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Stream Life Cycle Assessment Model for Aircraft Preliminary Design

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Abstract: The growing environmental public awareness and the consequential pressure on every industrial field has made environmental impact assessment increasingly important in the last few years. In this scope, the most established tool used in the specialized literature is the life cycle assessment. Applying this method to the life cycle of an aircraft requires it to be broken down into at least four phases: production, operation, maintenance and disposal. In the assessment, the evaluation of the environmental impact of fuel consumption can be performed linearly and has already been studied over many years, while calculating the impact of other life phases is more complicated, and it is still under study. This paper describes a simple and effective method developed to assess the environmental impact of an aircraft at a preliminary design stage and the implemented model that resulted from it. A detailed consideration of all life cycle phases is essential to serve as a reference for the ecological assessment of novel aircraft concepts. Thereby, the developed method is based on some parametric equations that take into account preliminary information, such as the mass breakdown, the technology used and some program considerations. The results obtained have been compared with those of the literature for verification and validation and have proved to be quite reliable. In fact, the comparison with known analyses, conducted on individual aircraft in a very precise manner, has showed that the proposed model is capable of giving results that fell within ±10% of the reference values. This is due to the broad generality of the model, which does not require a large number of specific data as a starting point to obtain reasonably reliable results for use during project development. In the near future, the use of this model can assist the design of aircraft architectures that comply with the European Green Deal of reducing net greenhouse gas emissions by at least 55% by 2030 and of having no net emissions of greenhouse gases by 2050.

Keywords: environmental impact; life cycle assessment; environmental project requirements; aviation industry; aircraft preliminary design

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1. Introduction

Flightpath 2050 [1,2], published in 2011 by the European Union, confirms the need to reduce the negative environmental impact (EI) of civil aviation. Nowadays, aircraft are mainly designed to have minimal operating costs. The EI of civil aviation could be reduced by designing aircraft not only based on costs but also based on their influence on the environment by including environmental aspects in the aircraft design optimization path. In the future, environmental requirements (ERs) will gain importance due to new aviation standards. The aim of this paper is to present a first step towards the integration of ER into preliminary aircraft design.

This objective can be achieved through the application of life cycle assessment (LCA) methodology. The LCA is defined in ISO 14040 [3] as "the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system during its life cycle". By assessing potential environmental impacts of an aircraft during the early stages of its development, LCA may help designers with the integration of ER into the whole ensemble of design requirements [4,5]. Gathering EI data to support decision making during conceptual and preliminary design is crucial in order to achieve the goal of reducing the footprint of the aviation sector. An LCA is divided into four phases [6]: scope definition; inventory analysis; impact assessment and interpretation. As the name suggests, the first phase defines the goal and scope of the LCA. This includes, among other aspects, the definition of the product system, system boundaries, assumptions and limitations. The second LCA phase involves the "compilation and quantification of inputs and outputs for a product throughout its life cycle" [3]. This means the calculation of all inputs from the environment and all outputs released into the environment. The third phase consists of an analysis of the EI of a product, the aircraft life in this case, based on the number of inputs and outputs calculated in the second LCA phase. Several methodologies exist to conduct the assessment, and each of them aims at linking outputs to the environment with standard impact categories [7], e.g., global warming potential. 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" [3].

However, LCA is a data-intensive technique which requires detailed information about a product life cycle; conversely, an aircraft design is ever-changing during the early phases, and its characteristics are uncertain [8]. Since a full LCA can be time- and resource-consuming, there is a need to use simplified methods. In order to evaluate the reliability of simplified methods, it is important to study what type of information they need, how they use design data and which kind of results they produce [9]. These approaches go by the name of streamlined life cycle assessment (SLCA), a slimmed down version of a full LCA [10]. The acronym SLCA is used here to refer to Streamlined LCA, however the same acronym is also used for Social LCA, which is a completely different discipline and will not be covered in this article. It has been estimated that SLCA can reveal up to 80% of the main environmental issues in a fraction of the time of a full LCA. SLCA methodologies are particularly suitable for the great uncertainty of the design phase [11]. Much research aimed at implementing reliable and objective approaches in this field, and a notable example is provided by professor S. Suh's works [12,13], where the basis of today's developments could be identified. His most noteworthy book is "*The computational structure of life cycle assessment*" [12], where LCA computational structure (CS) is presented and discussed. The book captures the arithmetical rules involved in carrying out a streamlined LCA study, representing a first step towards the possibility of developing LCA models.

Some examples of LCA application can also be found directly in the aviation industry. Main LCA methodologies applied here are economic input–output (EIO) [14] and process-based [15]. The first one links environmental impact with economic value [16] while the second one calculates the whole impact as the sum of all those of aircraft components [12]. Many articles have used the A320 as case study [17,18] because of its widespread employment.

In wider terms, the literature review shows that LCAs have been gaining increasing interest in civil aeronautical research in recent years. Nevertheless, this research is still in its infancy as few works have conducted and integrated LCAs into conceptual aircraft design. In comparison to the few existing approaches, the aim of this paper is to give a more general and efficient approach for the integration of LCA into aircraft design by providing equations that have been successfully integrated into an LCA parametric model.

This model is an evolution of the work carried out in the thesis [19]. Two ideas are fundamental to this development:

- The aviation sector is different from other industrial sectors. This is because the number of different manufactured products is quite small. Thereby, the environmental impact of a single product is of little interest;
- The aviation sector is evolving through architectures that employ hybrid propulsion and use energy sources of different kinds with the aim of drastically reducing the impact of fossil-derived carbon fuels.

Starting from these two statements, the assessment method develops the following characteristics. The first one is a general approach which requires minimal changes in order to adapt to aircraft of different categories. This is because it is based on parametric equations that use information from preliminary design as the input. The second characteristic is the level of detail, since all phases of the aircraft's life are considered and broken down as follows: production, operations, maintenance and end of life. In addition, for each of the phases, the required data are simultaneously specific and well-defined at the preliminary design stage, e.g., the aircraft is divided into systems, subsystems and major components, and an environmental impact is associated with each of them. Lastly, there is a possibility to analyze innovative architectures, e.g., hybrid electric aircraft, due to the consideration of new technologies in the database. From this perspective, fuels that can be assessed are kerosene based, biofuels, liquid hydrogen and electricity. All the consequently changes into operations phase are also considered.

Many articles in the literature almost exclusively analyze the production and operational phases. For example, Johanning and Scholz [20] argue that the operational phase contributes predominantly to the environmental impact of an aircraft, representing 99.8% of the total. Similar conclusions have been drawn by numerous other authors [21–23]. However, considering only these two phases of a product's life is a limitation since it does not give the possibility of precisely understanding the effect of innovative technologies which usually significantly affect the development phase. Furthermore, these studies often simplify the analysis of the operational phase, typically considering flight hours as an average value per year or over the entire lifespan, often neglecting maintenance events. Yet, maintenance events are critical to ensuring reliable flight operations and are influenced by the timing of the flight itself, including factors such as the number and duration of flights performed [24].

A model implemented in Python®, named Aircraft Life Cycle Impact Assessment, has been developed and put into practice. It can be utilized to quickly obtain results and check the validity of the approach, with the purpose of easily varying the parameters of the equations in calibration. In order to validate results obtained through the method presented in this work, four studies have been taken as comparison cases. Studies that have applied a rigorous replicable method and have taken the A320 as a case study have been chosen. This last requirement is due to the high similitude between A320 and CeRAS [25] aircraft, whose data are available online for researcher and universities. Comparison studies are presented in Section 5.

The article is divided into three parts. Section 2 thoroughly explains the developed method by presenting general equations and the path followed to build the database. In the third section, a case study, the CeRAS aircraft design, is analyzed, and results are briefly commented on. Eventually, in the last section, a comparison between four prominent articles on aircraft LCA is presented, with the objective of validating the proposed model.

2. Method

Basically, the method can be summarized as a set of parametric equations. If reliable data could be easily calculated then carrying out a valid LCA would not be difficult. However, two major obstacles arise due to the great number of components that take place in an aircraft. The first is to be able to find or calculate EI data for each component. The second challenge is the application of the algorithm itself. In particular, the process of building the database has been of such an importance that it will be separately presented in the last subsection.

2.1. Inputs

At a preliminary stage of the design, it is difficult to ascertain much information about the aircraft [26]. Usually, the only set values are the kind of subsystems and components mounted onboard and their weights [27], e.g., it is possible to know that a battery system composed of Li-ion cells will be mounted and that its weight is estimated to be 100 kg, but it is probable that the maximum energy it will produce, or its energy density, has not been clearly defined. The breakdown of the aircraft adopted is that in Table 1. It is important to remember that one of the major challenge is having the possibility to evaluate also innovative architectures. For this reason, in the ensemble of components some of newly experimentation and adoption have been included. The result is that this method, and so the model, can evaluate aircraft that derives their energetic need from four different sources, which are kerosene-based fuels,; biofuels; liquid hydrogen, to be used both in fuel cells or though burning in specifically designed engine; and electricity. Obviously, all of them take some particular components, for example, electric powertrains to be used for propulsion purposes or a special cryogenic tank to store LH2. After the input of systems and/or subsystem weights, the method derives the weight of every single component. This is possible making reference to a database build from statistics which contains some aircraft designs, each one referred to a specific category. This step is very important as system-level inputs are translated into component-level ones in order to perform smoother and more reliable computation. However, if statistical values are not reliable enough, there is always the possibility to create a completely new architecture database. The only requirement is for the designer to have deep knowledge at the preliminary design stage.

Table 1. Aircraft breakdown.

Aircraft				
Structure	**Power Plant**	**Systems**	**Furnishing**	**Operator Items**
Wing Fuselage Tail Nacelles Landing gear	Engines Fuel system	Hydraulic system ECS TMS De-icing FCS Avionic instruments Electric system	Thermoacoustic insulation Furnishing Lighting	Operational items Operational equipment

2.2. Equations

Equations implemented have been divided in those used to calculate production impact, those used for maintenance and those used for fuel consumption. This division is useful to clearly separate and remember the iterative procedure. As will be evident, equations are very similar to each other since they follow the same basic idea.

2.2.1. Production Equations

$$\text{EI production of component}(i) = \left[\sum_{j=1}^{N} \text{EI raw material production}(j) + \sum_{k=1}^{N} \text{EI manufacturing process}(k)\right] \times \text{weight of component}(i) \quad (1)$$

$$\text{EI aircraft production} = \sum_{i=1}^{N} \text{EI production of component}(i) \quad (2)$$

The method is iterative, and at every step a new component is taken into account. Its manufacture impact is searched in the database and multiplied by its weight. At the end, the resultant value is summed to the total aircraft production EI. This procedure is repeated for every component. To develop a model that achieves this process in a reasonable time is fundamental. If results were to be obtained over a long period of time, the model would lose relevance to the design process.

2.2.2. Maintenance Equations

$$\text{EI maintenance of subsystem}(i) = [\sum_{j=1}^{N} \text{EI production of component}(j)] \times \text{repaired percentage of subsystem}(i) \quad (3)$$

$$\text{Repaired percentage of subsystem}(i) = \frac{\sum_{j=1}^{N} [\text{substitution times component}(j) \times \text{weight of component}(j)]}{\text{weight of subsystem}(i)} \tag{4}$$

$$\text{EI aircraft maintenance stops} = \sum_{i=1}^{N} \text{EI maintenance work}(i) \times \text{maintenance hours}(i) \tag{5}$$

$$\text{EI aircraft maintenance} = \sum_{i=1}^{N} \text{EI maintenance of subsystem}(i) + \text{EI aircraft maintenance stops} \tag{6}$$

Here, the procedure followed is very similar to the manufacturing one. The only calculus needed in addition is the one concerning the number of times every component will be substituted. The method hypothesizes that the EI of reparation can be compared to that of mounting a new component in order to be as conservative as possible without affecting the results.

Regarding maintenance stops, the approach derives the downtime hours from the regulations knowing that A to D checks are usually set for every fixed hours of flight time. In this way, it is possible to derive both the EI of line maintenance, related to the use of in-airport ground support, and of base maintenance in dedicated facilities.

2.2.3. Operative Life

$$\text{EI operations} = \text{number of operations} \times [\text{EI fuel consumption}(i) + \text{EI airport consumption}] \tag{7}$$

Basically, the main impact of operative life is that deriving from producing and consuming the fuel [28]. However, the EI of airport and ground structures usage has also been added. To evaluate the quantity of fuel consumed, the method uses type mission characteristics in terms of distance flown and fuel burned. Input values are obtained by multiplying these data for the number of missions that the aircraft is designed to complete during its life. Type mission values are under study in a preliminary design. Thereby, models also offer the possibility for the designer to analyze the best use of the aircraft from an environmental point of view.

It is important to remember that the same emissions released at different altitudes have different environmental effects. When emissions are released close to the ground, they can have a more immediate and concentrated impact on local air quality. This can lead to increased levels of pollutants such as particulate matter, nitrogen oxides and sulfur dioxide. On the other hand, emissions released at higher altitude can have a more widespread impact, as they can be transported over longer distances by atmospheric winds and currents. This can lead to dispersion over larger areas and the creation of secondary pollutants, and all this contributes more significantly to climate change due to their longer atmospheric lifespan. This is true especially with greenhouse gases like CO_2 [29]. However, accounting for these effects is complex, and studies on the subject are limited and often unreliable [30]. To simplify the assessment, the method assumes that emissions have a consistent EI regardless of altitude.

2.2.4. End-of-Life Scenario

Aircraft decommissioning and recycling is a multi-disciplinary process, with environmental, operational, safety, legal and economic aspects. Today, 85% to 90% of the weight content of retired aircraft is re-used or recycled, reflecting the fact that both re-usable parts and recycled materials represent significant residual value [31]. The overall aircraft end-of-life process has been modeled following the European project PAMELA [32] in three phases: decommissioning, disassembling and disposal. This last phase is the only one whose EI has been taken into account in the method. The hypothesis was derived from the point of view of the materials; all metallic materials are considered completely recyclable. Plastic materials, on the other hand, present a percentage of recycling taken from European average values [33]. Thereby, 32.5% is recycled, while the rest is incinerated or landfilled, with a proportion of 2 to 1. The impact of a component's disposal, however, is considered in its production. In this way, in the end-of-life scenario, only the impact derived from the work of final dismantling of the aircraft is considered.

The equation used is:

$$\text{EI EOF} = \text{hours of dismantling} \times [\text{EI machine usage} + \text{EI plant usage}] \tag{8}$$

2.3. Method Workflow

Parametric equations used in the present study are presented in Table 2. These only contain constants related to global warming potential; more data are available in Appendix A or at the GitHub repository URL. In Figure 1 the workflow of the proposed method is depicted.

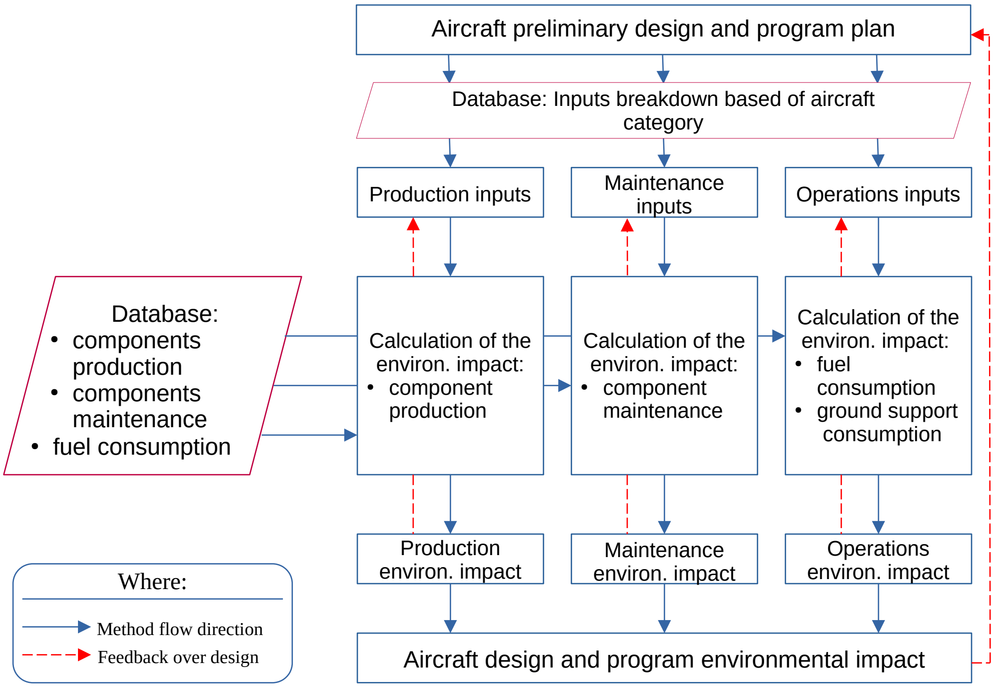

Figure 1. Method workflow.

2.4. Database

Building a large and reliable database in life cycle assessment studies is the most compelling challenge due to the limited quantity of data available, especially about aircraft components environmental impact. For this work, the most important source of information has been the *Ecoinvent v.3.8* database. Here, datasets are provided as individual unit process data, and comprehensive documentation for all aspects of the database is available. For more information, see [34], or to explore data quality guidelines, see [35]. The database offers the possibility to employ different system models; the one used, in accordance with the hypothesis on recycling, is the cut-off system model. It is based on the recycled content, or cut-off, approach. In this system model, waste is the producer's responsibility, and there is an incentive to use recyclable products that are available burden-free [33]. The *Ecoinvent Association* has carried out a long and compelling study on cataloging and assessing environmental impacts of the production of a wide variety of materials and components as objectively as possible. Its characteristic of covering many different fields has led to this database being widely adopted in many recent LCA works. Without this hard work, it would have been impossible to produce many articles, this included.

Table 2. Parametric equations.

	Global Warming Potential (kg CO_2 eq)
Wing EI	4.0×10^1 × wing weight (kg)
Fuselage EI	2.7×10^1 × fuselage weight (kg)
Tail EI	8.7×10^1 × tail weight (kg)
Landing gear EI	1.6×10^1 × landing gear weight (kg)
Nacelle EI	5.8×10^1 × nacelle weight (kg)
Equipped engines EI	3.4×10^1 × equipped engines weight (kg)
Fuel system EI	7.0×10^0 × fuel system weight (kg)
Hydr. generation EI	4.2×10^0 × hydr. generation weight (kg)
Hydr. distribution EI	2.6×10^0 × hydr. distribution weight (kg)
ECS EI	7.5×10^0 × ECS weight (kg)
De-icing system EI	1.5×10^0 × de-icing system weight (kg)
FCS EI	3.9×10^0 × FCS weight (kg)
Avionic Instruments EI	1.5×10^2 × avionic instruments weight (kg)
Elec. generation EI	4.0×10^1 × elec. generation weight (kg)
Elec. common inst. EI	2.1×10^1 × elec. common inst. weight (kg)
Structure EI	3.5×10^1 × structure weight (kg)
Power plant EI	3.3×10^1 × power plant weight (kg)
Systems EI	4.4×10^1 × system weight (kg)
Furnishing EI	4.9×10^0 × furnishing weight (kg)

Firstly, the path followed to build the dataset used in the model has to attempt to derive it directly from the values clustered in the *Ecoinvent* database. However, this has been possible for a limited number of components. The reason for this is that one of the most important sources of information for the *Ecoinvent* database is the automotive world. Nevertheless, even if automotive components are quite similar to those of aerospace, they are manufactured in a completely different way since aircraft requirements are much more stringent, and their environmental impact is different as a consequence. Thereby, using *Ecoinvent* data as a starting point, every major part of the aircraft has been modeled starting from the constituent materials. Then, to each of them has been associated with one or more manufacturing process until the finishing processes. In this way, for each component, it has been possible to build a fairly well-stocked database, including all major parts. The procedure is visually explained in the following Figure 2.

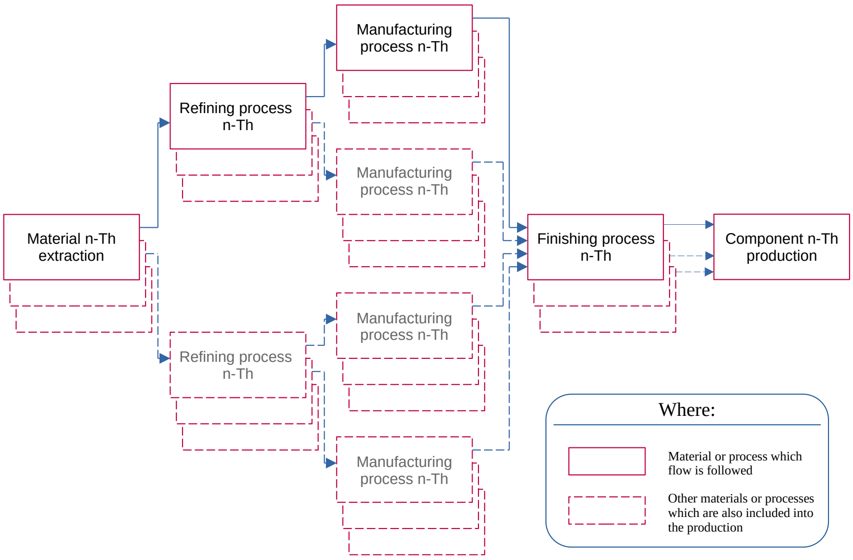

Figure 2. Component production process.

With regard to uncertainty about impacts, the database was constructed by attempting to collect as many data as possible from each source in order to obtain the average characteristics of the components which, thanks to the high number of observations, reduce the uncertainty on the result. After that, in modeling through *Ecoinvent* this uncertainty was combined with the basic uncertainty of primary data, for which the reference is [35]. The goal has always been, where possible, to minimize uncertainty with the help of statistics.

The whole database, where every component is taken into account and its EIs for different impact categories are tabulated, is located in a GitHub repository, which can be found in Appendix A.

3. Case Study

The design chosen for the assessment is a reference architecture named CeRAS, which stands for Central Reference Aircraft Data System. It is a central database hosting reference design data of commercial aircraft with the intention to help research projects dealing with conceptual to preliminary aircraft design studies as well as technology integration and assessment [25].

3.1. Manufacturing Scenario

This design has been chosen both because it gives a large amount of information on the aircraft that are usually very difficult to find and also because the architecture proposed is quite similar to that of the A320. Due to this peculiarity, the comparison with many articles about aircraft life cycle assessment is simplified. CeRAS characteristics and systems are presented in Table 3.

Table 3. CeRAS characteristics.

Description	Unit	Value
Design passenger capacity	-	150
Maximum design range	NM	2750
Engine type	-	2 × turbofan engine
Maximum take-off weight (MTOW)	kg	77,000
Operating empty weight (OEW)	kg	42,092
Maximum fuel weight	kg	18,700
Structure	kg	22,018
Power plant	kg	7751
Systems	kg	5378
Furnishings	kg	3006
Operator items	kg	3939

Since no data are available to account for all the non-recurring costs, such as aircraft development, tests and evaluations or production plant operation, these aspects have not been considered in the manufacturing environmental impact.

3.2. Operative Scenario

The operative scenario considered is derived from statistics and the average route, taken as a mean value in the log-normal distribution of short-medium flights [36], is 964 km. The overall life considered for the single aircraft is 25 years and 1875 flights per year.

Regarding maintenance, the only components whose replacement has been considered are tires, brakes and wheels, since they are usually changed after a fixed number of uses that depends only on the category of the aircraft. Thereby, the total number of changes is easily derived.

4. Results

Results are here reported for illustrative purposes, and the only impact category whose values can be found in Table 4 is climate change, expressed in kg of CO_2 equivalent. This is despite many more impact categories being considered by the method, whose values can be calculated using the model:

Stratospheric ozone depletion; human carcinogenic toxicity; fine particulate matter formation; terrestrial acidification; human non-carcinogenic toxicity; marine eutrophication; ionizing radiation; terrestrial ecotoxicity; land use; ozone formation, terrestrial ecosystems; ozone formation, human health; fossil resource scarcity; water consumption; mineral resource scarcity; freshwater ecotoxicity; global warming; freshwater eutrophication; marine ecotoxicity.

The whole set of results for every impact category can be found in the GitHub repository indicated in the data availability and in Appendix A.

Table 4. Results over the entire life cycle.

Phase	Results
Manufacturing	1.32×10^6 kg CO_2 equivalent
Operations	7.10×10^8 kg CO_2 equivalent
Operations (PKM)	163.5 g CO_2 equivalent
Maintenance	8.07×10^5 kg CO_2 equivalent
End of life	9.17×10^2 kg CO_2 equivalent

It can be seen from these values that the operative life, accounting for both mission and maintenance impacts, occupies the larger portion of the entire environmental impact, representing as much as 99%. However, this is due to the production of fuel and its subsequent burning, with every single kilogram of kerosene burned producing almost 3.66 kg of CO_2 equivalent.

The global warming potential (GWP) breakdown for aircraft subsystem production can be visualized in Figure 3.

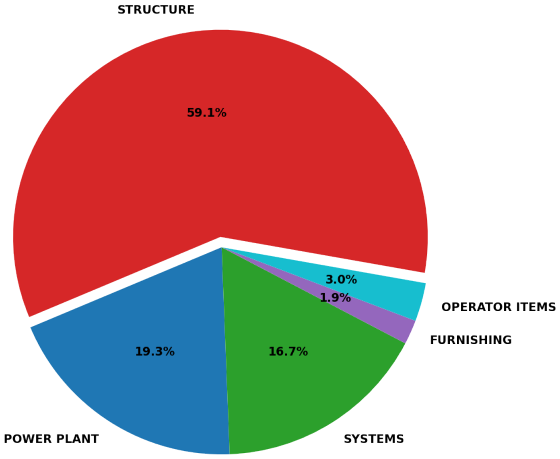

Figure 3. Global warming potential breakdown of manufacturing phase.

5. Discussion

The number of publications that have applied a rigorous methodology that eases the comparison of results is still restricted. Here, it has been decided to summarize four of them that have been used as a starting base and also as a comparison point when the model has been correctly implemented:

- The first one is S. Howe's thesis [17], which aimed to identify the key challenges relating to environmental efficiency within the aviation industry by examining routing strategies, analyzing the viability of alternative fuels and conducting a holistic life cycle assessment of a commercial airliner, the Airbus A320;
- In the same years, T. Lewis [18] employed two different methods in order to analyze the environmental impacts of commercial air transport, the first being a process-based

LCA utilizing the *Ecoinvent* database, and the second being an economic input–output life cycle assessment;

- In their master's thesis, J. Lopes [28] analyzed the environmental impact of an Airbus A330-200 using a process-based methodology; in particular, he took into account every life phase, from cradle to grave, placing more emphasis on the operations where data deriving from a real airliner were used in order to obtain more consistent results;
- The last article is the more recent, and it has been published by A. Rahn et al. [15]. The study aimed to use discrete-event simulation in accordance with life cycle assessment. Discrete-event simulation consists of state variables that change at discrete points in time during a simulation and thus model and execute a process as a series of individual events. Its main advantage is the ability to simulate complex systems wherein inputs and variables can be quickly exchanged to gain insight into their significance.

Differences are visually explained in Table 5. Another pair of references which have not been used for the comparison are J. Verstraete [14] and A. E. Scholz et al. [37].

Table 5. Comparison between life phases taken into consideration in studies.

	Production	**Operation**	**Maintenance**	**End of life**
This work	●	●	●	●
Howe's work	●	●	○	●
Lewis's work	●	●	○	○
Lopes's work	●	●	○	●
Rahn's work	●	●	●	●

The main difference of the approach presented in this article resides in the fact that it is more generalized. In this way, the model can calculate the impact of many different aircraft by just changing the inputs and losing very little confidence in the results if correctly calibrated for the aircraft category. In fact, the comparison with these detailed analyses conducted on individual aircraft showed that the proposed model was able to give results that fell within ±10% of the reference values.

This section is divided into three subsections; in this way, it is possible to compare results obtained through the method previously described with results reported in the state-of-the-art articles. While Rahn's study is quite detailed for every life phase, others are usually more focused on one single stage.

5.1. Comparison over the Entire Life

Comparing results previously explained with those found by Rahn's study, both calculated for the aircraft design proposed by CeRAS, it is possible to immediately notice that the impact of the end of life is positive in one case and negative in the other. The simple reason behind that is the approach used. In this work, it was decided to account for the environmental impact of aircraft disposal the same way as in every other phase. On the contrary, in the other paper, the base idea is that recycling components and materials gives an environmental discount due to the minor use of virgin material being much more impactful. Looking at the other phases, it is possible to see that numbers are quite similar, especially in the manufacturing stage where the difference is around 5% and where every component, from structure to systems, has been taken in account in both the analyses. Differences over the operative life derive from the fact that the typical mission considered is slightly different; in the analysis presented in this paper, an average route of around 960 km repeated for a life of 25 years has been considered, while in Rahn's work, even if life length is the same, the average route is around 1200 km. To overcome this issue, it is possible to compare results normalized per passenger per kilometer of flight (PKM). In this way, resultant values are quite similar, as shown in Table 6.

Table 6. Comparison over the entire life cycle.

Phase	Rahn et al. [15]	Δ
Manufacturing	1.40×10^6 kg CO_2 eq.	−5. 93%
Operations	7.34×10^8 kg CO_2 eq.	−3.29%
Operations (PKM)	164 g CO_2 eq.	−0.28%
Maintenance	7.89×10^5 kg CO_2 eq.	+2.25%
End of life	-7.07×10^5 kg CO_2 eq.	Non-comparable

In this analysis, both the EIs due to maintenance work and due to component substitution are included. In particular, using statistical data of A to D checks for the liner category, it has been possible to calculate their impact. A similar statistical approach has been used to decide substitution rates of components, e.g., it has been considered that tires need to be changed after every 250 landings. Due to the small difference between results, the approach used must have been quite similar to that adopted by Rahn's study.

5.2. Comparison of Manufacturing Stage

Howe's work has been chosen to compare the environmental impact of the production of the aircraft. The reason is that Howe's paper is very accurate regarding impacts derived from production; it also compares the environmental impact of structures consisting 100% of composites or 100% of aluminum. The only obstacle is the use of a different scale of impact indicators, but it can be overcome through a comparison with percentages. In fact, it is easier to compare the impact of every system divided by the impact of the whole aircraft, since it is independent from the scale used, than moving from one scale to the other. The weight of one subsystem EI for the whole aircraft production EI is indicated, as shown in Table 7.

Table 7. Howe production impacts comparison.

	Howe's Work	This Work
Wing	35.00%	31.01%
Fuselage	24.00%	23.58%
Engines	18.00%	24.47%
Tail	16.00%	10.14%
Landing gear	7.00%	3.85%

As can be immediately seen, results are quite similar, especially for the wing and the fuselage where there is a minor difference. The environmental impact on tails and landing gear would be even closer if Howe's study had considered the structure as also consisting of the nacelles and pylons, as is achieved by the proposed method. Nevertheless, the weight of these components in Howe's study was probably spread evenly over other subsystems.

5.3. Comparison of Operative Life

Neither of the last two studies of Lopes and Lewis are especially accurate from the point of view of manufacturing, since they consider only the structure and the engines. On the other side, from the point of view of the operative life, they are very reliable, providing an accurate study for different missions that can be completed. Moreover, Lewis considered three aircraft deriving from the Airbus family, the A320, A330 and A380. These are the reasons behind the choice of using their results as reference values. To overcome the problem of different routes, results are presented in Table 8 normalized per passenger per kilometer.

Table 8. Operative life impact normalized PKM.

This Work	Lopes's Work	Lewis's Work		
CeRAS design	**A330-200**	**A320**	**A330**	**A380**
163.5 g	126 g	164 g	103 g	118 g

In operative life environmental impact, the size of the aircraft, and the longer routes it can fly as a consequence, becomes more evident as an important factor. Moreover, the number of passengers increases from around 150 in an A320 to approximately 330 onboard an A330 and up to more than 800 in an A380. These two characteristics lead to the results showing that the A330 is usually more efficient from the point of view of environmental impact, always considering that the aircraft flies with a load factor of at least 80–85%.

6. Conclusions

The method presented and the model resulting from it have been derived from LCA methodologies merged with some parametric analysis concepts typical of the life cycle cost discipline. The methodology has been designed to have a broad generality, in order to be reliable for the evaluation of different aircraft categories and the possibility of analyzing each aircraft life phase and even aircraft with non-traditional architectures, which use innovative technologies. The proposed model is based on a database where most of aircraft components are modeled using the *Ecoinvent* datasets. Uncertainty about their environmental impact has been reduced by using data deriving from different sources and by using mean values where possible. Finally, the results from the CeRAS case study have been used to carry out a comparison with articles dealing with the same topic. All the comparisons made have shown how results deriving from the developed model are comparable to other literature works. This means that, even if not specifically calibrated to an individual aircraft or category, the model is capable of predicting the environmental impact of the product with reasonable precision, i.e., an uncertainty of ±20%, on the results, in accordance with the common uncertainty of data during the conceptual design phase. The presented model is generalized and accurate. If correctly implemented, it gives the possibility to analyze different architectures and designs, also including innovative technologies, in a simple and fast way. Having analyzed the positive aspects of the model, it is important to state that this is a preliminary work, which brings with it a few limitations. Furthermore, the method relies on a limited database, where components have been modeled in an essential way. Finally, not all the processes that occur during the life of the aircraft have been considered, both because their number is very high and also because it is often difficult to obtain reliable information. However, the intention of the authors is to expand the method to include more processes and obtain a database based on more reliable data, especially regarding innovative technologies whose environmental costs are now difficult to evaluate.

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Data Availability Statement: Two links are attached here. The first one is the URL to the CeRAS project, where all data about this architecture can be found. The second one is a GitHub repository where the EI database used to write this article has been made available by the authors to any reader who wishes to replicate the results. https://ceras.ilr.rwth-aachen.de/tiki/tiki-index.php?page=Welcome, accedded on 11 January 2024; https://github.com/pitoviv/Environmental-Impact-Database.git, accedded on 11 January 2024.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of Open Access Journals
EI	Environmental impact
ER	Environmental requirement
LCA	Life cycle assessment
SLCA	Streamlined life cycle assessment
EIO	Economic input–output
CS	Computational structure
CO_2	Carbon dioxide
LH_2	Liquid hydrogen
EOF	End of life
ECS	Environmental control system
TMS	Thermal management system
FCS	Flight control system
CeRAS	Central reference aircraft data system
PKM	Passengers per kilometer of flight

Appendix A

This appendix reports some EI constants. These are related to the case study, CeRAS, and they are expressed at both system and subsystem level in Table A1. Three impact categories are here reported: terrestrial acidification, ozone formation and global warming. This choice was made because they are of major importance, and their effect is visible both at a local level and at a global one. Formulas that use these constants to calculate the EI of every system and subsystem are very simple:

$$\text{system EI} = \text{system weight} \times \text{EI constant} \tag{A1}$$

$$\text{subsystem EI} = \text{subsystem weight} \times \text{EI constant} \tag{A2}$$

where the EI constant can equally be any of those belonging to the three impact categories. These values can be of use to practically verify all the findings presented in the previous section. Obviously, these constants give reliable results only when applied to aircraft belonging to the same category of that used as the case study or very similar to it, although both the method and the model previously explained have the possibility of being adapted to many categories of aircraft.

The possibility to use all the data achieved in the study to conduct further analysis is granted by the authors. The database used is publicly available in Appendix A. Moreover, every assumption made, chosen material, the production process and their combination can be found in [19]. The same document describes the long modeling process that led to the construction of the dataset and how the environmental impact of each component found in an aircraft has been calculated.

Table A1. Parametric constants.

	Terrestrial Acidification (kg SO_2 eq)	**Ozone Formation (kg NO_x eq)**	**Global Warming (kg CO_2 eq)**
Wing	1.7×10^{-1}	1.0×10^{-1}	4.0×10^{1}
Fuselage	1.4×10^{-1}	7.1×10^{-2}	2.7×10^{1}
Tail	3.3×10^{-1}	1.8×10^{-1}	8.7×10^{1}
Landing gear	5.3×10^{-2}	4.0×10^{-2}	1.6×10^{1}
Nacelle	2.4×10^{-1}	1.3×10^{-1}	5.8×10^{1}
Equipped engines	6.4×10^{-1}	9.6×10^{-2}	3.4×10^{1}
Fuel system	5.0×10^{-2}	2.5×10^{-2}	7.0×10^{0}
Hydr. generation	5.4×10^{-2}	1.5×10^{-2}	4.2×10^{0}
Hydr. distribution	9.9×10^{-3}	6.5×10^{-3}	2.6×10^{0}
ECS	5.8×10^{-2}	2.6×10^{-2}	7.5×10^{0}
De-icing system	6.5×10^{-3}	3.7×10^{-3}	1.5×10^{0}
FCS	1.4×10^{-2}	9.4×10^{-3}	3.9×10^{0}
Avionic Instruments	7.7×10^{-1}	5.1×10^{-1}	1.5×10^{2}
Elec. generation	9.4×10^{-1}	1.9×10^{-1}	4.0×10^{1}
Elec. common inst.	8.8×10^{-2}	4.9×10^{-2}	2.1×10^{1}
Structure	1.5×10^{-1}	8.9×10^{-2}	3.5×10^{1}
Power Plant	6.2×10^{-1}	9.4×10^{-2}	3.3×10^{1}
Systems	3.4×10^{-1}	1.5×10^{-1}	4.4×10^{1}
Furnishing	1.2×10^{-2}	7.6×10^{-3}	4.9×10^{0}

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