck, C.; Repmann, M.; et al. Integration of Non-CO_2 Effects of Aviation in the EU ETS and under CORSIA Final Report. 2020, p. 207. Available online: https://elib.dlr.de/133619/ (accessed on 5 January 2023).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.