ADAPTING LIFE CYCLE IMPACT ASSESSMENT METHODS FOR APPLICATION IN AIRCRAFT DESIGN

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Abstract

Minimizing not only costs but also environmental impact becomes more and more important in aircraft design. The environmental impact of future aircraft can be calculated in aircraft design using life cycle assessment. Life cycle assessments are widely used to calculate environmental impacts of products during their life cycle based on the inputs and outputs that the product exchanges with the environment. For most products, these inputs and outputs occur on the ground. In contrast to that the major part of the emissions of an aircraft occurs during cruise in an altitude of several kilometers. If the environmental impact of an emission depends on altitude, this should be considered in a life cycle assessment. Therefore this paper investigates to what extent existing life cycle impact assessment methods consider the effects of altitude-dependent emissions. It is also investigated if existing methods have to be adapted to be able to deal with the special requirements of life cycle assessments of aircraft. The results show that the effects of contrails and aviation-induced cirrus clouds as well as altitude-dependent environmental impacts of NO_x emissions are not sufficiently covered by existing impact assessment methods. Therefore it is proposed how existing methods for an altitude-dependent calculation of the environmental impact of those emissions can be integrated into existing impact assessment methods. It is analyzed how this integration affects the results of a life cycle assessment and of aircraft design using the medium range aircraft Airbus A320-200 as reference aircraft and a turboprop aircraft as example. Integrating contrails and aviation-induced cirrus clouds as well as NO_x emissions leads to a considerable increase of the environmental impact of aircraft. The calculated total environmental impact of the reference aircraft rises by about 110 %. The percentage of contrails and cirrus clouds on the total environmental impact rises from 0 % to 32 % while that of NO_x emissions rises from 8 % to 24 %. The proposed adaption of existing life cycle impact assessment methods allows improving the accuracy of the life cycle assessment results of aircraft. Additionally new effects can be considered in environmental aircraft design optimization concerning, for instance, flight mission profile or emissions that have previously been wrongly rated as safe.

1. INTRODUCTION

In [1], a simplified Life Cycle Assessment (LCA) methodology for aircraft has been presented. The methodology allows the calculation of the Environmental Impact (EI) of an aircraft in conceptual aircraft design. ISO 14040 defines LCA as the „compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system during its life cycle" [2]. LCAs consist of four phases. The first phase is called "Goal and scope definition". As the name suggests, it defines the goal and scope of an LCA. The second phase is called "Life Cycle Inventory analysis" (LCI). It involves the calculation of the amount of all inputs from the environment and all outputs released into the environment. The third phase of an LCA is called "Life Cycle Impact Assessment" (LCIA). It consists of an analysis of the EI of a product (e.g. an aircraft). The EI is calculated based on the amount of inputs and outputs calculated in the second LCA phase. The fourth and last phase of an LCA is called "Interpretation". In this phase, the findings are evaluated and conclusions are drawn [2]. The general concept of the integration of LCA into conceptual aircraft design is illustrated in FIG. 1.

This paper concentrates on the third phase, the LCIA. Several methodologies exist for the LCIA (e.g. the ReCiPe method [3]). These methodologies evaluate the EI using so called impact categories. Impact categories represent „environmental issues of concern" [2] like, for instance, climate change or fossil fuel depletion.

For the LCIA in [1], the ReCiPe method has been used. The ReCiPe method represents an up to date and commonly used method for the LCIA phase. Nevertheless, it calculates the EI independent of altitude even though several publications show that the EI of certain emissions depends on altitude (e.g. [5]). Additionally, certain emissions and effects are not considered. For instance, NO_x emissions as well as Contrails and aviation-induced Cirrus Clouds (CC) are not considered in the impact category climate change. This is because the values used by ReCiPe in the impact category climate change, are the Global Warming Potentials (GWP) presented by the Intergovernmental Panel on Climate Change (IPCC) in 2007 [4]. In that report, certain emissions did not get a central value for GWP because of uncertainty concerning their EI. Additionally the GWPs are provided independent of altitude. However, for LCAs of aircraft, altitude should be considered. This is because most part of the emissions during a flight occurs in cruise altitude and not on the ground.

To give an example, IPCC reports that NO_x emissions of aviation have an important impact on climate [6] underlining that such emissions should be considered in an LCA of aircraft. Nevertheless, IPCC does not provide a central value for the GWP of NO_x emissions due to the lack of agreement in existing studies. [4] Accordingly, the ReCiPe method does not consider NO_x emissions in the impact category climate change either.

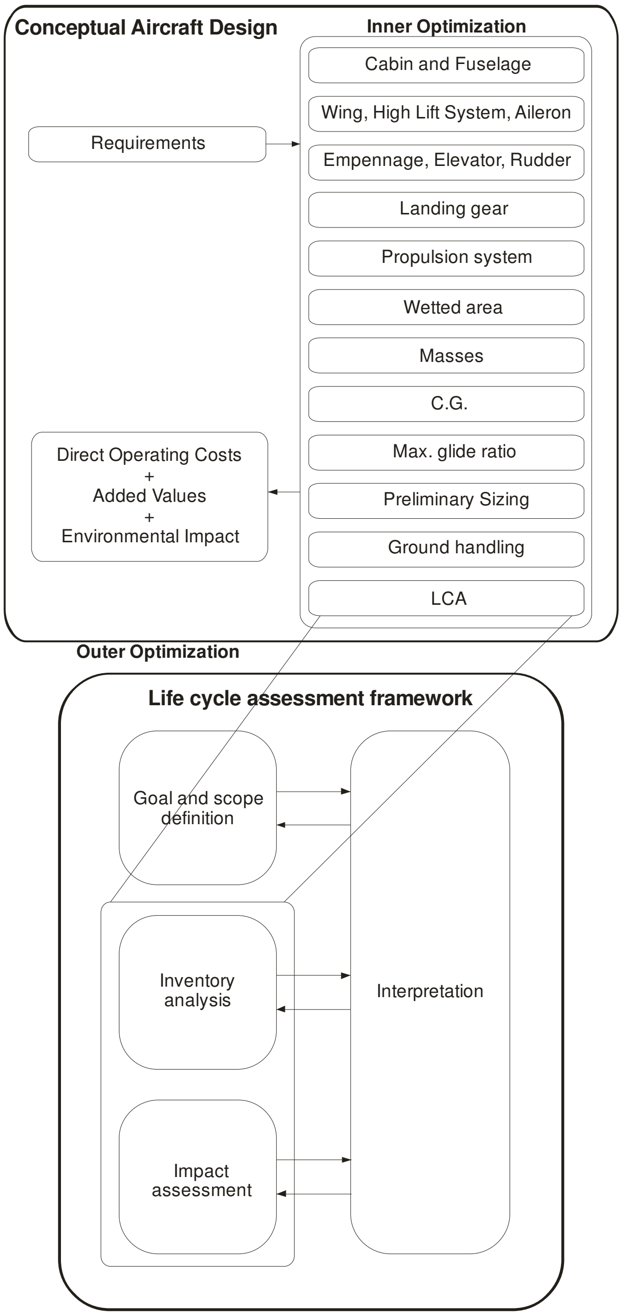


FIG. 1 Integration of LCA into conceptual aircraft design (own diagram in combination with figure from [2])

On the one hand, NO_x emissions lead to more ozone in the atmosphere leading to a positive Radiative Forcing (RF). On the other hand, NO_x emissions shorten the life-time of methane which reduces the amount of ozone both leading to a negative RF. Altogether, if NO_x is emitted on the ground, it has a slight cooling effect. If NO_x is emitted in a common cruise altitude of commercial aircraft of about 11 km, it has a warming effect. [5]

Neglecting such effects would distort the results of an LCA of aircraft. This paper therefore tries to tackle the described issue by adapting LCIA methods for application in aircraft design.

The outline of the paper is as follows. Section 2 presents a short literature review about the current state in research. Section 3 presents a method that allows integrating the effects of CC and NO_x emissions into existing LCIA methods. In Section 4, it is analyzed how the integration affects the results of an LCA of aircraft and the aircraft design itself. In Section 5, the findings are discussed while Section 6 concludes the paper.

2. LITERATURE REVIEW

A literature review in [1] shows that only few other authors have already performed LCAs of aircraft. In a first step, this section analyses how these authors handled the issue of not considered altitude effects in current LCIA methods:

Neither Chester [7] nor Lopez [8] adapted their LCA methodologies to account for the effects of cruise altitude that are not considered in existing LCIA methods. Franz et al. indirectly considered the effects of non CO_2 emissions in a simplified way by doubling the calculated CO_2 emissions [9]. It stays unclear if Weiss et al. considered altitude effects in their LCA of aircraft [10]. It is obvious that there is need for more research on how to adapt LCIA methods for application on aircraft.

In a second step, it is investigated if methods exist considering the altitude-dependent environmental effects of CC and NO_x emissions. It is also analyzed if their influence on aircraft design has been investigated by other authors:

Köhler et al. [5] offer a method to consider the effects of NO_x emissions in different altitudes concerning their RF. Rädel et al. [11] offer a method to consider the effects of CC in different altitudes concerning their RF. Schwartz et al. [12] bring the results of [5] and [11] together. The impact of NO_x emissions and CC is set in relation to the impact of CO_2 emissions. The method proposed by [12] has already been used by several other authors (e.g. [13], [14]). It can also be used to adapt existing LCIA methods. Such an adaption would allow integrating and analyzing the altitude-dependent effects of NO_x emissions and CC. Nevertheless, the uncertainty concerning the impacts of NO_x emissions and especially of CC on climate change has to be kept in mind. It also increases the uncertainty of the LCA results.

Schwartz [12], the CATS project [13] (another research project tackling the impact of aviation on climate) and Egelhofer [14] came to the conclusion that saving fuel and flying lower could substantially reduce the impact of aircraft on climate. [13] and [14] point out that flying lower causes more fuel burn and partially cancels the beneficial effect of flying lower. True is that flying lower has to go along with flying slower (if the wing area remains the same) to achieve fuel savings at reduced altitude. Flying slower, however, results in increased Direct Operating Costs (DOC). Research in [12], [13] and [14] has been focused on the impact of aircraft on climate. In contrast to that, the LCA approach presented here focuses on the total EI including not only the impact category climate change but also 17 other midpoint categories.

The following section presents how existing LCIA methods can be adapted to integrate altitude-dependent effects of NO_x and CC. The ReCiPe method is used as application example because it has also already been used in [1].

3. METHODS

Based on the literature review presented in the previous section, the method of Schwartz et al. [12] is selected to adapt the ReCiPe method. In this section, the ReCiPe method will be shortly introduced and its adaption will be described. The ReCiPe method is only used as application example. In principle, any LCIA method can be adapted using the equations and explanations given in the next paragraphs.

The nomenclature used in this section is the same as that used for the LCA methodology presented in [1]. This allows to more easily understand and integrate the proposed adaption of the LCIA method into the LCA methodology of [1].

As shown in FIG. 2 and explained in more detail in [1], the ReCiPe method allows to calculate eighteen so called midpoint and three so called endpoint categories. Additionally, a so called Single Score (SS) can be obtained summarizing the EI of the evaluated product in one score. In conceptual aircraft design, the SS can be integrated into the objective function so that EI becomes a part of aircraft design optimization.

To obtain the SS, the eighteen midpoint categories MP_j (j = 1 … 18) have to be calculated first:

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

with the input or output x of a certain substance i and the characterization factor $CF_{midpoint}$. In [1], the functional unit passenger-kilometer (pkm) is chosen for the LCA of aircraft. Therefore all inputs and outputs x also have to be calculated per pkm. The required $x_{pkm,i}$ can be calculated using the methodology presented in [1].

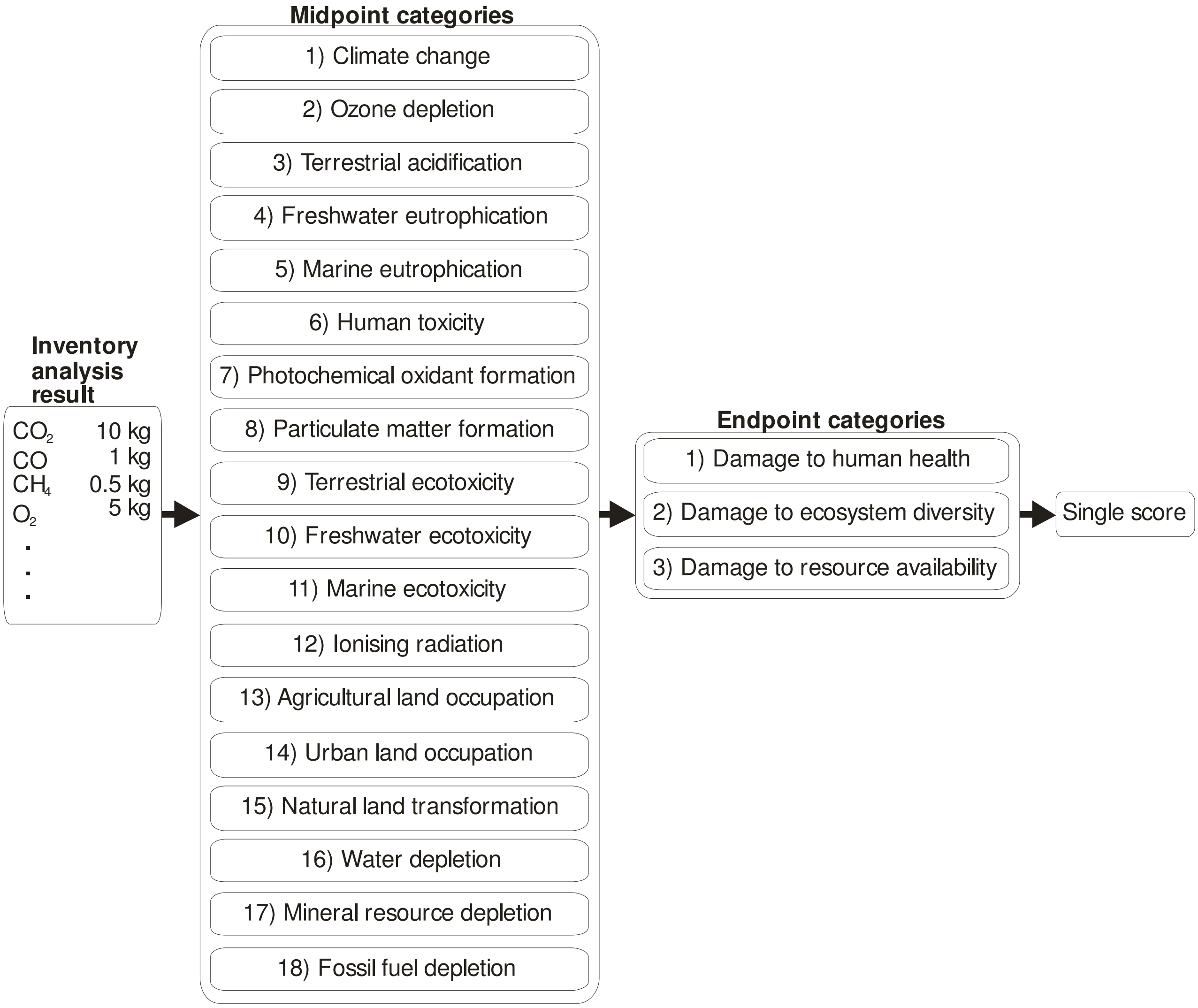


FIG. 2 Illustration of the ReCiPe method

With the results of the midpoint categories, the three endpoint categories EP_k (k = 1 … 3) can be calculated:

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

Finally, SS can be obtained using weightings W_k, normalization factors NF_k and the results for the three endpoint categories EP_k:

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

The ReCiPe method provides all *CF*, *NF* and *W* required for equations 1 … 3 in a publicly available table [15]. The *CF*, *NF* and *W* needed for the proposed LCA methodology for conceptual aircraft design are also provided in [1].

To integrate the altitude-dependent effects of CC and NO_x emissions, only the midpoint category climate change (midpoint category 1 according to FIG. 2) needs to be adapted:

$$MP_1 = \sum_{i=1}^{n} x_{pkm,i} \cdot CF_{midpoint,i,1} \quad (4)$$

In this equation, the characterization factors $CF_{midpoint,i,1}$ of the midpoint category climate change are needed. In the ReCiPe method, these CFs are equivalent to the GWPs of a certain substance i as reported by IPCC. Except for NO_x and CC, ReCiPe provides theses CFs in [15]. To adapt the ReCiPe method, altitude-dependent CFs for NO_x and CC are needed. The next paragraphs aim at providing these CFs:

Schwartz et al. [12] do not use GWPs for their calculation but so called Sustained Global Temperature Potentials (SGTP). SGTPs are an alternative to GWPs for the comparison of emissions concerning their impact on climate and were proposed by Shine et al. [16]. Nevertheless, GWPs and SGTPs „produce very similar results" [16]. Therefore normalized SGTPs can be used for the calculation of altitude-dependent $CF_{midpoint,i,1}$ as well:

$$CF_{midpoint,i,1}(a) = \frac{SGTP_{i,t} \cdot s_i(a)}{SGTP_{CO2,t}} \quad (5)$$

with the forcing factor s_i depending on altitude *a*. t represents the considered time horizon for the *SGTP* values.

TAB. 1 Sustained global temperature change potential $SGTP_{i,100}$ from [12]

Input/Output *i*	Sustained Global Temperature Potential $SGTP_{i,100}$
CO_2 [K/kg CO_2]	3.58E-14
Short O_3 [K/kg NO_x]	7.97E-12
Long O_3 [K/kg NO_x]	-9.14E-13
CH_4 [K/kg NO_x]	-3.90E-12
Contrails [K/NM]	2.54E-13
Cirrus [K/NM]	7.63E-13

The ReCiPe method used in [1] is applied using the so called hierarchist perspective which means that all $CF_{midpoint,i,1}$ refer to a time horizon of 100 years. Therefore the *SGTP* values also have to refer to a time horizon of 100 years. TAB. 1 provides values for SGTP for that time horizon (values from [12]).

Values for s_i can be taken from FIG. 3 (adapted from [12]). In the figure, the tropopause is highlighted with a bold black line (representing a common cruise altitude for civil passenger aircraft). It can be seen that the forcing factors are quite high in that altitude. It can also be seen that the forcing factors have the tendency to decrease with lower altitudes. Due to this fact, it becomes obvious that lower cruise altitudes lead to lower $CF_{midpoint,i,1}$ leading to lower MP_1 and finally to lower EI.

It has to be noted that for the calculation of the share of CC on MP_1, *x* does not stand for an input or output but for the average distance traveled per flight in NM [12].

As already explained in Section 1, NO_x impacts climate by the following effects. The amount of O_3 is increased and the lifetime of CH_4 is shortened which again decreases the amount of O_3 in the atmosphere. Therefore $CF_{midpoint,NOx,1}$ has to be calculated by:

$$CF_{midpoint,NOx,1}(a) = \sum \frac{SGTP_{i,100} \cdot s_i(a)}{SGTP_{CO2,100}} \quad (6)$$

$$\text{with } i = \text{Short } O_3, \text{Long } O_3, CH_4$$

Accordingly, $CF_{midpoint,CC,1}$ has to be calculated by:

$$CF_{midpoint,CC,1}(a) = \sum \frac{SGTP_{i,100} \cdot s_i(a)}{SGTP_{CO2,100}} \quad (7)$$

$$\text{with } i = \text{Contrails, Cirrus}$$

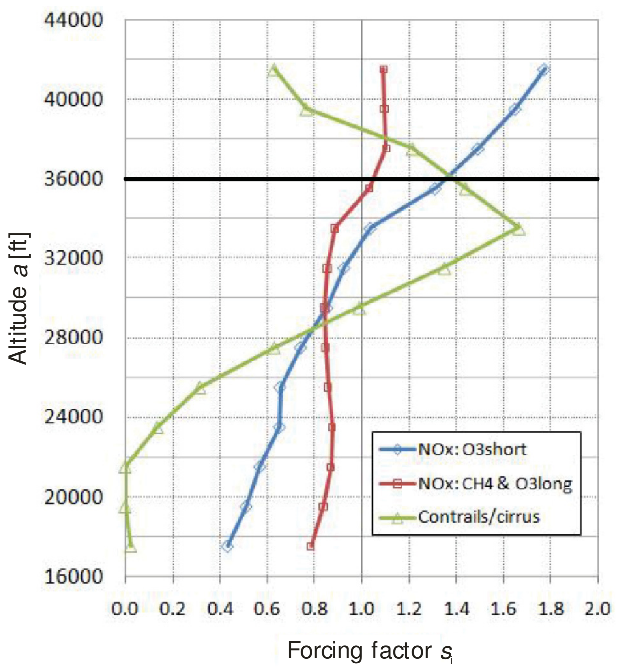


FIG. 3 Forcing factors $s_i(a)$ of NO_x and CC depending on altitude (adapted from [12])

Using the equations described in this Section, the altitude-dependent impact of NO_x and CC on climate can be integrated into the ReCiPe method.

4. RESULTS

4.1. Influence on LCA Results

In this subsection, it is analyzed how the previously described method influences LCA results of aircraft. An Airbus A320-200 is selected as reference aircraft.

FIG. 4 shows the percentage of the considered in- and outputs on the EI of the aircraft. The figure compares the percentage of the considered in- and outputs before (upper diagram) and after (lower diagram) the ReCiPe method has been adapted. Only in- and outputs with a contribution of at least 1 % are shown. It can be seen that due to the inclusion of the influence of NO_x and CC on climate, their percentage on the overall EI increases. In the application example, the percentage of CC rises from 0 % to 32 % while that of NO_x emissions rises from 8 % to 24 %. Due to the adaption, NO_x and CC become important components of the overall EI. The EI of the input crude oil and the output CO_2 is independent of altitude. Therefore their share on the overall EI decreases from 46 % to 22 % (crude oil) and from 44 % to 21 % (CO_2).

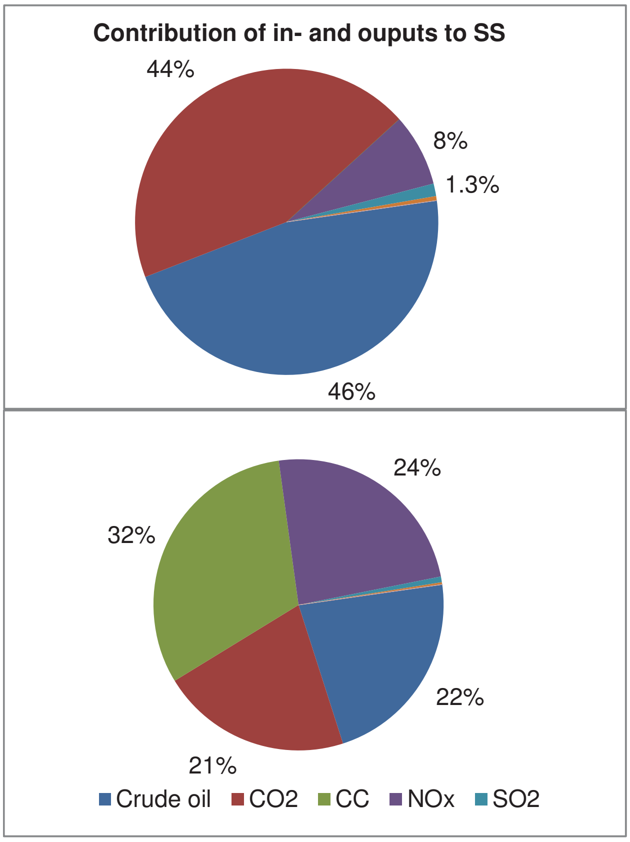


FIG. 4 Percentage of different considered in- and outputs on the EI of an Airbus A320-200 before (upper diagram) and after (lower diagram) adapting the LCIA method

FIG. 5 compares the percentage of the considered processes before and after the LCIA method has been adapted. Only processes with a contribution of at least 1 % are shown. It can be seen that the percentage of cruise flight on the overall EI increases from 43 % to 70 %. Consequently, the percentage of all other processes is lowered. This is because the additionally considered effects of NO_x and CC mainly affect cruise flight. After the adaption of the LCIA method, cruise flight has the highest share of all considered processes on the overall EI.

FIG. 6 compares the percentage of the midpoint categories before and after the LCIA method has been adapted. Only midpoint categories with a contribution of at least 1 % are shown. It can be seen that the percentage of the impact category climate change on the overall EI increases from 44 % to 73 %. The percentage of all other impact categories is lowered. This is because the additionally considered effects of NO_x and CC only affect the impact category climate change. Before the adaption of the impact assessment method, the midpoint category fossil depletion had the highest share on the overall EI. After the adaption, the midpoint category climate change is having the highest influence on EI.

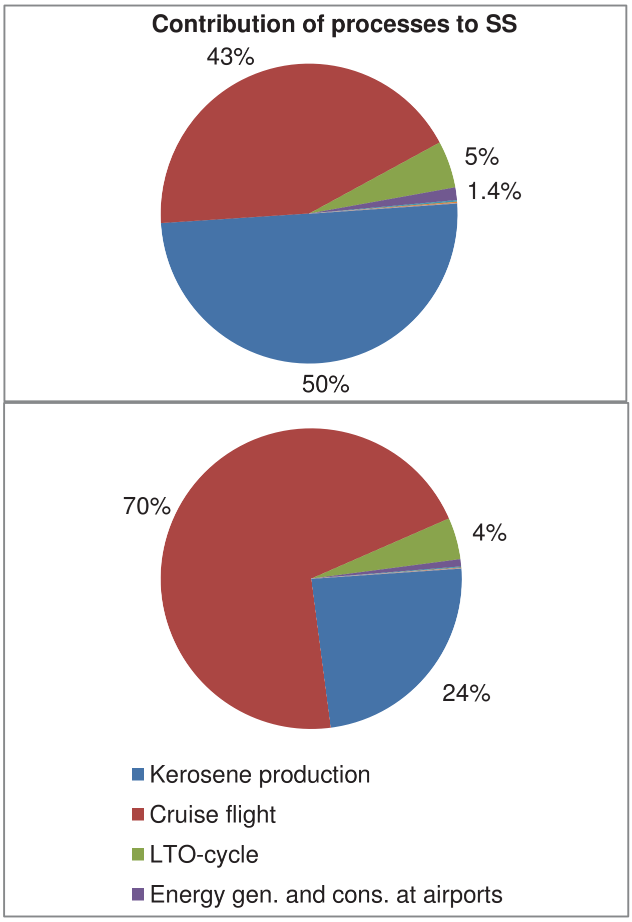


FIG. 5 Percentage of different considered processes on the EI of an Airbus A320-200 before (upper diagram) and after (lower diagram) adapting the LCIA method

FIG. 7 compares the percentage of the endpoint categories before and after the LCIA method has been adapted. It can be seen that the percentage of the category damage to human health increases from 50 % to 72 % while that of the category damage to ecosystem diversity increases from 4 % to 6 %. As a consequence, the percentage of the category damage to resource availability is lowered. This is because the only increased midpoint category climate change influences the categories human health and ecosystem diversity while it has no influence on the resource availability.

FIG. 8 compares the percentage of the considered life cycle phases before and after the LCIA method has been adapted. The operational phase has already completely dominated the EI before the adaption of the LCIA method. The adaption affected only the operational phase so that the share of that phase increased even more. In the figure, the increase of the share is almost not visible because the operational phase has already held almost the entire share.

In total, the adaption of the LCIA method results in more than a doubling of the total EI (expressed by the SS) of the selected reference aircraft. The absolute value of SS rises by about 110 % from 0.0080 points/pkm to 0.0168 points/pkm.

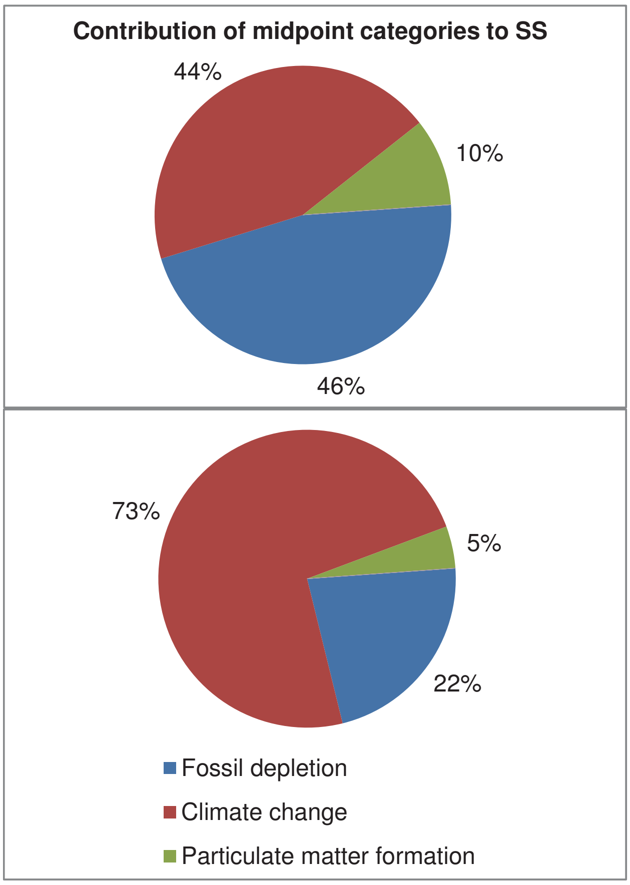


FIG. 6 Percentage of the midpoint categories on the EI of an Airbus A320-200 before (upper diagram) and after (lower diagram) adapting the LCIA method

4.2. Influence on Aircraft Design Results

In this subsection, the influence of the adaption of the LCIA method on conceptual aircraft design is investigated. A turboprop aircraft including the future technologies strut braced wing and natural laminar flow is chosen as application example. The aircraft is designed using the conceptual aircraft design software PrOPerA developed by the Aircraft Design and Systems Group (AERO).

The optimization is performed in the same way as in [17] to keep the design results comparable. The only difference is that the taper ratio is increased from 0.2 to 0.35 to have a better protection of the outboard wing against stall. The design presented here additionally considers the proposed adaption of the LCIA method. The aircraft is solely optimized for minimum EI. To optimize the aircraft for minimum EI, the value of SS from Equation 3 is minimized. For the optimization, an evolutionary algorithm is used with a population size of 35 and 60 generations. The design results are compared to the redesign results of the reference aircraft that has also been redesigned with PrOPerA.

The following seven design parameters are optimized for minimum EI: landing field length s_{LFL}, ratio of maximum landing mass to maximum take-off mass m_{ML}/m_{MTO}, cruise Mach number M_{CR}, effective wing aspect ratio $A_{W,eff}$ (taking account of the 36 m span limitation), wing sweep at 25 % chord φ_{25}, wing thickness ratio t/c and propeller diameter d_{prop}.

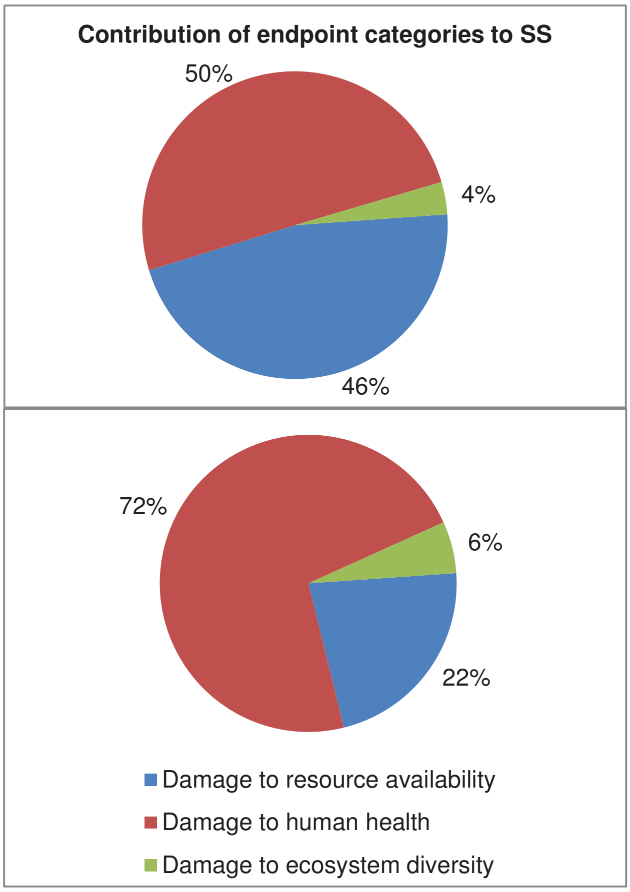


FIG. 7 Percentage of the endpoint categories on the EI of an Airbus A320-200 before (upper diagram) and after (lower diagram) adapting the LCIA method

As in [17], take-off field length s_{TOFL} is kept constant and set equal to the value of the reference aircraft. This helps to save calculation time and is acceptable because shorter s_{TOFL} are not advantageous anyway. For the optimization of s_{LFL}, the value of s_{TOFL} is set as upper limit. Aircraft usually require slightly shorter s_{LFL} than s_{TOFL}. Therefore it makes sense to set s_{TOFL} to the allowable upper limit and to set the value of s_{LFL} free.

The design results are presented in FIG. 9. It can be seen that the optimized design is very similar to that in [17]. For the Mach number, a value of 0.4 has been set as lower limit. The optimized value of the Mach number lies at that lower limit which is roughly half the Mach number of the reference aircraft. The aspect ratio increases by more than 60 % compared to the reference aircraft. The increase of aspect ratio comes from a reduction of wing area at nearly unmodified span. The lower wing area mainly comes from the lower mass of the turboprop aircraft. The mass is reduced mainly because of the lower fuel consumption and additional snowball effects.

Such a design potentially allows to lower the required fuel mass on the chosen DOC mission of about 600 NM by more than 40 %. SS representing the total EI of the aircraft can potentially be lowered by 70 %. More in depth analysis of the optimization results of such an EI optimized aircraft design is presented in [17].

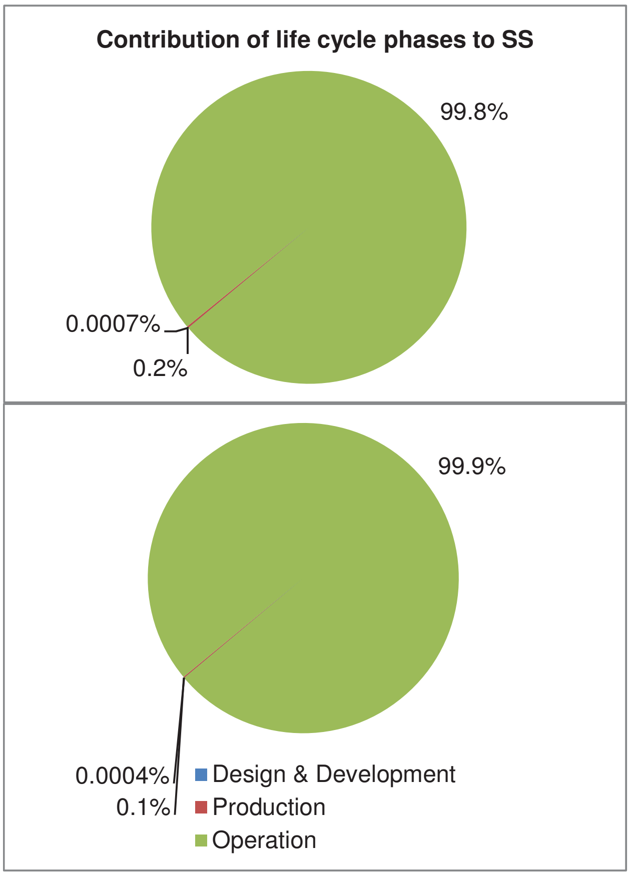


FIG. 8 Percentage of the life cycle phases on the EI of an Airbus A320-200 before (upper diagram) and after (lower diagram) adapting the LCIA method

5. DISCUSSION

The consideration of the altitude-dependent effects of CC and NO_x emissions leads to more than a doubling of the SS. This fact underlines the importance of adapting existing LCIA methods to the special requirements of LCAs of aircraft. Otherwise EI of aircraft might be substantially underestimated.

It is not surprising that the design results for the EI optimized turboprop aircraft before and after the adaption of the LCIA method are similar: Before the method has been adapted, low fuel consumption has been the most import design criterion for low EI while flight altitude did not have an influence on EI. After the adaption of the LCIA method, flying in lower altitudes has become another crucial design criterion. Now, low fuel consumption and flying low together are the two most important design criterions. The turboprop aircraft chosen as design example offers low fuel consumption at reduced cruise speeds. Mainly due to these reduced cruise speeds, it needs to be operated in lower altitudes. Therefore the turboprop aircraft automatically fulfills the two most important design criterions for low EI. Consequently, there is no big difference in the optimum aircraft before and after the adaption.

The results for the most important design criteria seem reasonable. As already stated in Section 2, Schwartz [12], the CATS project [13] and Egelhofer [14] also identified lower fuel consumption and the reduction of cruise altitude as most important design criteria. In contrast to [12] and [13], the presented research approach considers not only the impact category climate change but also 17 other midpoint categories. Nevertheless, climate change has been identified as the most important midpoint category so that saving fuel and flying lower stay the two most important design criteria for minimum EI.

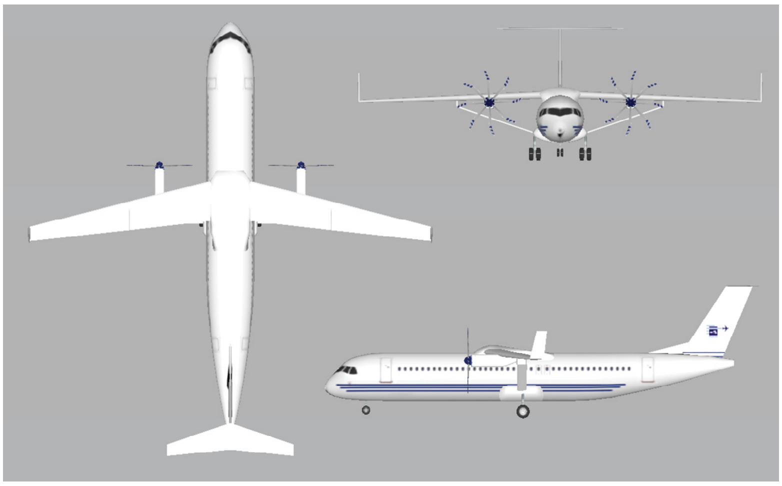
An interesting aspect is that the integration of the altitude-dependent influence of NO_x and CC can completely change the evaluation of the eco friendliness of certain aircraft concepts. For instance, before the LCIA method has been adapted, the presented method would have evaluated the cruise flight of a hydrogen-powered aircraft emitting only water with an SS of 0 (which means no EI). After the adaption, CC are considered, so that the emission of water in common cruise altitudes becomes harmful for the climate. Suddenly, the method considers that water emissions of hydrogen-powered aircraft lead to a substantial negative impact on climate. This example underlines the importance of the adaption of existing LCIA methods especially in the context of aviation.

6. SUMMARY AND CONCLUSION

IPCC [4] does not provide altitude-dependent values for the GWP of CC (caused by water emissions during cruise) and NO_x because of the existing uncertainty concerning their influence on climate. In the impact category climate change, the ReCiPe method is based on the GWP values of IPCC [4]. Therefore ReCiPe does not consider CC, NO_x and their altitude dependency either making the standard LCA results of aircraft at least questionable.

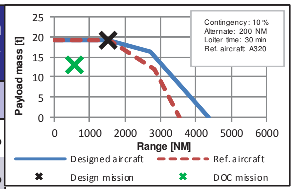
The paper shows that nowadays, methods exist allowing to consider the altitude-dependent impact of NO_x and CC on climate change. It is presented how these effects can be integrated into the ReCiPe method. It is also shown that the integration of these effects into the LCIA considerably changes the LCA results of aircraft compared to an LCA that does not consider these effects.

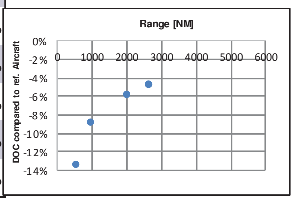
For the reference aircraft Airbus A320-200, the absolute value for the total EI rises by about 110 %. Concerning the in- and outputs affecting EI, the percentage of CC on the total EI rises from 0 % to 32 %, that of NO_x emissions rises from 8 % to 24 % while the percentage of CO_2 emissions goes down from 44 % to 21 %. Concerning the processes affecting EI, the cruise flight gains importance. Its percentage on the total EI rises from 43 % to 70 % so that the percentage of kerosene production goes down from 50 % to 24 %.

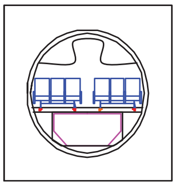


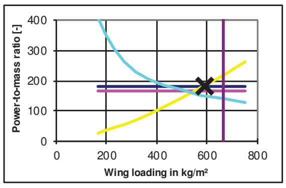
Parameter	Value	Deviation from A320*
Main aircraft parameters		
m_{MTO}	55200 kg	-25%
m_{OE}	28300 kg	-31%
m_F	7600 kg	-41%
S_W	93 m²	-24%
$b_{W,geo}$	36.0 m	6%
$A_{W,eff}$	15.50	63%
E_{max}	19.20	≈ + 9%
P_eq,ssl (per eng.)	5000 kW	------
d_prop	6.6 m	------
η_prop	88 %	------
PSFC	5.85E-8 kg/W/s	------
h_{ICA}	20000 ft	-50%
s_{TOFL}	1770 m	0%
s_{LFL}	1520 m	5%
t_{TA}	32 min	0%

Parameter	Value	Deviation from A320*
Requirements		
m_{MPL}	19256 kg	0%
R_{MPL}	1510 NM	0%
M_{CR}	0.40	-47%
max(s_{TOFL} , s_{LFL})	1770 m	0%
n_{PAX} (1-cl HD)	180	0%
m_{PAX}	93 kg	0%
SP	29 in	0%

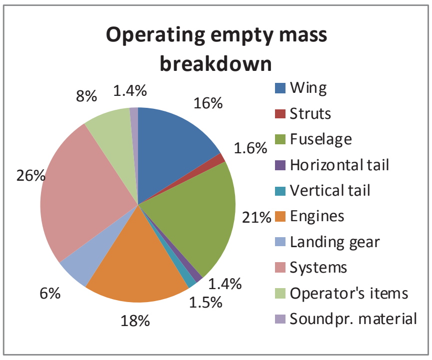


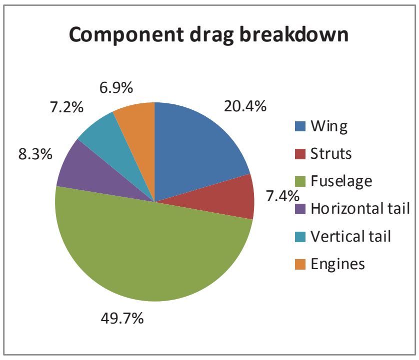






Parameter	Value	Deviation from A320*
DOC mission requirements		
R_{DOC}	589 NM	0%
$m_{PL,DOC}$	13057 kg	0%
EIS	2030	-----
c_{fuel}	1.32 USD/kg	0%
Results		
$m_{F,trip}$	2600 kg	-44%
$U_{a,f}$	3030 h	11%
DOC (AEA)	86 %	-14%
SS	0.01	-70%





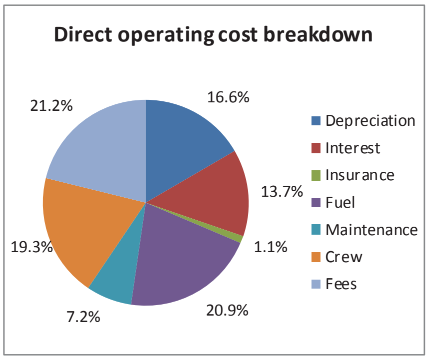


FIG. 9 Design results for the application example solely optimized for minimum EI

Before the LCIA method has been adapted, low fuel consumption has been the most import design criterion for low EI. Flight altitude did not have an influence on EI. After the adaption of the LCIA method, flying in lower altitudes has become another crucial design criterion. Consequently, low fuel consumption and flying low together became the two most important design criteria.

Due to their considerable impact, the consideration of the altitude-dependent effects of CC and NO_x is considered as necessary intermediate step towards a more accurate LCA calculation of aircraft. The presented improvements of the impact assessment allow to more accurately assessing the EI of aircraft.

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NOMENCLATURE

Symbols

a	Altitude
$A_{W,eff}$	Effective wing aspect ratio
$b_{W,geo}$	Geometrical span
BPR	Bypass-ratio
c_{fuel}	Fuel cost
$C_{D,0}$	Zero-lift drag coefficient
$CF_{endpoint,j,k}$	Characterization factor for a certain substance and endpoint category
$CF_{midpoint,i,j}$	Characterization factor for a certain substance and midpoint category
$CF_{midpoint,NOx,1}$	Characterization factor for NO_x in the impact category climate change
$CF_{midpoint,CC,1}$	Characterization factor for CC in the impact category climate change
d_{prop}	Propeller diameter
DOC (AEA)	Direct operating costs calculated using the method of the Association of European Airlines
E_{max}	Maximum glide ratio
EIS	Entry into service
EP_k	Endpoint category
h_{ICA}	Initial cruise altitude
M_{CR}	Cruise Mach number
$m_{F,trip}$	Fuel mass for the DOC range
m_{ML}	Maximum landing mass
m_{MPL}	Maximum payload mass
m_{MTO}	Maximum take-off mass
m_{OE}	Operating empty mass
MP_j	Midpoint Category
m_{PAX}	Passenger mass
$m_{PL,DOC}$	Payload mass for the DOC calculation
NF_k	Normalization factor
n_{PAX} (1-cl HD)	Number of passengers in a one class high-density layout
$P_{eq,ssl}$	Equivalent take-off power at static sea level
$PSFC$	Power specific fuel consumption
R_{DOC}	Range for the DOC calculation
R_{MPL}	Range at maximum payload
s_i	Forcing factor of a certain substance
s_{LFL}	Landing field length
s_{TOFL}	Take-off field length
$SGTP_{i,t}$	Sustained Global Temperature Potential of a certain substance after a certain time
$SGTP_{i,100}$	Sustained Global Temperature Potential of a certain substance after 100 years
$SGTP_{CO2,100}$	Sustained Global Temperature Potential of CO_2 after 100 years
S_W	Wing area
SP	Seat pitch
SS	Single Score
t_{TA}	Turnaround time
T_{TO}	Take-off thrust
t/c	Wing thickness ratio
$U_{a,f}$	Utilization per year on DOC range
W_k	Weighting
$x_{pkm,i}$	Input/output of a certain substance per passenger kilometer
η_{prop}	Propeller efficiency during cruise
φ_{25}	Wing sweep at 25 % chord

Abbreviations

CC	Contrails and aviation-induced Cirrus clouds
DOC	Direct Operating Costs
EI	Environmental Impact
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
pkm	Passenger kilometer
RF	Radiative Forcing
SGTP	Sustained Global Temperature Potential
SS	Single Score

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