

# A FIRST STEP TOWARDS THE INTEGRATION OF LIFE CYCLE ASSESSMENT INTO CONCEPTUAL AIRCRAFT DESIGN

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## Abstract

In civil aviation, an increasing awareness of the importance of environmental protection can be noticed. Amongst others, a better environmental protection could be achieved by giving it a higher weighting in the multi objective design optimization of future aircraft as civil aircraft are nowadays mainly designed for lowest operating costs. To be able to include the environmental protection in the design evaluation, the Environmental Impact (EI) of an aircraft has to be known which could be achieved by integrating a Life Cycle Assessment (LCA) into conceptual aircraft design. This paper aims at presenting a first step towards the integration of LCA into conceptual aircraft design. The EI of various contributors being part of the life cycle of an aircraft are analyzed using simplified and transparent calculations. It is shown that processes occurring once in the life-cycle of an entire aircraft fleet have a minor influence on the EI as their impact is distributed over all passenger-kilometers traveled by the whole fleet. Processes occurring each flight have the highest contribution to the EI of an aircraft as their impact is only distributed over the passenger-kilometers of a single flight. An evaluation of the EI using the World ReCiPe H/A method shows that fossil fuel depletion has the highest percentage with around 47 % of the total EI, followed by climate change with an impact of around 44 %. The results of the presented simplified analysis are compared to the results of the few other existing LCA results of aircraft. It is shown that the simple approach of this paper already is in quite a good agreement with the results of other LCAs. It can be concluded that the presented approach can already be used for a simple, first calculation of the EI of an aircraft. The integration of LCA into conceptual aircraft design will allow to assess and influence the EI of future aircraft over the entire life cycle early in the design process.

## 1. INTRODUCTION

The Flightpath 2050 [1] published 2011 by the European Union shows rising interest in reducing the negative Environmental Impact (EI) of civil aviation. Nowadays, aircraft are mainly designed for lowest operating costs. In the future, the EI of civil aviation could be reduced by designing aircraft not only based on costs but also on their influence on the environment which can be achieved by integrating environmental aspects into the objective function of conceptual aircraft design optimization. The major part of the future EI of an aircraft is determined in early phases of aircraft design in which current environmental analysis is mostly limited to the analysis of the pollutant emissions in the operational phase. To be able to make the environmental protection a more important design criterion, a more comprehensive approach should be used including the actual EIs over the entire life cycle. This can be achieved with a Life Cycle Assessment (LCA) defined in ISO 14040 as the „compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system during its life cycle” [2]. An LCA is subdivided into four LCA phases [2]:

- 1) Goal and Scope definition
- 2) Inventory Analysis
- 3) Impact Assessment
- 4) Interpretation

As the name suggests, the **first** phase defines the goal and scope of an LCA. This includes, amongst others, the definition of the product system, system boundaries, assumptions and limitations.

The **second** LCA phase, the inventory analysis, involves, by definition, the „compilation and quantification of inputs and outputs for a product throughout its life cycle” [2]. This means the calculation of the amount of all inputs from the environment and all outputs released into the environment including, for example, crude oil for the production of kerosene or Carbon Dioxide (CO<sub>2</sub>) as a result of the combustion process inside the engine.

The **third** phase of an LCA, the impact assessment, aims at „understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” [2]. This phase consists of an analysis of the EI of a product (e.g. an aircraft) based on the amount of inputs and outputs calculated in the second LCA phase. Several methodologies exist for the calculation of the EI of a product (e.g. [30]). The methodologies evaluate the EI using so called impact categories. Impact categories represent „environmental issues of concern” [2] like, for

instance, Climate Change (CC). In the first step (called “classification”), the methodologies allocate the inputs and outputs from the second LCA phase to impact categories which is visualized on the left side of FIG. 1. For example, the output hydrocarbons (HC) is allocated to the impact category CC because it has an impact on CC. In the second step (called “characterization”), all allocated emissions are multiplied by a factor representing their effect on an impact category and normalizing them to a certain unit (visualized on the right side of FIG. 1). For instance, in the impact category CC, all inputs and outputs are normalized to CO<sub>2</sub>-equivalent (CO<sub>2</sub> eq) emissions. In the example of FIG. 1, HC emissions are multiplied by the factor 10.6 to convert them to CO<sub>2</sub> eq emissions. This means that, in this case, the impact of a certain amount of HC on CC is 10.6 times higher than that of the same amount of CO<sub>2</sub>. The results for all impact categories represent the result of the impact assessment.

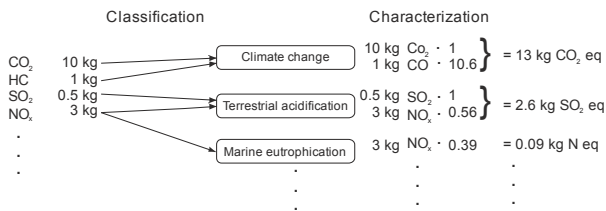


FIG. 1 Visualization of the impact assessment (adapted from [32])

In the **fourth** phase, „the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” [2].

The paper aims at investigating how such an LCA could be integrated into conceptual aircraft design. The general concept of this integration is illustrated in FIG. 2.

On the upper side of the figure, the structure of the used conceptual aircraft design tool is shown. The tool consists of several modules, each one taking care of certain design aspects. Within an inner optimization, the tool finds a consistent aircraft design optimized for a certain design goal (for instance: minimum Direct Operating Costs (DOC)) for a given set of requirements and design parameters. In an outer optimization, the requirements and design parameters themselves can be varied and optimized for a certain design goal. On the lower side of the figure, the framework of an LCA (from [2]) is shown. It is intended to integrate the inventory analysis and impact assessment as another module in the existing design tool structure so that, amongst others, the EI can also become a design goal for the optimization.

For the integration of the LCA module, the paper intends to develop a simple and transparent method in a similar fashion as existing DOC methods by providing equations that can be implemented into any aircraft design tool.

The outline of the paper is as follows. Section 2 presents a literature review about LCA related research in aeronautical engineering. Section 3 presents and analyzes existing LCA results of aircraft. Section 4 contains preliminary studies and a simplified calculation method for the integration of LCA into conceptual aircraft design. The presented methodology can be integrated into any conceptual aircraft design tool providing a first simplified estimation of the EI of an aircraft design. Section 5

concludes the paper.

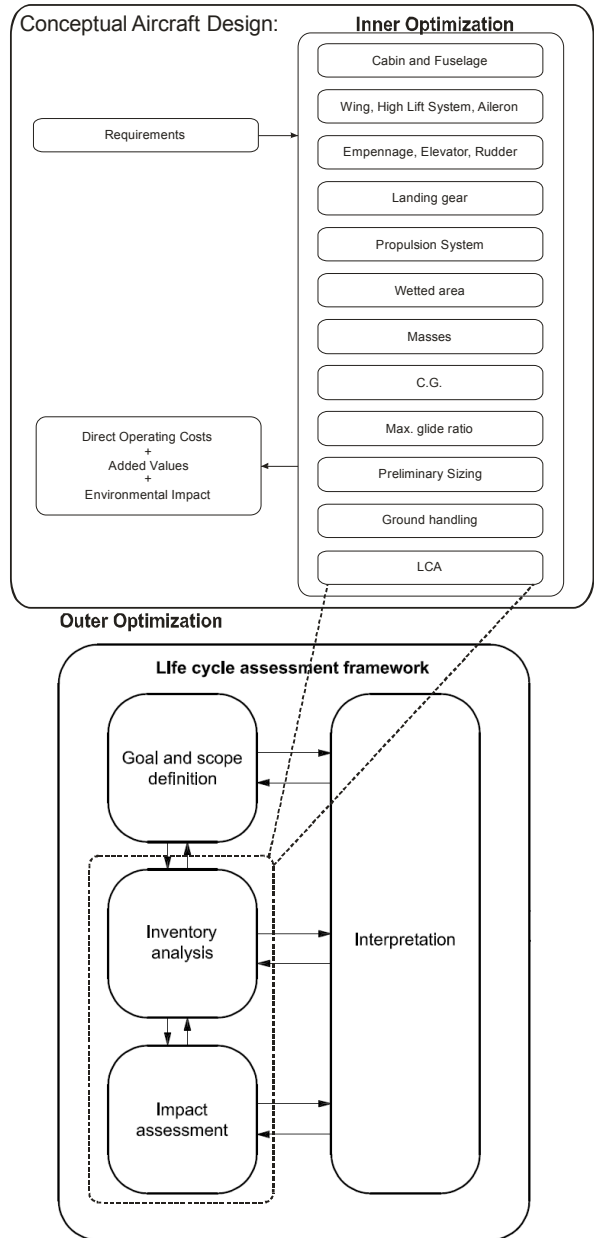


FIG. 2 Integration of LCA into conceptual aircraft design (own diagram in combination with figure from [2])

**2. LITERATURE REVIEW**

Due to decreasing fossil fuel resources, there has been a growing interest in predicting the energy and fuel consumption in the 1960s. Against this backdrop, the first LCAs have been published in this decade (e.g. [4]). Additionally, the popular study „The Limits to Growth” [5] was published in 1972, reinforcing the trend to predict the limited resources of earth. In the 1970s and 1980s, the methods to conduct LCAs have been improved (e.g. [6]) and extended to other fields of application (e.g. [7]). In the 1990s and 2000s, the International Organization for Standardization (ISO) developed norms and standards for the conducting of LCAs ([2], [3]). Nowadays, LCAs are used in many fields and their expansion continues due to

the increasing importance of the consideration of economical factors in product development. [8]

Following this trend, LCAs gain rising interest in aeronautical research as well. However, existing methods concentrate on single phases of the life cycle or on single aircraft parts. For instance, Krieg made an LCA for the operational phase of aircraft in 2009 [9] and Lindner et al. made an LCA for an aircraft cabin element in 2011 [10]. LCAs for single aircraft parts mainly aim at identifying the driving factors for the EI of a part. If such driving factors can be found, for example, in the production phase, it might be possible to reduce the EI by switching to a more environmentally friendly production method.

In the literature, only two publications could be identified containing an LCA of an entire aircraft over the whole life cycle. In 2008, Chester conducted an LCA of different modes of transportation over their entire life cycle, to be able to compare them to each other [11]. In 2010, Lopes conducted an LCA for the aircraft Airbus A330-200 over the entire life cycle [12]. However, a comparison of the results of Lopes with those of Chester shows certain deviations (Section 3). Additionally, the LCAs of Chester and Lopes are not integrated into conceptual aircraft design which means that they allow to evaluate the EI of a specific aircraft over the entire life cycle but they do not allow evaluations of other aircraft. Therefore an analysis of the influence of the integration of LCAs into conceptual aircraft design is not possible either.

Only two research approaches could be identified, amongst others trying to integrate LCAs into the aircraft design process. Weiss et al. developed a methodology evaluating aircraft in terms of their „socio-eco-efficiency“. For the ecological part of the evaluation, an LCA has been used. ([20], [21])

In the recently completed research project “Air Transport Vehicle Life Cycle Analysis”, Franz et al. developed a methodical approach for the integration of LCA into aircraft design. The research project also included the consideration of life cycle costs and social aspects. ([22], [23])

Summarized, the literature review shows that LCAs have been gaining rising interest in civil aeronautical research in the last years. Nevertheless, this research is still in its infancy as there are only few publications about conducting and integrating LCAs into conceptual aircraft design.

In comparison to the few existing approaches, this paper intends to give a more practical approach for the integration of LCA into aircraft design by providing equations that can be integrated into any aircraft design tool. With the presented calculations, it is also intended to compare the importance of the different contributors concerning their EI to identify processes that can be neglected.

**3. EXISTING LCA RESULTS OF AIRCRAFT**

In a first step, existing results concerning LCAs of aircraft will be analyzed and compared. The aim is to get a first impression of the importance and contribution of the different phases. Here, the results for the impact category CC are compared because many other authors also use CC as representative impact category.

The LCAs compared in this section are those from Chester [11] and Lopes [12] because these are the only LCAs that could be identified in the literature containing an LCA of a full aircraft over the entire life-cycle and because their scope covers similar life-cycle components.

The best way to compare two LCAs would be if they used the same impact assessment methodology. However, this is not the case here because Lopes used, amongst others, the ReCiPe Midpoint H/H method while Chester did not use one of the popular methodologies. Anyhow, both authors present results for the same impact category CC and can therefore be compared.

FIG. 3 shows the results of Chester for the three aircraft he analyzed. It can be seen, that cruise flight and LTO-cycle (called “Operation” in the diagram) account for 75 ... 81 % of the total contribution to CC. FIG. 4 shows the results of Lopes for the Airbus A330-200. Here, the operation is responsible for 99.9 % of the CC. These differences in the results cannot be explained just because they used different impact assessment methodologies. To some extent, the difference could be explained if Lopes considered the production of fuel as part of the operation which stays unclear however.

Thus, following the results of Lopes, it is questionable if life cycle processes other than cruise flight and LTO-cycle should be considered at all concerning CC, while following the results of Chester, the influence of other processes should not be neglected. Nevertheless, even Lopes states that for certain impact categories like agricultural land occupation, the “Other components” play an important role so that they should not be neglected [12].

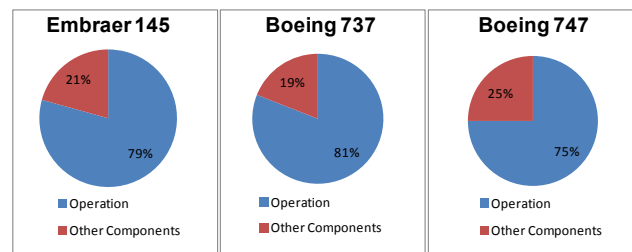


FIG. 3 Results for CC according to Chester (own diagram based on the results of [11])

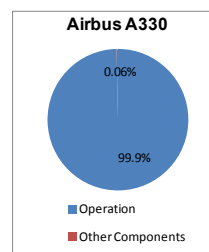


FIG. 4 Results for CC according to Lopes (own diagram based on the results of [12])

The comparison of the absolute amount of g CO<sub>2</sub> eq per passenger-kilometer (pkm) concerning CC from [11] and [12] in FIG. 5 shows that the sum of all phases (the sum of the values for the red and blue part of the columns) leads to similar values between 124 ... 180 g CO<sub>2</sub> eq per pkm. One pkm stands for the transport of one passenger over one kilometer. In this paper, pkm always refers to the

actually transported number of passengers and their kilometers traveled.

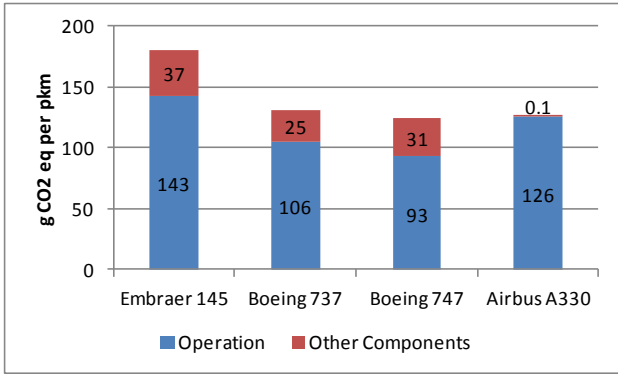


FIG. 5 Comparison of the absolute values for CC for Embraer 145, Boeing 737 and Boeing 747 according to [11] and Airbus A330 according to [12]

Summarized, there is a general tendency for the absolute amount of CO<sub>2</sub> eq per pkm but there is no general agreement on the contributions of the different life-cycle components yet, so that further research is needed.

#### 4. INTEGRATION OF LCA INTO CONCEPTUAL AIRCRAFT DESIGN

##### 4.1. Preliminary Considerations

The aim of this subsection is to present preliminary considerations concerning the calculation of the EI of an aircraft over its entire life-cycle in a simplified way. The calculation methodology will follow in the next subsection.

Amongst others, the simplified calculations are intended to provide an overview of the importance of the different processes. Therefore, the calculations have to cover important processes throughout the life-cycle. The selected processes within the life-cycle are: Electric energy due to computer use during design, wind tunnel testing, flight test campaign, use of production facilities, cruise flight, Landing and Take-Off (LTO) cycle, energy generation and consumption at airports, operation of ground handling vehicles, kerosene production, reuse and landfill at the end-of-life (FIG. 6).

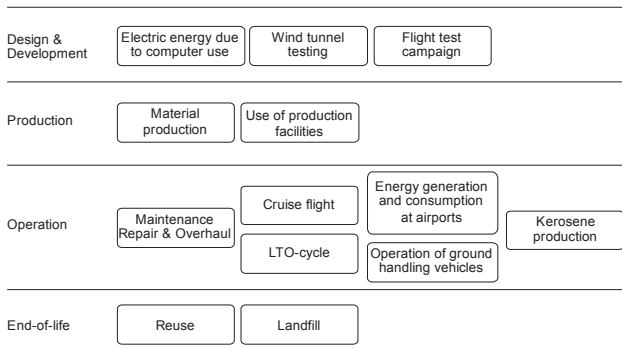


FIG. 6 Considered processes within the life-cycle

All EIs have to refer to a certain unit representing the function of a product [2]. The function of a civil aircraft is to transport payload (passengers and freight) over a certain

distance. Therefore ton-kilometers (tkm) could be chosen as functional unit which means that all results of the presented calculations would refer to the transport of one ton over one kilometer. However other authors (e.g. [11], [12]) and other modes of transportation usually use pkm as functional unit. Having the same functional unit allows to compare results more easily. For better comparability, the functional unit pkm has been chosen in this paper which means that all results of the presented calculations will refer to the transport of one passenger over one kilometer.

As an aircraft also transports freight, the emissions have to be allocated which means that only a part of the EI is considered to be caused by the transport of passengers while the other part is considered to be caused by the transport of freight. In 2011, the worldwide volume of airfreight transportation was 185 billion tkm while the worldwide revenue air passenger traffic was 5150 billion pkm [13]. According to [14], 50 % of the freight are transported by passenger aircraft. It is assumed that the average passenger mass (including baggage) is 95.25 kg as this is the average between the suggested domestic and international passenger mass in [15]. Altogether, this means that in 2011, about 19 % of the payload mass of passenger aircraft was freight. Therefore, in this paper, only 81 % of the emissions caused over the life-cycle are allocated to the transport of passengers:

$$P_{alo,PAX} = 81\%$$

As already mentioned in Section 1, several methodologies exist for the calculation of the EI of a product. Amongst the most popular methods are "ReCiPe" [33], "Eco-indicator 99" [34] and "CML 2002" [35]. The ReCiPe method is built on the CML and the Eco-indicator method. It is intended to be a further development of these two methods [33]. Therefore it has been chosen for the impact assessment in this paper.

All methods have in common, that they calculate the EI of a product within different impact categories. The meaning of some impact categories is difficult to understand while their uncertainty is not that high (e.g. freshwater eutrophication). Such impact categories are called midpoint categories. The meaning of other impact categories is easier to understand but their calculation has high uncertainty (e.g. damage to human health). Such impact categories are called endpoint categories.

The ReCiPe method offers both categories. Eighteen midpoint and three endpoint categories can be calculated. Additionally, a so called "Single score" can be obtained. The single score summarizes the EI of a product in one score. Such a single score is useful for the integration of the EI into aircraft design optimization. However, it has to be noted that the uncertainty of the result rises from midpoint over endpoint categories until the single score. Nevertheless the results of the midpoint categories have to be aggregated somehow to be able to integrate them into design optimization.

To obtain the single score, the eighteen midpoint categories  $MP_j$  ( $j = 1 \dots 18$ ) have to be calculated first:

$$MP_j = \sum_{i=1}^n x_{pkm,i} \cdot CF_{midpoint,i,j} \quad (1)$$

with the input or output  $x$  of a certain substance  $i$  which is

the result of the second LCA phase and the characterization factor  $CF_{\text{midpoint}}$ .

After that, the three endpoint categories  $EP_k$  ( $k = 1 \dots 3$ ) are calculated based on the results of the eighteen midpoint categories:

$$EP_k = \sum_{j=1}^{18} MP_j \cdot CF_{\text{endpnt},j,k} \quad (2)$$

In a last step, the results for the three endpoint categories are normalized, weighted and summed up to obtain the single score SS:

$$SS = \sum_{k=1}^3 NF_k \cdot W_k \cdot EP_k \quad (3)$$

using normalization factors  $NF$ , weightings  $W$  and the results of the endpoint categories  $EP$ .

The ReCiPe method provides all characterization factors, normalization factors and weightings needed for the calculation in a publicly available table [31]. Using the information in the table, the method can be integrated into any conceptual aircraft design tool.

In FIG. 7, the ReCiPe method is illustrated and all midpoint and endpoint categories are listed.

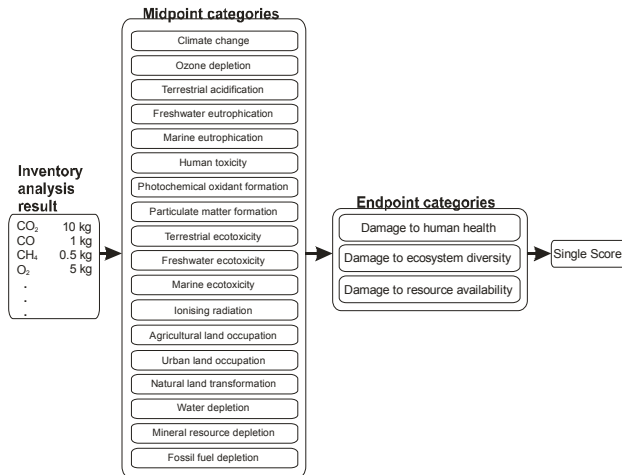


FIG. 7 Illustration of the ReCiPe method

It has to be kept in mind, that the knowledge about detailed aircraft parameters is low in conceptual aircraft design even though deep knowledge would be needed for an accurate LCA. Therefore many assumptions and simplifications have to be made leading to reduced accuracy and higher uncertainty.

#### 4.2. Simplified Analysis of Main Inputs and Outputs in the Life-Cycle

In this section, the EI of various contributors being part of the life cycle of an aircraft will be calculated. It is intended to provide a simple calculation of some important processes within the life-cycle of an aircraft. To make the integration in existing aircraft design tools as simple as possible, the final calculation procedure is supposed to be independent of LCA tools or databases. By providing a

method usable in any tool, the LCA calculation and the decision process is transparent and reproducible for everybody. Partly, the presented methods are inspired by approaches suggested by authors listed in Section 2.

Due to the complexity of the life-cycle of an aircraft, calculating the actual EIs is a very difficult and time consuming process. Therefore, before starting this complicated process, the impacts will be evaluated in a simplified way to identify the importance of the various contributors to justify a future detailed analysis of important contributors and a neglect of unimportant components.

The average number of transported passengers per flight  $n_{PAX}$  can be calculated by

$$n_{PAX} = n_{\text{seat,max}} \cdot p_{\text{seat}} \cdot p_{\text{lf}} \quad (4)$$

with the maximum number of seats in a one class layout  $n_{\text{seat,max}}$ , the average percentage of sold seats compared to the maximum number of seats in a one class layout  $p_{\text{seat}}$  and the average load factor  $p_{\text{lf}}$ .

The average distance traveled  $d$  is:

$$\text{per flight:} \quad d_f = R_{MPL} \cdot p_d \quad (5)$$

$$\text{per year:} \quad d_a = n_{f,a} \cdot d_f \quad (6)$$

$$\text{per operational life:} \quad d_l = n_{a,o} \cdot d_a \quad (7)$$

$$\text{per aircraft fleet:} \quad d_{l,b} = n_{a/c,b} \cdot d_l \quad (8)$$

with the maximum range at maximum payload  $R_{MPL}$ , the percentage of average traveled distance  $p_d$  compared to  $R_{MPL}$ , the number of flights per year  $n_{f,a}$ , the average number of years in the operational life  $n_{a,o}$  and the total number of aircraft built  $n_{a/c,b}$ .

To make sure that all results of the LCA refer to the same functional unit, the inputs and outputs of processes that occur once per flight, like the ground handling processes, have to be divided by the number of pkm per flight. The inputs and outputs of processes occurring once in the life-cycle of a single aircraft, like the production of an aircraft, have to be divided by the total number of pkm during its operational life. Inputs and outputs of processes occurring once in the life-cycle of the whole aircraft fleet, like the design of an aircraft, have to be divided by the pkm of the whole fleet.

Summarized, the inputs and outputs have to be divided by the following number of pkm to refer to the functional unit:

$$\text{per flight:} \quad pkm_f = n_{PAX} \cdot d_f \quad (9)$$

$$\text{per year:} \quad pkm_a = n_{PAX} \cdot d_a \quad (10)$$

$$\text{per operational life:} \quad pkm_l = n_{PAX} \cdot d_l \quad (11)$$

$$\text{per aircraft built:} \quad pkm_{l,b} = n_{PAX} \cdot d_{l,b} \quad (12)$$

These simple considerations have a big impact on the results of an LCA. For instance, if the total number of aircraft built is 20000, the emission of a certain substance from a process occurring once in the life-cycle of the entire aircraft fleet (e.g. the design process) would need to be 20000 times higher than the emission of the same substance from a process occurring once in the life-cycle

of a single aircraft (e.g. production) to cause the same EI per pkm. Assuming 60000 flight cycles, an emission occurring once in the life-cycle would even need to be 1.2 billion (20000-60000) times higher than the emission of a process occurring once per flight to cause the same EI per pkm.

The total number of aircraft built within the fleet  $n_{a/c,b}$  and the number of flight cycles heavily depend on the aircraft category. Here  $n_{a/c,b}$  has been estimated based on the current number of orders and the expected demand for the next 20 years from [39]. While  $n_{a/c,b}$  might be around 20000 for the current medium range aircraft families of Airbus and Boeing accommodating around 100 ... 200 passengers,  $n_{a/c,b}$  might only be around 2000 in the very large aircraft class (Airbus A380). Besides that, the design service goal for the A320 was 60000 flight cycles [36] while that of the A380 was 19000 flight cycles [37].

Obviously, the higher the number of aircraft built and the higher the number of flight cycles, the lower the importance of non-recurring processes.

#### 4.2.1. General Assumptions for the Simplified Calculation

For the following calculation method, the weight variant WV000 of an Airbus A320-200 with CFM56-5A engines has been used as application example [38]. TAB. 1 lists the main parameters of the considered aircraft version.

TAB. 1 Main parameters of the considered A320-200 version

| Parameter | $n_{seat,max}$ | $m_{MPL}$ [kg] | $m_{OE}$ [kg] | $m_{MTO}$ [kg] | $R_{MPL}$ [km] |
|-----------|----------------|----------------|---------------|----------------|----------------|
| Value     | 180            | 19256          | 41244         | 73500          | 2797           |

Besides that, the presented calculation is based on the following assumptions concerning important LCA parameters:

As explained above:

$$n_{a/c,b} = 20000$$

$p_{seat}$  is calculated based on the number of seats sold by Airbus in 2007 (calculated based on data in [24]) and the maximum number of seats that the sold aircraft could theoretically have accommodated in a one class layout (calculated using data in [40] and [41]):

$$p_{seat} = 84\%$$

The average load factor has been chosen according to [29]:

$$p_{lf} = 78\%$$

According to [36], the original design service goal set by Airbus for the A320 was 25 years. The same number of years is assumed for  $n_{a,o}$ :

$$n_{a,o} = 25 \text{ years}$$

The average flight duration of the A320 family fleet is 1.82 h [36] which corresponds to an average distance per flight  $d_f$  of about 1100 km (calculated in the redesign). Therefore,  $p_D$  is

$$p_D = 39\%$$

#### 4.2.2. Calculation of the Inputs and Outputs of Representative Life-Cycle Components

The following calculation method is supposed to serve as a general practical approach for a first calculation of the amount of important input and output flows over the life-cycle of an aircraft. To make sure that other designers can easily integrate the calculation into their design tools, it is intended to provide a handy method. To keep the method handy, not all processes within the life cycle are considered but only those that are expected to be most important.

For the calculation of certain processes, information has been taken out of LCA databases. These databases list all inputs and outputs that are part of the life cycle inventory of a certain process. The lists usually contain a large number of inputs and outputs so that considering all of them would unfortunately lead to an unhandy method.

For this reason, it has been decided that the presented method only includes the most important inputs and outputs. As explained in Section 4.1, aircraft will be evaluated based on their single score of the World ReCiPe H/A method. The contribution of the inputs and outputs to the single score is used to evaluate their importance. The presented method will only consider inputs and outputs contributing more than a certain percentage to the single score which represents the so called cut-off criterion.

The following subsections present the calculations for the selected processes within the life-cycle of an aircraft.

##### 4.2.2.1. Design and development

The electric energy needed for the use of computers during the design of the aircraft, wind tunnel tests and the flight test campaign have been selected as representative processes within the design and development of an aircraft.

The design and development occurs once in the life-cycle of the whole aircraft fleet. Therefore, the inputs and outputs of the design and development have to be spread over the pkm of all aircraft built to normalize them to the functional unit. The input/output of such processes per pkm  $x_{pkm,i}$  can be calculated by

$$x_{pkm,i} = \frac{x_i}{pkm_{l,b}} \cdot p_{alo,PAX} \quad (13)$$

All  $x_{pkm,i}$  calculated in this section represent the results for the life cycle inventory of the design and development phase.

##### Electric energy due to computer use during aircraft design

The required electric energy  $E$  can be calculated as:

$$E = n_d \cdot E_d \quad (14)$$

with the engineering days  $n_d$  invested in the design of an aircraft and the electric energy consumption of an office computer per day  $E_d$ .

According to [42], the average total electric energy consumed by an office computer within four years is 305 kWh. Assuming 250 working days per year,  $E_d$

becomes 0.31 kWh.

$n_d$  can be estimated as:

$$n_d = \frac{c_{dev} \cdot P_e}{c_{e,d}} \quad (15)$$

with the costs of an aircraft development  $c_{dev}$ , the percentage that has been spent for engineering hours  $p_e$  and the daily costs per engineer  $c_{e,d}$ .

According to [43], the development costs of the Boeing 787 were 13.4 Billion USD, those of the A380 were 18 Billion USD and those of the E-jet series were 0.85 Billion USD. For the application example of this paper, development costs of 10 Billion USD have been assumed.

Additionally, it is assumed that  $c_{dev}$  is 75 % and that  $c_{e,d}$  is 266 USD (assuming a monthly salary of 50000 €, 21.75 monthly working days and a USD-EURO conversion of 0.72 [29]).

$E$  can now be calculated using the given data.

The provision of 1 kWh leads to the Emission Factors (EF) and contributions to the single score listed in TAB. 2 (from [16]: "Electricity Mix; AC; consumption mix; at consumer; <1 kV" (EU-27)) using a cut-off criterion for the flow contribution of 0.5 %.

Whenever crude oil is listed in a table, the paper refers to crude oil with a heating value of 42.3 MJ/kg.

TAB. 2 Emissions per kWh according to [16]

| Substance        | Crude oil | CO <sub>2</sub> | SO <sub>2</sub> | PM <sub>10</sub> |
|------------------|-----------|-----------------|-----------------|------------------|
| EF [kg/kWh]      | 0.72      | 0.56            | 3.3E-3          | 14.2E-5          |
| Contribution [%] | 75.7      | 20.6            | 2.8             | 0.6              |

Using  $E$  and the EFs in TAB. 2, the total emission  $x$  of a certain substance  $i$  can be calculated by

$$x_i = E \cdot EF_i \quad (16)$$

### Wind tunnel testing

During the development of an aircraft, several tests have to be performed. Wind tunnel tests are one important part of these tests. Over the last decades, the aircraft manufacturers were able to reduce the number of wind tunnel test days [44] due to a more extensive use of computational fluid dynamics calculations. Nowadays, it can be assumed that around 1000 wind tunnel test days are required for the development of a new aircraft [44]. According to [45] the carbon footprint of the operational phase of the wind tunnel test facilities of NASA is between 330 t CO<sub>2</sub> eq per year and 21000 t CO<sub>2</sub> eq. per year. According to [46], the National Transonic Facility at NASA Langley Research Center can be used for the wind tunnel testing of a Boeing 787. Therefore, for a rough estimation, a carbon footprint of 18600 t CO<sub>2</sub> eq per year can be assumed for the operational phase of the wind tunnel test campaign because it is the carbon footprint of that facility [45]. Together with the number of test days, this leads to about 51000 t CO<sub>2</sub> eq for the wind tunnel testing of an aircraft. Due to lack of other data and for simplification, it is assumed that the amount of CO<sub>2</sub> eq emissions due to wind tunnel testing is equal to the amount of CO<sub>2</sub> emissions. Therefore an output of 51000 t of CO<sub>2</sub> is assumed to be caused by wind tunnel testing:

$$x_{CO_2} = 51000t$$

### Test flight campaign

Another part of the development phase is the test flight campaign for the certification of the aircraft. In this paper, the emissions caused by the fuel consumption during the flights and the emissions from the production of the test aircraft are considered.

The fuel consumption is simply estimated by

$$m_F = n_{f,c} \cdot m_{f,h} \quad (17)$$

with the number of test flights hours until the certification is achieved  $n_{f,c}$  and the average burned fuel mass per hour  $m_{f,h}$ .

The data in TAB. 3 leads to an average value of 3100 h for  $n_{f,c}$ . A redesign of the application example leads to a value of 1700 kg/h for  $m_{f,h}$ .

Neglecting the LTO-cycles within the flight test campaign, the inputs and outputs caused by  $m_F$  can simply be calculated using Equation 23 and the data in TAB. 10 and 11 (as explained in Section 4.2.2.3).

TAB. 3 Flight test hours for several aircraft (expected and total)

| Aircraft                    | A350 | A380 | B787 | CSeries |
|-----------------------------|------|------|------|---------|
| Number of flight test hours | 2500 | 4911 | 2666 | 2500    |

For the test flight campaign, several aircraft also have to be manufactured. The calculation of the inputs and outputs  $x_i$  coming from this process is presented in the following Section 4.2.2.2. To calculate the inputs and outputs for the production of the test aircraft  $x_{a/c,t,i}$ , with Equation 18, the inputs and outputs  $x_i$  calculated with Equations 21 and 22 from Section 4.2.2.2 simply have to be multiplied by the number of test aircraft  $n_{a/c,t}$ :

$$x_{a/c,t,i} = x_i \cdot n_{a/c,t} \quad (18)$$

Based on the data in TAB. 4, it is suggested to choose a number of 5 test aircraft for  $n_{a/c,t}$ .

TAB. 4 Number of test aircraft for several aircraft (expected and total)

| Aircraft                | A350 | A380 | B787 | CSeries |
|-------------------------|------|------|------|---------|
| Number of test aircraft | 5    | 5    | 7    | 5       |

### 4.2.2.2. Production phase

The production phase occurs once in the life-cycle of an aircraft. Inputs and outputs of that phase have to be spread over all pkm of one aircraft to normalize them to the functional unit.  $x_{pkm,i}$  can be calculated by

$$x_{pkm,i} = \frac{x_i}{pkm_i} \cdot P_{alo,PAX} \quad (19)$$

All  $x_{pkm}$  calculated in this section represent the results for the life cycle inventory of the production phase.

### Material production

For the manufacturing of the aircraft, material is needed. Knowing the percentage  $p_{m,i}$  of a certain material  $i$  in relation to the operating empty mass of the aircraft, the masses of the different materials  $m_{m,i}$  used can be

calculated only based on the knowledge of the operating empty mass  $m_{OE}$  of the aircraft:

$$m_{m,i} = p_{m,i} \cdot m_{OE} \quad (20)$$

In older civil passenger aircraft, aluminum has been the dominating material while composites are the dominating material of the latest aircraft. Material breakdowns of an older (Airbus A330, [12]) and a new aircraft (Airbus A350, [47]) are given in TAB. 5. If the material breakdown of an aircraft design is not known, it is suggested to work with the values in TAB. 5.

TAB. 5 Material breakdown of an A330 [12] and an A350 [47]

| Material | Aluminum | Composites | Steel | Titanium | Misc. |
|----------|----------|------------|-------|----------|-------|
| A330     | 72       | 12         | 7     | 6        | 3     |
| A350     | 20       | 52         | 7     | 14       | 7     |

The production of the materials itself causes input and output flows from and into the environment. They can be calculated by multiplying the mass of a certain material  $i$  that is actually taken from the environment ( $m_{n,i}$ ) with the emission factors of the respective materials given in the tables of the next paragraphs:

$$x_i = m_{n,i} \cdot EF_i \quad (21)$$

$m_{n,i}$  can be calculated using Equation 30 from Section 4.2.2.4 "End-of-Life". It is the mass of used materials subtracted by the mass of reused materials.

For simplification, only aluminum, composites and steel have been considered in the presented analysis.

### Aluminum

The main inputs and outputs for the production of aluminum are taken from the European reference Life Cycle Database (ELCD) [16] assuming a share of 50 % aluminum sheets and 50 % aluminum extrusion profiles. The processes taken from [16] are "Aluminum sheet, production mix, at plant, primary production, aluminum semi-finished sheet product, including primary production, transformation and recycling (RER)" and "Aluminum extrusion profile, production mix, at plant, primary production, aluminum semi-finished extrusion product, including primary production, transformation and recycling (RER)".

Again, a cut-off criterion of 0.5 % has been used. Flows fulfilling this criterion, their EFs and their contributions are listed in TAB. 6.

TAB. 6 Inputs and outputs coming from the production of 1 t aluminum (50 % sheets, 50 % extrusion profiles) from [16]

| Substance        | Crude oil | CO <sub>2</sub> | SO <sub>2</sub> | PM <sub>10</sub> | CF <sub>4</sub> |
|------------------|-----------|-----------------|-----------------|------------------|-----------------|
| EF [kg/t]        | 7089      | 2539            | 8.7             | 1.62             | 0.019           |
| Contribution [%] | 86.5      | 10.9            | 0.9             | 0.8              | 0.6             |

### Composites

For simplification, it is assumed that only Carbon Fiber Reinforced Plastic (CFRP) is used as composite material.

For the calculation of the inputs and outputs coming from the production of CFRP, the flows suggested by [12] have been assumed. With a cut-off criterion of 0.5 %, this leads to the inputs and outputs listed in TAB. 7.

TAB. 7 Inputs and outputs coming from the production of 1 t CFRP

| Substance        | Crude oil | CO <sub>2</sub> | SO <sub>2</sub> | PM <sub>10</sub> |
|------------------|-----------|-----------------|-----------------|------------------|
| EF [kg/t]        | 98500     | 83200           | 450             | 19               |
| Contribution [%] | 74.3      | 22.0            | 2.7             | 0.6              |

### Steel

The main inputs and outputs for the production of steel are taken from ELCD [16] ("Steel sections (ILCD), production mix, at plant, blast furnace route / electric arc furnace route, 1 kg (GLO)").

Flows fulfilling a cut-off criterion of 0.5 %, their EFs and their contributions are listed in TAB. 8.

TAB. 8 Inputs and outputs coming from the production of 1 t steel sections

| Substance        | CO <sub>2</sub> | PM <sub>10</sub> | Crude oil | SO <sub>2</sub> | N <sub>2</sub> O | Hg     | Pb     |
|------------------|-----------------|------------------|-----------|-----------------|------------------|--------|--------|
| EF [kg/t]        | 1454            | 1.18             | 27.5      | 2.6             | 0.08             | 8.2E-5 | 1.9E-3 |
| Contribution [%] | 82.0            | 7.5              | 4.4       | 3.3             | 1.4              | 0.7    | 0.5    |

### Use of production facilities

As suggested by [22], information published by Airbus [24] can be used for the calculation of emissions and energy use per sold aircraft seat  $n_s$  coming from the production of the aircraft. The inputs and outputs per manufactured seat are listed in TAB. 9. It has to be noted that the numbers refer to the year 2007 and that for the calculation of the CC emissions „only combustion of natural gas and heating fuel is reported" [24].

The number of considered substances in TAB. 9 ... 13 is low so that no cut-off criterion needed to be used.

TAB. 9 Inputs and outputs per manufactured seat at Airbus in 2007 [24]

| Substance        | CO <sub>2</sub> | NO <sub>x</sub> | H <sub>2</sub> O |
|------------------|-----------------|-----------------|------------------|
| EF [kg/seat]     | 2640            | 1.97            | 23540            |
| Contribution [%] | 98.2            | 1.8             | 0.0              |

Using the information in TAB. 9, inputs and outputs  $x$  coming from the production of the aircraft can be calculated by:

$$x_i = n_{seat,max} \cdot p_{seat} \cdot EF_i \quad (22)$$

### 4.2.2.3. Operation

#### Cruise flight

Most part of the EI of an aircraft comes from the fuel burn in the operational phase.

A stoichiometric combustion of 1 kg kerosene and 3.4 kg oxygen produces 1.23 kg water and 3.15 kg CO<sub>2</sub>. Therefore, the inputs and outputs in the following TAB. 10 are always part of the kerosene combustion process.

TAB. 10 Inputs and outputs of a stoichiometric combustion of 1 kg kerosene

| Substance        | CO <sub>2</sub> | O <sub>2</sub> | H <sub>2</sub> O |
|------------------|-----------------|----------------|------------------|
| EF [kg/kg]       | 3.15            | 3.4            | 1.23             |
| Contribution [%] | 100             | 0.0            | 0.0              |

The combustion also produces other emissions. Amongst others, their amount depends on the thrust setting. Therefore these additional emissions have to be considered depending on the flight phase.

TAB. 11 lists the main additional emissions per kg fuel



burned in the flight phases climb, cruise and descent for an A320 on a 500 NM trip from [25]. Among the emissions in TAB. 11, NO<sub>x</sub> contributes most to the EI, followed by SO<sub>2</sub>. For the calculation of emissions of other aircraft and stage lengths, it is suggested to take the values of the most similar aircraft in [25].

TAB. 11 Additional emissions per kg kerosene burned in the flight phases climb, cruise and descent for an A320 on a stage length of 500 NM [25]

| Substance        | SO <sub>2</sub> | NO <sub>x</sub> | CO   | HC    |
|------------------|-----------------|-----------------|------|-------|
| EF [g/kg]        | 0.84            | 16.5            | 1.72 | 0.071 |
| Contribution [%] | 4.5             | 95.5            | 0.0  | 0.0   |

In the flight phases climb, cruise and descent on the previously selected average flight distance of 1100 km, the application example burns a fuel mass  $m_f$  of about 4.1 t (coming from a redesign of the reference aircraft and excluding the LTO-cycle). The total emissions  $x$  of a substance  $i$  in these flight phases can be calculated by multiplying  $m_f$  with the corresponding emission factor  $EF$  from TAB. 10 and 11:

$$x_i = m_f \cdot EF_i \quad (23)$$

### Landing and Take-off Cycle

Within the LTO-cycle, the emissions can be calculated for existing engines according to the ICAO Aircraft Engine Emissions Databank [26]. For the calculation of emissions of other engines, it is suggested to take the values of the most similar engine in [26].

The application example can be operated with different engines. Here the engine CFM56-5A5 has been chosen. The times per mode  $t_{mode}$ , fuel flow  $FF$  and emission factors are listed in TAB. 12. The fuel mass burned per mode is

$$m_{f,i} = t_{mode,i} \cdot FF_i \quad (24)$$

Again, the total emissions are:

$$x_i = m_{f,i} \cdot EF_i \quad (25)$$

TAB. 12 Fuel flow and emissions during the LTO cycle for the engine CFM56-5A5 from [26]

| LTO-Phase | $t_{mode}$ [min] | $FF$ [kg/s] | EF [g/kg] and Contribution [%] | NO <sub>x</sub> | CO   | HC   |
|-----------|------------------|-------------|--------------------------------|-----------------|------|------|
| Approach  | 4                | 0.276       | EF [g/kg]                      | 8.94            | 2.8  | 0.45 |
|           |                  |             | Contribution [%]               | 100             | 0.0  | 0.0  |
| Idle      | 26               | 0.098       | EF [g/kg]                      | 4.29            | 18.5 | 1.53 |
|           |                  |             | Contribution [%]               | 99.8            | 0.0  | 0.2  |
| Take-off  | 0.7              | 0.972       | EF [g/kg]                      | 24.79           | 1.1  | 0.23 |
|           |                  |             | Contribution [%]               | 100             | 0.0  | 0.0  |
| Climb out | 2.2              | 0.799       | EF [g/kg]                      | 19.98           | 1.1  | 0.23 |
|           |                  |             | Contribution [%]               | 100             | 0.0  | 0.0  |

Emissions within climb, cruise, descent and the LTO-cycle have to be spread over the pkm of one flight to normalize them to the functional unit.  $x_{pkm}$  can be calculated by

$$x_{pkm,i} = \frac{x_i}{pkm_f} \cdot P_{alo,PAX} \quad (26)$$

### Energy generation and consumption at airports

As suggested by [9], the influence of airports is calculated using Hamburg Airport as it is a good representation of an average airport. Data can be found in [28]. In 2010, the

airport had almost 13 Mio PAX ( $n_{PAX,AP}$ ) and 1619 employees ( $n_{emp}$ ). Important inputs and outputs per employee due to energy consumed and produced at Hamburg Airport are listed in TAB. 13.

TAB. 13 Inputs and outputs due to energy consumption and production at Hamburg Airport per employee in 2010 from [28]

| Substance        | CO <sub>2</sub> | PM <sub>10</sub> | SO <sub>2</sub> | NO <sub>x</sub> |
|------------------|-----------------|------------------|-----------------|-----------------|
| EF [kg/employee] | 22100           | 49               | 122             | 14.7            |
| Contribution [%] | 71.8            | 17.9             | 9.1             | 1.2             |

Airports are not only used to transport passengers but also to transport freight. Using the data in [28] and assuming an average passenger mass of 95.25 kg (as in Section 4.1), the percentage of passenger mass compared to freight mass  $p_{PAX,AP}$  is 95 %. Therefore 95 % of the emissions of the airport have been allocated to passenger transportation.

Altogether, the inputs and outputs per pkm can be calculated by

$$x_{pkm,i} = \frac{EF_i \cdot n_{emp}}{n_{PAX,AP} \cdot d_f} \cdot P_{PAX,AP} \quad (27)$$

### Operation of Ground Handling Vehicles

[28] also contains information about CO<sub>2</sub> emissions due to the use of ground handling vehicles. In 2010, these CO<sub>2</sub> emissions were around 2.9 t per employee.

The CO<sub>2</sub> emissions per pkm can again be calculated using Equation 27.

### Kerosene production

The main inputs and outputs caused by the production of kerosene are taken from ELCD [16] ("Kerosene, consumption mix, at refinery, from crude oil, 700 ppm sulphur").

Flows fulfilling a cut-off criterion of 0.5 %, their EFs and their contributions are listed in TAB. 14.

TAB. 14 Inputs and outputs coming from the production of 1 kg kerosene from [16]

| Substance        | Crude oil | CO <sub>2</sub> | SO <sub>2</sub> |
|------------------|-----------|-----------------|-----------------|
| EF [g/kg]        | 1110      | 259             | 1.58            |
| Contribution [%] | 91.3      | 7.5             | 1.0             |

The input and output flows from and into the environment caused by the production of kerosene can be calculated by multiplying the required fuel mass  $m_{f,i}$  by the EFs in TAB. 14:

$$x_i = m_{f,i} \cdot EF_i \quad (28)$$

Again, the inputs and outputs per pkm can be calculated by

$$x_{pkm,i} = \frac{x_i}{pkm_f} \cdot P_{alo,PAX} \quad (29)$$

### 4.2.2.4. End-of-life

The disposal phase mainly influences the outputs into the environment.

In the research project PAMELA-LIFE, it has been investigated how the end-of-life phase of an aircraft can be improved from an environmental point of view. According to Airbus [27], the project demonstrated that 85 % of an aircraft can be „reused, recovered or recycled”. A more detailed distribution of the percentage of materials reused, recycled and incinerated depending on the aircraft component can be obtained from [12]. Based on [12], average values for reuse and landfill have been calculated (TAB. 15).

TAB. 15 Percentage of reuse  $p_{ru,i}$  and landfill  $p_{df,i}$ , based on a calculation of average values with [12]

| Material     | Aluminum | Steel | CFRP |
|--------------|----------|-------|------|
| Reused [%]   | 2        | 56    | 5    |
| Landfill [%] | 24       | 21    | 48   |

As shown in Equation 30, the percentage of the reused mass  $p_{ru}$  together with the mass needed to produce the aircraft  $m_{m,i}$  lead to the actual mass needed  $m_{n,i}$  of a certain material. The landfill mass  $m_{df}$  is considered as a direct emission into the environment (Equation 31). Recycled and incinerated masses are not considered any further for simplification.

$$m_{n,i} = m_{m,i} \cdot (1 - p_{ru,i}) \quad (30)$$

$$m_{df,i} = m_{c,i} \cdot p_{df,i} \quad (31)$$

### 4.3. Short Summary of the Calculation Method

This subsection is intended to shortly summarize the calculation methodology presented in the previous subsections.

First, basic LCA parameters need to be calculated as explained in Section 4.1, the beginning of Section 4.2 and Section 4.2.1.

After that, the inputs and outputs per pkm  $x_{pkm,i}$  from all considered processes have to be calculated. The resulting list of inputs and outputs and their amounts represents the result of the inventory analysis as shown on the left side of FIG. 7 and in TAB. 16.

Using that list and the  $CF_{midpoint}$ ,  $CF_{endpoint}$ ,  $NF$  and  $W$  given in TAB. 18 and 19 from [31], the single score representing the total EI of an aircraft can be calculated using Equations 1 ... 3. Whenever "individual" is stated in TAB. 19, the value for  $CF_{endpoint}$  depends on the type of substance or land use. As the presented method does not influence the affected midpoint categories, the individual values are not needed for the calculation.

By integrating the single score into the objective function, the EI becomes part of aircraft design optimization.

The proposed calculation methodology will be presented and continuously updated in a working paper in [49] so that it can be easily implemented into any conceptual aircraft design tool.

### 4.4. Results of the Simplified Analysis

The results for the inventory analysis of the application example using the simplified methodology of this paper are presented in TAB. 16.

TAB. 16 Results for the inventory analysis of the application example

| Substance        | Amount [g/pkm] |
|------------------|----------------|
| Crude oil        | 35             |
| CO <sub>2</sub>  | 99             |
| NO <sub>x</sub>  | 0.5            |
| SO <sub>2</sub>  | 0.08           |
| PM <sub>10</sub> | 0.005          |
| Hg               | 4.1E-11        |
| CF <sub>4</sub>  | 9.8E-8         |
| N <sub>2</sub> O | 4.0E-8         |
| CO               | 0.07           |
| HC               | 0.004          |
| Pb               | 9.5E-10        |
| O <sub>2</sub>   | 95.3           |
| H <sub>2</sub> O | 35.2           |

Equations 1 ... 3 can now be used for the impact assessment of the application example. The results for the midpoint and endpoint categories as well as the single score are listed in TAB. 17.

TAB. 17 Results of the impact assessment of the application example using the World ReCiPe H/A method

| Impact category     | Amount                          | Unit [per pkm]            |
|---------------------|---------------------------------|---------------------------|
| Midpoint categories | Climate change                  | 99.2 g CO <sub>2</sub> eq |
|                     | Ozone depletion                 | 0 g CFC-11 eq             |
|                     | Terrestrial acidification       | 0.3 g SO <sub>2</sub> eq  |
|                     | Freshwater eutrophication       | 0 g P eq                  |
|                     | Marine eutrophication           | 0.02 g N eq               |
|                     | Human toxicity                  | 0.001 g 1,4-DB eq         |
|                     | Photochemical oxidant formation | 0.5 g NMVOC               |
|                     | Particulate matter formation    | 0.1 g PM <sub>10</sub> eq |
|                     | Terrestrial ecotoxicity         | 2E-7 g 1,4-DB eq          |
|                     | Freshwater ecotoxicity          | 1E-7 g 1,4-DB eq          |
|                     | Marine ecotoxicity              | 3E-6 g 1,4-DB eq          |
|                     | Ionising radiation              | 0 g U235 eq               |
|                     | Agricultural land occupation    | 0 m2a                     |
|                     | Urban land occupation           | 0 m2a                     |
|                     | Natural land transformation     | 0 m2                      |
|                     | Water depletion                 | 0.04 m3                   |
|                     | Mineral resource depletion      | 2E-9 g oil eq             |
| Fossil depletion    | 34.9 g Fe eq                    |                           |
| Endpoint categories | Damage to human health          | 2E-7 DALY                 |
|                     | Damage to ecosystem diversity   | 8E-10 species             |
|                     | Damage to resource availability | 6E-3 \$                   |
| <b>Single score</b> | <b>0.0101 points</b>            |                           |

A further analysis of the results of the impact assessment can be used to evaluate and compare the influence of the considered inputs, outputs and processes on the EI.

The percentage of the midpoint categories on the single score is shown in FIG. 8. It can be seen that fossil depletion has the highest percentage (47 %), followed by CC (44 %) and particulate matter formation (9 %).

TAB. 19 Values for  $CF_{\text{midpoint}}$  from [31]

| Parameter              | Midpoint category               | In- / output |                 |                 |                 |                  |        |                 |                  |         |         |      |                |                  |
|------------------------|---------------------------------|--------------|-----------------|-----------------|-----------------|------------------|--------|-----------------|------------------|---------|---------|------|----------------|------------------|
|                        |                                 | Crude oil    | CO <sub>2</sub> | NO <sub>x</sub> | SO <sub>2</sub> | PM <sub>10</sub> | Hg     | CF <sub>2</sub> | N <sub>2</sub> O | CO      | HC      | Pb   | O <sub>2</sub> | H <sub>2</sub> O |
| $CF_{\text{midpoint}}$ | Climate change                  | -            | 1               | -               | -               | -                | -      | 7390            | 298              | -       | -       | -    | -              | -                |
|                        | Ozone depletion                 | -            | -               | -               | -               | -                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Terrestrial acidification       | -            | -               | 0.56            | 1.00            | -                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Freshwater eutrophication       | -            | -               | -               | -               | -                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Marine eutrophication           | -            | -               | 0.039           | -               | -                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Human toxicity                  | -            | -               | -               | -               | -                | 518184 | -               | -                | 0.115   | 15779   | -    | -              |                  |
|                        | Photochemical oxidant formation | -            | -               | 1               | 0.081           | -                | -      | -               | 0.046            | 0.476   | -       | -    | -              |                  |
|                        | Particulate matter formation    | -            | -               | 0.22            | 0.20            | 1                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Terrestrial ecotoxicity         | -            | -               | -               | -               | -                | 102    | -               | -                | 3.9E-05 | 0.07    | -    | -              |                  |
|                        | Freshwater ecotoxicity          | -            | -               | -               | -               | -                | 3.29   | -               | -                | 3.4E-05 | 4.8E-03 | -    | -              |                  |
|                        | Marine ecotoxicity              | -            | -               | -               | -               | -                | 593    | -               | -                | 7.7E-04 | 1.55    | -    | -              |                  |
|                        | Ionising radiation              | -            | -               | -               | -               | -                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Agricultural land occupation    | -            | -               | -               | -               | -                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Urban land occupation           | -            | -               | -               | -               | -                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Natural land transformation     | -            | -               | -               | -               | -                | -      | -               | -                | -       | -       | -    | -              |                  |
|                        | Water depletion                 | -            | -               | -               | -               | -                | -      | -               | -                | -       | -       | -    | 0.001          |                  |
|                        | Metal depletion                 | -            | -               | -               | -               | -                | -      | -               | -                | -       | -       | 1.80 | -              |                  |
|                        | Fossil depletion                | 1            | -               | -               | -               | -                | -      | -               | -                | -       | -       | -    | -              |                  |

TAB. 18 Values for  $CF_{\text{endpoint}}$ ,  $NF$  and  $W$  from [31]

| Parameter              | Midpoint category               | Endpoint categories    |                               |                                 |
|------------------------|---------------------------------|------------------------|-------------------------------|---------------------------------|
|                        |                                 | Damage to human health | Damage to ecosystem diversity | Damage to resource availability |
| $CF_{\text{endpoint}}$ | Climate change                  | 1.40E-06               | 7.93E-09                      | -                               |
|                        | Ozone depletion                 | individual             | -                             | -                               |
|                        | Terrestrial acidification       | -                      | 5.80E-09                      | -                               |
|                        | Freshwater eutrophication       | -                      | 4.44E-08                      | -                               |
|                        | Marine eutrophication           | -                      | -                             | -                               |
|                        | Human toxicity                  | 7.00E-07               | -                             | -                               |
|                        | Photochemical oxidant formation | 3.90E-08               | -                             | -                               |
|                        | Particulate matter formation    | 2.60E-04               | -                             | -                               |
|                        | Terrestrial ecotoxicity         | -                      | 1.51E-07                      | -                               |
|                        | Freshwater ecotoxicity          | -                      | 8.61E-10                      | -                               |
|                        | Marine ecotoxicity              | -                      | 1.76E-10                      | -                               |
|                        | Ionising radiation              | 1.64E-08               | -                             | -                               |
|                        | Agricultural land occupation    | -                      | individual                    | -                               |
|                        | Urban land occupation           | -                      | individual                    | -                               |
|                        | Natural land transformation     | -                      | individual                    | -                               |
|                        | Water depletion                 | -                      | -                             | -                               |
|                        | Metal depletion                 | -                      | -                             | 7.15E-02                        |
| Fossil depletion       | -                               | -                      | 1.65E-01                      |                                 |
| $NF$                   |                                 | 1.35E-02               | 9.17E-04                      | 2.45E+02                        |
| $W$                    |                                 | 400                    | 400                           | 200                             |

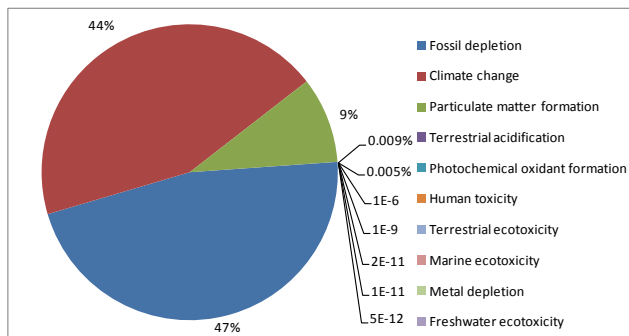


FIG. 8 Percentage of the midpoint categories on the single score of the application example

The percentage of the considered in- and outputs on the single score is shown in FIG. 9. It can be seen that crude oil has the highest percentage as it causes the fossil depletion in the previous figure. In the presented analysis, CO<sub>2</sub> is the main cause for CC. Therefore CO<sub>2</sub> has the same percentage as CC in the previous figure. NO<sub>x</sub>, SO<sub>2</sub> and PM<sub>10</sub> cause particulate matter formation. Together, they form the percentage of the particulate matter formation in FIG. 8.

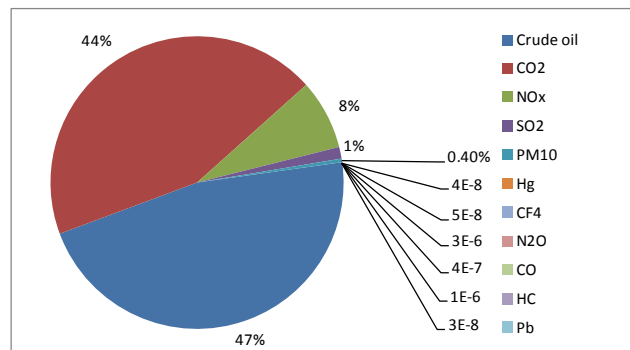


FIG. 9 Percentage of different in- and outputs on the single score of the application example

The percentage of the considered processes on the single score is shown in FIG. 10. It can be seen that kerosene production has the highest percentage (50%). This process is responsible for the depletion of crude oil and a small part (about 8%) of the CO<sub>2</sub> emissions. Together, cruise flight and LTO-cycle are responsible for about 48% of the single score. This is due to the fact that they cause the main part of the CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub> emissions.

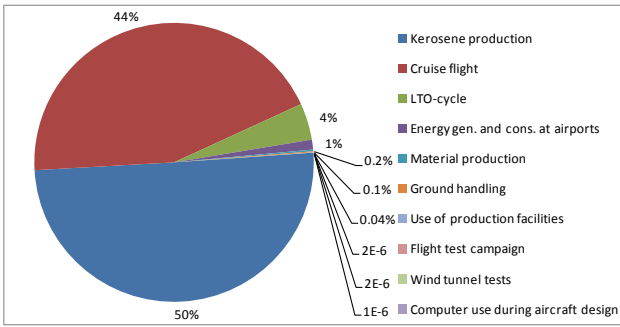


FIG. 10 Percentage of the considered processes on the single score of the application example

The results show that kerosene production, cruise flight and LTO-cycle completely dominate the single score. It can also be seen that the flight test campaign, the wind tunnel tests and the computer use during aircraft design have the smallest contribution. As already mentioned, this is due the fact, that these processes occur only once in the life-cycle of the entire aircraft fleet. As a fleet size of 20000 aircraft has been assumed, such processes would need 20000 times higher emissions than processes occurring once in the life-cycle of a single aircraft, to reach the same amount of emissions per pkm.

In a last step, the presented results will be compared to those shown in Section 3. FIG. 11 compares the result of the presented analysis for CC with the result calculated by [11] and [12] as shown in FIG. 5. It can be seen that even though only a simplified calculation has been presented, the absolute value of about 99 g CO<sub>2</sub> eq per pkm (which is the sum of the blue and red part of the A320-column) is similar to the results of [11] and [12]. There is a deviation of -24 % to the B737 which suits best for a comparison with the Airbus A320 (from the aircraft presented in Section 3) as it is an aircraft for a similar number of passengers and range. Even though only simplified calculations were used in this paper, the fairly good accordance of the result for CC can be explained by the fact that cruise flight and LTO-cycle dominate the emissions causing CC and that the emissions in these processes are relatively well known.

It had been expected that the calculated value is slightly lower than the actual value as the presented simplified calculation neglected several processes within the life-cycle.

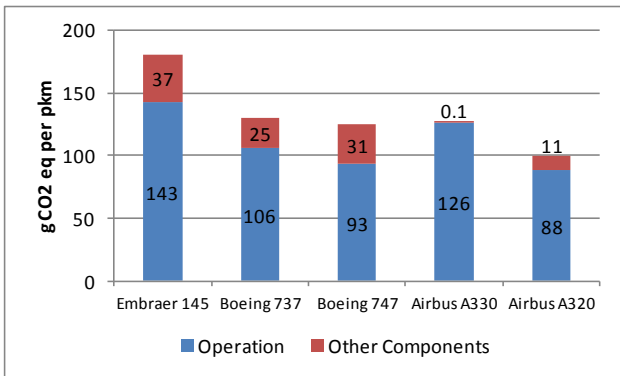


FIG. 11 Comparison of the result for CC of the A320 with the results of the other authors (Embraer 145, Boeing 737 and Boeing 747

according to [11], Airbus A330 according to [12], Airbus A320 from own calculation)

FIG. 12 compares the influence of cruise flight and LTO-cycle against the influence of all other processes on CC. Together, cruise flight and LTO-cycle are responsible for 89 % of the impact assessment result for CC. This is in between the results of [11] and [12] as shown in FIG. 3 and 4.

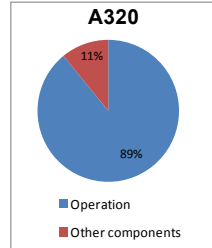


FIG. 12 Comparison of operation and other components concerning their influence on CC

#### 4.5. Lessons Learned and Future Work

This subsection presents the lessons learned and future work for the integration of an LCA into conceptual aircraft design based on the methodology presented in the previous subsections.

- For processes occurring once in the life-cycle of the entire aircraft fleet, the calculation in the previous subsection leads to a contribution to the single score below 0.001 %. It could be criticized that the big fleet size of the application example of this paper is responsible for the low contribution. However, even reducing the fleet size by a factor of 100 would still lead to a contribution below 0.1 % so that it is concluded that such processes can generally be neglected or calculated in a simplified way.
- The presented calculations are simplified and cover only some of the processes within the life-cycle of an aircraft. Therefore, the presented methodology is only a first step towards the integration of an LCA into conceptual aircraft design. Further research is intended to investigate the single LCA processes in more detail aiming at underpinning the presented results and further developing the methodology and equations to increase the accuracy of the presented method.
- During the operation of an aircraft, emissions occur in different altitudes. The EI of emissions depends on altitude. Current EI methods like the chosen ReCiPe method do not fully take account of that effect. In the future, it is intended to integrate that effect by extending the ReCiPe method so that it can also consider emissions in different altitudes. Several methods exist for the consideration of the effects of altitude on CC (i.e. [50]). However, the influence of altitude also has to be investigated and integrated for all other impact categories.
- As already stated, there will always be some uncertainty about the results of an LCA as they are usually based on simplifications and assumptions. Further research is therefore also intended to critically check data quality and uncertainty.

- Changing the EI in conceptual aircraft design is only possible if processes contributing to the EI can be influenced in the conceptual design phase. All processes analyzed in this paper except the operation of airports can be influenced in conceptual aircraft design showing that the EI can actually be changed. The influence on processes like wind tunnel tests, flight test campaign and the transport of components is limited but due to their low contribution to the total EI, a designer is still able to directly influence most of the EI.

## 5. SUMMARY AND CONCLUSION

This paper presents a first step towards the integration of an LCA into any conceptual aircraft design tool. Equations are given allowing to perform an inventory analysis as well as an impact assessment for several important processes throughout the life-cycle.

Using the World ReCiPe H/A method, the results of the presented methodology for the application example Airbus A320-200 show that processes occurring once in the life-cycle of the aircraft fleet have an influence smaller than 0.001 % of the entire EI so that such processes can be neglected.

The impact category fossil depletion has the highest contribution to the total EI (approx. 47 %) followed by CC (approx. 44 %). The fossil depletion is driven by the depletion of crude oil for the kerosene production. The CC is mainly driven by CO<sub>2</sub> emissions during cruise flight and LTO-cycle.

This is an interesting result as many authors mainly refer to CC. Eventually fossil depletion should get more consideration in public discussion.

The results of the presented simplified approach for the impact category CC have been compared to other existing LCA results. It is shown that the results are already in good agreement with those of other authors. Therefore, it is concluded that the methodology can be used for a first calculation of the EI of an aircraft.

The methodology allows to evaluate potential environmental improvements like the use of different material distributions concerning their benefit for the EI of an entire aircraft within its life-cycle. It also allows to analyze the influence of many other factors like a higher load factor on EI. Another intention of this research is to allow the investigation of the environmental influence of future technologies. Nowadays, the use of kerosene as engine fuel dominates the EI of aircraft. Nevertheless, future technologies replacing kerosene as engine fuel (like electric flight), might instantly lead to a drastic reduction of the EI and a new distribution of processes being responsible for the EI.

Future work will concentrate on increasing the accuracy and level of detail of the calculation and on analyzing how the integration of LCA influences aircraft design.

## ACKNOWLEDGEMENT

The project underlying this report was funded by the German Federal Ministry for Education and Research (support code (FKZ) 03CL01G). The authors are responsible for the content of this publication.

## NOMENCLATURE

### Symbols

|            |                         |
|------------|-------------------------|
| <i>c</i>   | cost                    |
| <i>CF</i>  | characterization factor |
| <i>d</i>   | distance                |
| <i>E</i>   | Electric energy         |
| <i>EP</i>  | endpoint category       |
| <i>FF</i>  | fuel flow               |
| <i>h</i>   | hour                    |
| <i>m</i>   | mass                    |
| <i>MP</i>  | midpoint category       |
| <i>NF</i>  | normalization factor    |
| <i>n</i>   | number (of)             |
| <i>p</i>   | percentage              |
| <i>pkm</i> | passenger-kilometer     |
| <i>R</i>   | range                   |
| <i>SS</i>  | single score            |
| <i>t</i>   | time                    |
| <i>W</i>   | weighting               |
| <i>x</i>   | input/output            |

### Indices

|             |                     |
|-------------|---------------------|
| <i>a</i>    | year                |
| <i>a/c</i>  | aircraft            |
| <i>alo</i>  | allocated           |
| <i>AP</i>   | airport             |
| <i>b</i>    | built               |
| <i>c</i>    | certification       |
| <i>CO2</i>  | carbon dioxide      |
| <i>d</i>    | distance            |
| <i>dev</i>  | development         |
| <i>emp</i>  | employee            |
| <i>f</i>    | flight              |
| <i>h</i>    | hour                |
| <i>H2O</i>  | water               |
| <i>i</i>    | counter variable    |
| <i>j</i>    | counter variable    |
| <i>k</i>    | counter variable    |
| <i>l</i>    | life                |
| <i>lf</i>   | load factor         |
| <i>ldf</i>  | landfill            |
| <i>max</i>  | maximum             |
| <i>mode</i> | mode                |
| <i>MPL</i>  | maximum payload     |
| <i>n</i>    | needed              |
| <i>MPL</i>  | maximum payload     |
| <i>NOx</i>  | nitrogen oxide      |
| <i>PAX</i>  | passengers          |
| <i>o</i>    | operational         |
| <i>OE</i>   | operating empty     |
| <i>pkm</i>  | passenger-kilometer |
| <i>ru</i>   | reuse               |
| <i>s</i>    | seat                |
| <i>SO2</i>  | sulfur dioxide      |
| <i>t</i>    | total               |

### Abbreviations

|           |                |
|-----------|----------------|
| <i>CC</i> | Climate Change |
|-----------|----------------|

|                    |  |
|--------------------|--|
| CF <sub>4</sub>    | Tetrafluoromethane   |
| CFRP               | Carbon Fiber Reinforced Plastics                             |
| CO                 | Carbon monoxide  |
| CO <sub>2</sub>    | Carbon dioxide   |
| CO <sub>2</sub> eq | CO <sub>2</sub> -equivalent                                  |
| DOC                | Direct Operating Costs                                       |
| EF                 | Emission factor  |
| EI                 | Environmental Impact   |
| ELCD               | European reference Life Cycle Database                       |
| GWP                | Global Warming Potential                                     |
| H <sub>2</sub> O   | Water  |
| HC                 | Hydrocarbon  |
| Hg                 | Mercury  |
| ISO                | International Organization for Standardization               |
| LCA                | Life Cycle Assessment  |
| LTO                | Landing and Take-off   |
| CH <sub>4</sub>    | Methane  |
| NO <sub>x</sub>    | Nitrous oxides   |
| N <sub>2</sub> O   | Dinitrogen oxide   |
| O <sub>2</sub>     | Oxygen   |
| Pb                 | Lead   |
| pkm                | Passenger-kilometer  |
| PM <sub>10</sub>   | Particulates with an aerodynamic diameter of less than 10 µm |
| SO <sub>2</sub>    | Sulfur dioxide   |
| TEC                | Total Energy Consumption                                     |
| tkm                | Ton-kilometer  |

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