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Aerospace Engineering

Aircraft Life Cycle Assessment: the implementation of a tool and three case studies

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Index

Chapter 1

Prologue

Over the last two decades environmental issues have become more and more present into the public discussion as first effects of scientist predicted climate change have come to evidence. Thereby, it is now ascertained that the impact of human life over the nature needs to be limited and reduced in order to let future generations enjoy the planet and its marvels. This thesis will focus over the impact produced by the transportation sector, in particular by the aviation sector. Reducing global transport greenhouse gas emissions will be challenging since the continuing growth in passenger and freight activity could outweigh all mitigation measures unless transport emissions can be strongly decoupled from GDP growth. In facts, the transport sector produced 7.0 GtCO2eq of direct GHG emissions, including non-CO2 gases, in 2010 and hence was responsible for approximately 23% of total energy-related CO2 emissions [51] . Into the transportation sector, air transport account for around 2% of the 42 billion tonnes of CO2 generated by human activities every year. Aviation has managed to limit its emissions growth despite passenger numbers increasing at an average of 5% each year and has made it through massive investment in new technologies and coordinated action to implement new operating procedures and infrastructural measures. In order to help the effort of aviation industry to reach a sustainable development, many researches have been made and some eco-design tools are now under study.

Work made across this thesis is placed into this sphere. In facts, the main scope for which it was born is to provide an useful environmental impact assessment tool that can be used by designers to quickly make comparisons between different project solutions in order to evaluate the optimum also having the possibility to use the environmental impact as a decision variable. To be more clear, it should be used the same way as design-to-cost tool are currently used. During the process, the name *ALiCIA*, which stands for Aircraft Life Cycle Impact Assessment, has been given to the tool and, so, this name will sometimes used to refer to it through the paper. The life-cycle of an aircraft can be divided into four main phases:

- `Design and development`;
- `Production`;
- `Operations`;
- `End of life`.

These phases have completely different environmental impacts, as will be shown into 6, but it is clear even thinking it logically, because the `Operations phase`, that may last around two decades, is surely the main contributor. However, early product development phases are decisive to determine the overall environmental impacts of an aircraft during its life cycle since it is during these phases that most important decisions are taken, in particular over propulsion system and structure materials. Thereby, in order to reduce overall environmental impacts, designers and engineers must be able to assess the consequences of their design choices.

Implementing such a tool has not been easy, as can be imagined, and in particular it has been of fundamental importance the process of finding studies and articles that could provide the necessary basis for all the hypothesis made and, secondly, it has been possible to build and test the tool thanks to data coming from two well-established regional aircraft, the *ATR42* and *ATR72*, whose analysis has served as input but also as comparison with results obtained.

1.1 Thesis breakdown

- 2: State-of-the-art revision of Life Cycle Assessment methods;
- 3: Analysis of impact categories characteristics and choice of the suitable ones;
- 4: Life phases materials and production processes inventory;
- 5: *Ecoinvent* processes chosen;
- 6: Studies over existing aircraft and a parametric analysis over electrification;
- 7: Two additional aircraft have been analyzed for further observations over innovative configurations;
- 8: User Manual: how to properly use ALiCIA.

Chapter 2

Life Cycle Assessment Methods

The concept of life cycle assessment is to evaluate the environmental effects associated with any given activity from the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth. This concept is often referred to as "cradle to grave" assessment. Usually, as clearly explained into B.W. Vigon et al. work [61], a life cycle assessment is performed through four phases that include:

- The scoping and goal definition or initiation step, which serves to tailor the analysis to its intended use, here referred as **scope definition**;
- The identification and quantification of energy and resource use and environmental releases to air, water, and land. This phase is called **inventory analysis**;
- The technical qualitative and quantitative characterization and assessment of the consequences on the environment, which is properly called the **impact analysis**;
- The evaluation and implementation of opportunities to reduce environmental burdens, often referred as the **improvement analysis**.

However, life cycle assessment is not necessarily a linear or step-wise process. Rather, information from any of the four phases can complement information from the other three. Environmental benefits can be realized from each component in the process. For example, the inventory analysis alone may be used to identify opportunities for reducing emissions, energy consumption, and material use. To easily understand the idea at the base of each phase, it is necessary to explain which activities they includes with a few more words. Inventory analysis will be treated as last because it is the central phase of the assessment and requires a more extended explanation.

2.1 LCA phases

- **Scope definition**: During scoping, the product, process, or activity is defined for the context in which the assessment is being made. The scoping process links the goal of the analysis with the extent, or scope, of the study clearly stating what will or will not be included and so setting the boundaries of the analysis;
- **Impact analysis**: The impact analysis component is a technical, quantitative, and/or qualitative process to characterize and assess the effects of the resource requirements and environmental loading identified in the inventory stage. Fundamentally, it seeks to establish a linkage between the product or process life cycle and potential

impacts. There are different methods to perform this analysis, some assessing emissions over different categories of impact, for example it is possible to study only the consumption of energy due to the product life cycle instead of the pollutants emissions, while other methods differ on the way they sum emissions. In facts, sometimes more than a pollutant can contribute to the same effect, e.g. not only CO2 emissions lead to greenhouse effect but also other gases as CO or CH4. In order to sum all the emissions that have the same effect, these need to be normalized. Weights given to each pollutant varies from method to method as so it is important to clearly state which impact analysis method has been used.

- **Improvement analysis**: The improvement analysis component of the life-cycle assessment is a systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw material use and waste emissions throughout the life cycle of a product, process, or activity.
- **Inventory analysis**: the inventory analysis, often called LCI that stands for Life Cycle Inventory, involves, by definition, the "compilation and quantification of inputs and outputs for a product throughout its life cycle" [31]. 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, CO2, as a result of the combustion process inside the engine. Different methods to perform this analysis have been implemented during the past years. The two main are the process analysis based and the input-output based, also referred as IO-LCI.

2.2 Process analysis based life cycle inventory

LCI compilation using a process flow diagram appears from early LCA literature, including Fava et al., Vigonn et al. and Consoli et al. [20][61][10]. Process flow diagrams show how sub-systems and processes of a product system are interconnected through commodity flows. Each process is represented by a number of inputs and outputs where the output of a process may be the input of another one, in this way is possible to model the entire production process as a linear flow of material and energy through various chained steps and, summing all the steps impacts, one can obtain the whole production process impact. Using plain algebra, the amount of commodities fulfilling a certain functional unit is obtained, and by multiplying the amount of environmental interventions generated to produce them, the LCI of the product system is calculated. However, computing LCI directly from a process flow diagram is not as easy as presented if following conditions are not met:

- Each production process produces only one material or energy;
- Each waste treatment process receives only one type of waste;
- The product system under study delivers inputs to, or receives outputs from another product system;
- Material or energy flows between processes do not have loops;

The first two conditions are related to the multi-functionality problem and to overcome them the solution adopted is to allocate emissions, i.e. if a process produces more than one product its impact is subdivided over the products using different scaling factors. Sometimes weights for allocation can derive from the mass of various products or from their economic value. The last condition requires that all processes in the product system under study do not utilize their own output indirectly, which means that the input in a process needs the output of the process to be produced. The problem can be solved both using an iterative method and through infinite algebra progression. An example of what it is meant for loops could be the production process of steel, where the blast furnace that produces the steel had required steel for its production, causing an abstract loop.

Using a similitude, this method is the counterpart of the engineering bottom-up method used into the cost analysis. Fundamentally, it requires to perfectly know every step of the product production process and all inputs and outputs. This is a great limitation and usually leads to the problem of truncation, where there is the risk that some information goes missing. Moreover, its boundaries are strictly connected to the level of knowledge that is possible to acquire over each process and so there could be high fidelity modeled steps while others very rough.

Nevertheless, if data are easily available, and there is enough time to model every process with the due depth, this method permits to achieve the best results over each life phase, conducting an appropriate analysis that lets the reader to develop a deep knowledge over the product, perfectly identifying criticalities.

2.3 Input-Output based life cycle assessment

In principle, all processes in an economy are directly or indirectly connected with each other. In that sense, process analysis based LCI is always truncated to a certain degree, since it is practically not viable to collect process-specific data for the whole economy, and this problem has led the use of input-output assessment, IOA, in LCI. In the original work by Leontief [34], the input-output table describes how industries are inter-related though producing and consuming intermediate industry outputs that are represented by monetary transaction flows between industries. The input-output model assumes that each industry consumes outputs of various other industries in fixed ratios in order to produce its own unique and distinct output. Environmental extensions of IO analysis can easily be made by assuming that the amount of environmental intervention generated by an industry is proportional to the amount of output of the industry and the identity of the environmental interventions and the ratio between them are fixed. Nonetheless, the biggest practical obstacle in applying IOA to LCI is the lack of applicable sectoral environmental data in most countries. Although there are some fragmentary emission inventory databases available, differences in the level of detail, base year and industry classification make it difficult to construct well-balanced sectoral environmental data in most countries, also keeping in mind that databases can be build only over industries that work in the same sector and in the same country because otherwise data cannot be compared.

The great advantage of IO-based LCI is that it can provide information on the environmental aspects of a commodity on the basis of a reasonably complete system boundary using less resources and time. However, although this possibility, IO method has some great limitations due to the fact of using economic inputs, the first and most obvious one being that the Market has reasons that reason does not understand, to paraphrase *Blaise Pascal*. That means that sometimes the value of a commodity is determined by factors external to the simple sum of pieces and work to create it, leaving apart the profit, and that can be due to events that happen around the world without any possibility to control them, e.g. wars or cataclysms. As a consequence, the economic value and the impact of a good are not always as connected as it should be for the IO analysis in order to be accurate enough. Moreover, it should be clearly noted that:

- The IO assessment method itself can provide LCIs only for pre-consumer stages of the product life cycle [53], while the rest of the product life cycle stages are outside the system boundary;

- The amount of imported commodities by the product system under study should be negligible otherwise errors due to truncation or miss specification of imports may well be more significant than that due to cut-off in process-based LCI;

- Data of IO-based LCI is normally older than process-based one, since it takes 1 to 5 years to publish IO tables based on industry survey.

2.4 Allocation

Most industrial processes generate multiple output streams in addition to waste streams. Usually, only certain of these output streams are of interest with respect to the primary product being evaluated. The term co-product is used to define all these output streams other than the primary product that are not waste streams and that are not used as raw materials elsewhere in the system examined in the inventory, e.g. fatty acids production from tallow for soap manufacture generates glycerine, a valuable secondary stream. When trying to assess this type of processes, the question of allocation arises. In facts, it is usually really difficult to subdivide the impact of the whole process over the multiple products and it requires to investigate every step at a very detailed level because each industrial system must be handled on a case-by-case basis. The most widely proposed and used method is to divide the impact on a mass basis. In this case, the co-products are considered of the same importance and so the only difference is on how much input flows into one or the other. This could be the case when a certain amount of wood is needed to produce several paper products and the analysis concerns only one of the products, a mass allocation scheme is the best solution. However, the case could be different and co-products could have a different value or even could not be compared through mass, e.g. a fuel cell produces contemporary electricity and water. To find a solution for these processes, it has been suggested that the selling price of the co-products could be used as a basis for this allocation. The great stumbling block for which this is not entirely satisfactory it is because the selling prices of the various co-products vary greatly with time and with independent competitive markets for each co-product. At the end, a mass allocation basis may not be ideal but it is a widely recognized practice and produces a predictable and stable result and so its the one used into the following work.

2.5 Hybrid methods

As it can be seen, both the process-based and input-output assessments have some criticality and the linear application of one of the two methods could lead to infinite problems, some of them being not surmountable. That is the sparkle that has permitted the creation of various hybrid methods whose basis are always IO and process flow principles but that try to overcome every limitation. Some of the methods mainly used are:

- `Tiered method`, that in essence is an hybrid analysis that combines input-output and process data within a process analysis framework to reduce the truncation error of a pure process analysis. Scenarios of application range from studies exclusively using input-output data except for the use and end-of-life phases, to studies which use input-output data strictly for those inputs to the system for which no process data is available;

- `Integrated hybrid`, first proposed in the early 2000s by S. Suh et al. [26] [54] [53], here process data is represented as a technology matrix and then connected to the input-output table. Thus, it attempts to solve the analysis strictly via matrix computations. The connections between the process and input-output matrices are vectors of inputs and outputs;

- `Toolbox approach`, that makes use of a toolbox for solving the same problem, it leads to the fact that different aspects of a given problem are approached using different tools. This means that the various tools are complementary to one another, and possibly overlapping, and that their results are fully separate. An example is the combined use of LCA with LCC, life cycle cost analysis, and in this case the scope is to support the same policy or business decision [25].

2.6 ISO compliance

The ISO standards that treat how an LCA analysis should be done are ISO 14040 and ISO 14044, that generally define the framework without specifying which computation method is to be used [30][31]. However, according to ISO, LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle which means that the IO assessment, that can perform only what is so-called cradle-to-gate analysis, is not an LCA study in strict sense of ISO standards. Therefore, only process-based LCI computation methods are considered to be fully compatible with ISO standards. In general sense, this implies that IO-based inventory alone is not considered as ISO compatible LCI but, if combined with inventory result from other stages of life cycle, as is the case for hybrid methods, the scope of the analysis is fully in line with the ISO standard. Another issue where non-compliance might occur is in allocation. However, in ISO 14041, a range of options is given, including mass and selling price based, with a requirement on transparency and on application of several methods if more of them apply.

2.7 Methods used into this thesis

After creating a solid understanding of the state-of-art, the thesis has been started developing basing on two ideas:

- The duality between process-based and IO assessments is highly compatible with the first phases of design process, i.e. conceptual design and preliminary design. In facts, during the conceptual phase data known are little and attained to high level requirements, thereby it would be impossible to assess the impact through the process-based LCI while it perfectly fits the IO method. A reverse reasoning can be done talking about preliminary design, where system boundaries are more defined;

- The scope of the work is not to assess the impact of the life of a single aircraft, whose data are perfectly known and whose production process can be divided into many different steps having enough data to model every input and output, but it aims to the creation of a framework that have a general validity and that can be used during the development to compare different possible solutions in order to find the best design under the point of view of sustainability.

The results of these ideas is that the method used for the life cycle assessment could be called a `streamlined LCA`, a slimmed down version of a full LCA, much similar to an integrated hybrid or a toolbox approach. Making a comparison with LCC analysis, an assessment during the design phase of the product is highly recommended as it can reveal a large percentage of the main environmental issues in a fraction of time of a full LCA since the main part of environmental impact, and in the same way of cost, is determined at design. A streamlined LCA gives the opportunity to eliminate stages that cannot be changed by developers, e.g. all phases that contribute to what are usually called "Indirect Expenses", to value only selected pollutants emissions, to use surrogate data and assumptions over inventory and, at last, to eliminate the improvement analysis leaving at the design team to make the due considerations if the project is worth or not. Another factor that contributes in making the analysis even more stream like is the possibility given by the implemented tool to do a conceptual assessment in a first time using the IO method and a statistical study over already existing aircraft and then, when more data are available, to make a preliminary analysis, in this way directly following the development flow. Last requirement was to make a framework capable of including new technologies, e.g hybrid electric propulsion, with the scope of comparing traditional and advanced design solutions. The fulfilling of this requirement needs to make assumptions and model new technologies basing primarily on scientific papers and thus not having direct production databases. Thereby, it would be incompatible both with a full process-based or input-output LCI. This, however, is just an introduction to the method used into the thesis, whom will be extensively explained into following chapters.

Chapter 3

Impact categories of life cycle impact assessment

Into the previous chapter, the different phases of life cycle assessment have been explained into details. After the life cycle inventory, that is the most crucial one and the one that, if poorly conducted, can take down every little brick on which the analysis was build, the life cycle impact assessment is fundamental to translate every resource use into an impact. Effects considered in a LCIA include many impact categories such as climate change, ozone depletion, eutrophication, acidification, human toxicity, cancer and non-cancer related, respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. Emissions and resources are assigned to each of these impact categories and then are converted into indicators using impact assessment models.

According to ISO 14044 [31], Life Cycle Impact Assessment, LCIA, proceeds through two mandatory and two optional steps:

- `Selection of impact categories and classification`, where the categories of environmental impacts, which are of relevance to the study, are defined by their impact pathway and impact indicator, and the elementary flows from the inventory are assigned to the impact categories according to the substances ability to contribute to different environmental problems;

- `Characterization`, where the impact from each emission is modeled quantitatively according to the underlying environmental mechanism. The impact is expressed as an impact score in a unit common to all contributions within the impact category, e.g. kg CO2 equivalents for greenhouse gases contributing to the impact category climate change, by the applying of characterization factors. A characterization factor is a substance-specific factor calculated with a characterization model for expressing the impact from the particular elementary flow in terms of the common unit of the category indicator;

- `Normalization`, where the different characterized impact scores are related to a common reference, e.g. the impacts caused by one person during one year, in order to facilitate comparisons across impact categories;

- `Weighting`, where a ranking and/or weighting is performed of the different environmental impact categories reflecting the relative importance of the impacts considered in the study. Weighting may be needed when trade-off situations occur in LCAs used for comparisons.

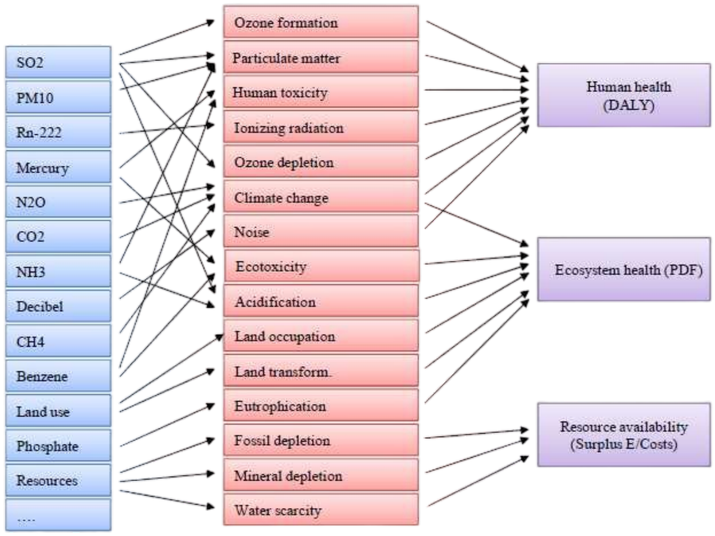


Figura 3.1: ReCiPe method path from emissions to endpoints

Obviously, this work, as many others before, has focused only over the first two mandatory phases, which have an obligation to be objective, leaving apart the normalization and weighting ones because they are of little interest.

Many impact assessment methodologies have been evolved into the last two decades, each of them different from the other by the impact categories chosen and the characterization factor used to convert emissions into impact scores of the desired impact categories. Summarizing each of them in a few lines could be very difficult and can have the effect of doing injustice to the amount of detail the method developers put in and what was taken into account during the development. Thereby, only the methodology chosen, that is ReCiPe, will be explained in a more detailed way.

3.1 ReCiPe

ReCiPe is one of the most recent and updated impact assessment methods available to LCA practitioners [18] [24]. The method addresses a number of environmental concerns at the midpoint level, with the use of 18 indicators, and then aggregates the midpoints into a set of three endpoint categories. In this way, LCA professionals can choose impact indicators at different stages in the cause-effect pathway. The relation between midpoint impact categories and their area of projection is shown in 3.1. Following the scheme, it can be seen that, for example, global warming is a midpoint category derived from the emissions of more than one pollutant, which through scientifically proven pathways has impact on human health and ecosystems, endpoint. The difference between midpoints and endpoints lies in the fact that while midpoint methods measure an effect before the damage to one of the areas of protection occurred, endpoint methods follow the consequences of certain emission until it causes damage. Midpoint methods, therefore, have relatively low uncertainty but the results tend to be harder to interpret given the number and complexity of included categories. On the other hand, the additional steps required to convert mid- to endpoint impacts introduce additional uncertainty but make the outcomes more accessible to non-experts. Furthermore, endpoint results can be aggregated, so that a single score expresses all the impacts given product has on environment. That requires normalization and weighting steps, which again increase the uncertainty and, through weighting, introduce subjective choices. All said, into the thesis the choice has been of working only with midpoints indicators in order to avoid all the possible complications attached with subjectiveness.

ReCiPe midpoints can be evaluated through three macro types, called perspectives, of characterization factors: Individualist, Hierarchist, Egalitarian. They differ over the time horizon taken into consideration and over the future socioeconomic development prospectives, since the individualistic perspective is based on the short-term interest, 20 years, and on technological optimism with regard to human adaptation, the hierarchist perspective is based on scientific consensus with regard to the time frame, 100 years, and plausibility of impact mechanisms and the egalitarian perspective is the most precautionary perspective, taking into account the longest time frame, more than 1000 years, and all impact pathways for which data is available. Into these scenarios assumptions over impact categories were grouped according to the "Cultural Theory" [57]. The choice has been to use the hierarchist scenario to be as scientific and objective as possible. Impact categories taken into account are the ones into the following figure 3.1.

Impact category	**CFm**	**Abbreviation**	**Unit**
climate change	global warming potential	GWP	kg CO2 eq to air
ozone depletion	ozone depletion potential	ODP	kg CFC-11 eq to air
ionizing radiation	ionizing radiation potential	IRP	kBq Co-60 eq to air
fine particulate matter formation	particulate matter formation potential	PMFP	kg PM2.5 eq to air
photochemical oxidant formation: ecosystem quality	photochemical oxidant formation potential: ecosystems	EOFP	kg NOx eq to air
photochemical oxidant formation: human health	photochemical oxidant formation potential: humans	HOFP	kg NOx eq to air
terrestrial acidification	terrestrial acidification potential	TAP	kg SO2 eq to air
freshwater eutrophication	freshwater eutrophication potential	FEB	kg P eq to fresh water
marine eutrophication	marine eutrophication potential	MEP	kg N eq to marine water
human toxicity: cancer	human toxicity potential	HTPc	kg 1,4-DCB eq to urban air
human toxicity: non-cancer	human toxicity potential	HTPnc	kg 1,4-DCB eq to urban air
terrestrial ecotoxicity	terrestrial ecotoxicity potential	TETP	kg 1,4-DCB eq to industrial soil
freshwater ecotoxicity	freshwater ecotoxicity potential	FETP	kg 1,4-DCB eq to fresh water

Impact category	**CFm**	**Abbreviation**	**Unit**
marine ecotoxicity	marine ecotoxicity potential	METP	kg 1,4-DCB eq to marine water
land use	agricultural land occupation potential	LOP	M2 * yr annual crop land
water use	water consumption potential	WCP	m3 water consumed
mineral resource scarcity	surplus ore potential	SOP	kg CU eq
fossil resource scarcity	fossil fuel potential	FFP	kg oil eq

Table 3.1: Impact categories

All of them are very important but, as previously said, it is usually quite difficult to understand the real effect they have over environment and human life. Moreover, not having some reference values, it is quite impossible to comprehend if an absolute value is relatively high or not. To solve these problems for some of the impact categories, which are of major importance, a little explanation is necessary into the following. Information is taken from [19]. Pollutants can be divided into some that have a global effect, such as those that cause climate change, for whom the region of emission is not so important, and other that instead have in prevalence an effect that will be localized into the area they are emitted, such as those provoking photochemical smog. However it requires an high level of detail to know where every process is done and to subdivide emissions into areas where they emitted. The conclusive advice is to consider in prevalence impacts that have a global effect and to base all design consideration upon these, even if all impact categories will be given into results of analysis.

3.2 Stratospheric ozone depletion

A number of persistent gaseous compounds released to the air may produce a growth of chlorine and bromine concentrations in the stratosphere, causing a reduction of the stratospheric ozone concentrations, with a time lag of many years. This reduction of stratospheric ozone is unequally distributed over the globe, with a tendency to be less important in equatorial regions and more important in polar regions and mid-latitudes. The consequence is an increase of solar radiation, particularly UVB, on earth's surface. Increased UVB radiation over long periods, years or decades, is known to have a detrimental influence on human health. The path followed is: after the emission of an ozone depleting substance, ODS, the tropospheric concentrations of all ODSs increase and, after a time, the stratospheric concentration of ODS also increases. This increase in ozone depleting potential leads to a decrease in the atmospheric ozone concentration, which in turn causes a larger portion of the UVB radiation to hit the earth. This increased radiation negatively affects human health, thus increasing the incidence of skin cancer and cataracts.

3.3 Climate change

Greenhouse gases have many types of impact: temperature rise, changes in precipitation, sea level rise, change of ocean currents, storms, hurricanes, and possibly others eventually leading to impacts on human health and on biotic natural resources. In this case the chain of events that take place is: the emission of a greenhouse gas will lead to an increased atmospheric concentration of greenhouse gases which, in turn, will increase the radiative forcing capacity, leading to an increase in the global mean temperature. Increased temperature ultimately results in damage to human health and ecosystems. The hierarchist perspective models effects due to greenhouse gases for a time horizon of 100 years and includes also climate-carbon feedbacks for non-CO2 greenhouse gases. Characterization factor at midpoint level are in this case of much importance and so are here reported for principal pollutants as written in [24]. If characterization factors for other pollutants are needed the reference is the table from page 29 to page 35 of the paper mentioned.

Pollutant name	Formula	Characterization factor H
Carbon dioxide	CO2	1
Methane	CH4	34
Fossil methane	CH4	36
Nitrous oxide	N20	298

Table 3.2: Characterization factors

3.4 Photochemical ozone formation

Photochemical smog is caused by the release of both natural and man-made substances into the atmosphere, and their reaction in the presence of sunlight. The most highly studied portion of photochemical smog is the creation of ground-level or tropospheric ozone from the interactions of volatile organic substances, or VOCs, and oxides of nitrogen. Ozone is a toxic gas which has been shown to cause respiratory distress in people and other mammals, as well as causing reductions in the primary production rates of aquatic and terrestrial plants. Ozone acts through the creation of free radicals, which are implicated in carcinogenesis as well as in the destruction of cellular membranes. Additionally, ozone can have a negative impact on vegetation, including a reduction of growth and seed production, an acceleration of leaf senescence and a reduced ability to withstand stressors. This formation process is more intense in summer. For damage due to ozone, the time horizon is not important as only short-living substances are involved and its impact is localized only into the region of emission.

3.5 Terrestrial acidification

Atmospheric deposition of inorganic substances, such as sulphates, nitrogen oxides and phosphates, causes a change in acidity in the soil. For almost all plant species, there is a clearly defined optimum level of acidity. A serious deviation from this optimum level is harmful for that specific kind of species and is referred to as acidification. The type of deposition can be divided into wet-type and dry-type. These depositions may cause undesirable effects on terrestrial and aquatic ecosystem, man-made resources and even human health. Substances generating these acids are sulfur compounds, e.g. SO2, H2S, DMS, nitrogen compounds, e.g. NO, NO2, ammonia, chlorine, hydrogen chloride. Main acidifying substances are sulfuric acid and nitric acid. Hydrogen chloride and organic acids also contribute to acidification occasionally. The path followed into modeling this impact is: the emission of NOx, NH3 or SO2 is followed by atmospheric fate before it is deposited on the soil. Subsequently, it will leach into the soil, changing the soil solution

H+ concentration. This change in acidity can affect the plant species living in the soil, causing them to disappear. As can be understand by the explanation, also this type of impact is strictly related to the region of emission of pollutants and so it is difficult to relate all the gases emitted during the whole life cycle of the aircraft to the area they are emitted so the advice is to use this output as a more abstract indicator.

3.6 Example of impact: production process of a car

This paragraph has the function of showing an example to ease the comprehension of what are the usual values for each impact category. In this case, the example is the comparison into the production of one kilogram of diesel car and electric car.

Impact category	Diesel car (1kg)	Electric car (1kg)
Global warming (kg CO2 eq)	7,09E+00	7,56E+00
Stratospheric ozone depletion (kg CFC11 eq)	3,08E-06	3,38E-06
Ionizing radiation (kBq Co-60 eq)	3,79E-01	4,52E-01
Fine particulate matter formation (kg PM2.5 eq)	1,58E-02	1,71E-02
Ozone formation, Terrestrial ecosystems (kg NOx eq)	2,04E-02	2,10E-02
Ozone formation, Human health (kg NOx eq)	1,92E-02	1,97E-02
Terrestrial acidification (kg SO2 eq)	3,33E-02	3,43E-02
Freshwater eutrophication (kg P eq)	3,42E-03	4,86E-03
Marine eutrophication (kg N eq)	4,78E-04	1,02E-03
Human carcinogenic toxicity (kg 1,4-DCB)	2,52E+00	2,80E+00
Human non-carcinogenic toxicity (kg 1,4-DCB)	2,23E+01	3,40E+01
Terrestrial ecotoxicity (kg 1,4-DCB)	5,51E+01	1,15E+02
Freshwater ecotoxicity (kg 1,4-DCB)	2,53E+00	2,90E+00
Marine ecotoxicity (kg 1,4-DCB)	3,17E+00	3,72E+00
Land use (m2a crop eq)	9,28E-02	8,89E-02
Water consumption (m3)	6,86E-02	7,36E-02
Mineral resource scarcity (kg Cu eq)	1,63E-01	2,22E-01
Fossil resource scarcity (kg oil eq)	1,79E+00	1,88E+00

Table 3.3: Example of impact

Chapter 4

Life Cycle Assessment

The main idea at the base of this thesis is to build a user-friendly tool to help designers considering environmental issues during designing process, as it is nowadays done with many others parameters, in order to propose an architecture that is a right compromise between all important characteristics. To achieve this result, the first phase, after studying the state of the art of life cycle assessment, has been putting into practice all the knowledge obtained. Hereafter, it is shown the assessment made to analyze the life cycles of an aircraft. The procedure applied, that includes all the passages needed into every LCA, has been the following:

1. Definition of the scope and objectives of the analysis, clearly setting boundaries to the system taken into consideration and defining the whole life of an aircraft as functional unit;

2. Compilation of the life cycle inventory, deciding which processes should be used to account for every component production and for the aircraft operations and maintenance, with associated hypothesis;

3. Impact assessment of emissions, divided between life phase, finding most important impact categories;

4. Application of assessment procedures over the cases study, research for eventual errors and misleading hypothesis;

5. Update of life cycle inventory and impact assessment in light of the newly acquired knowledge;

6. Application of the analysis made over cases study to create the tool and debug it.

Phases from one to five have been repeated until an acceptable degree of confidence over the study was reached.

4.1 Scope, objective and boundaries

The **scope** of this analysis should be already well understood but it will be here stated into one only phrase: The analysis of three cases study, both traditional and hybrid aircraft, through the application of life cycle assessment methods, in order to create a design tool that allows designer to use environmental issues as requirements during development.

The **functional unit** chosen is one aircraft entire life cycle. However, this unit has been divided into many others to simplify the work allowing to treat every phase separated from the others. In this way, functional subunits have been: one aircraft production, one aircraft operation, one aircraft maintenance and one aircraft disposal.

Methods used are two, the Economic Input Output LCA, used to create a database from the statistical analysis of aircraft already on the market and their production emissions, and the Process Based LCA, used to create the tool. During the studying of the state of the art, it was noticed a great resemblance between life cycle cost and life cycle assessment and so it was decided to use the first assessment method as a way to analyze the conceptual design of an aircraft, while the second method is more useful during the preliminary design, when more specific information is known and aircraft systems are more detailed. The practical use of these two methods is clearly explained into the following paragraphs.

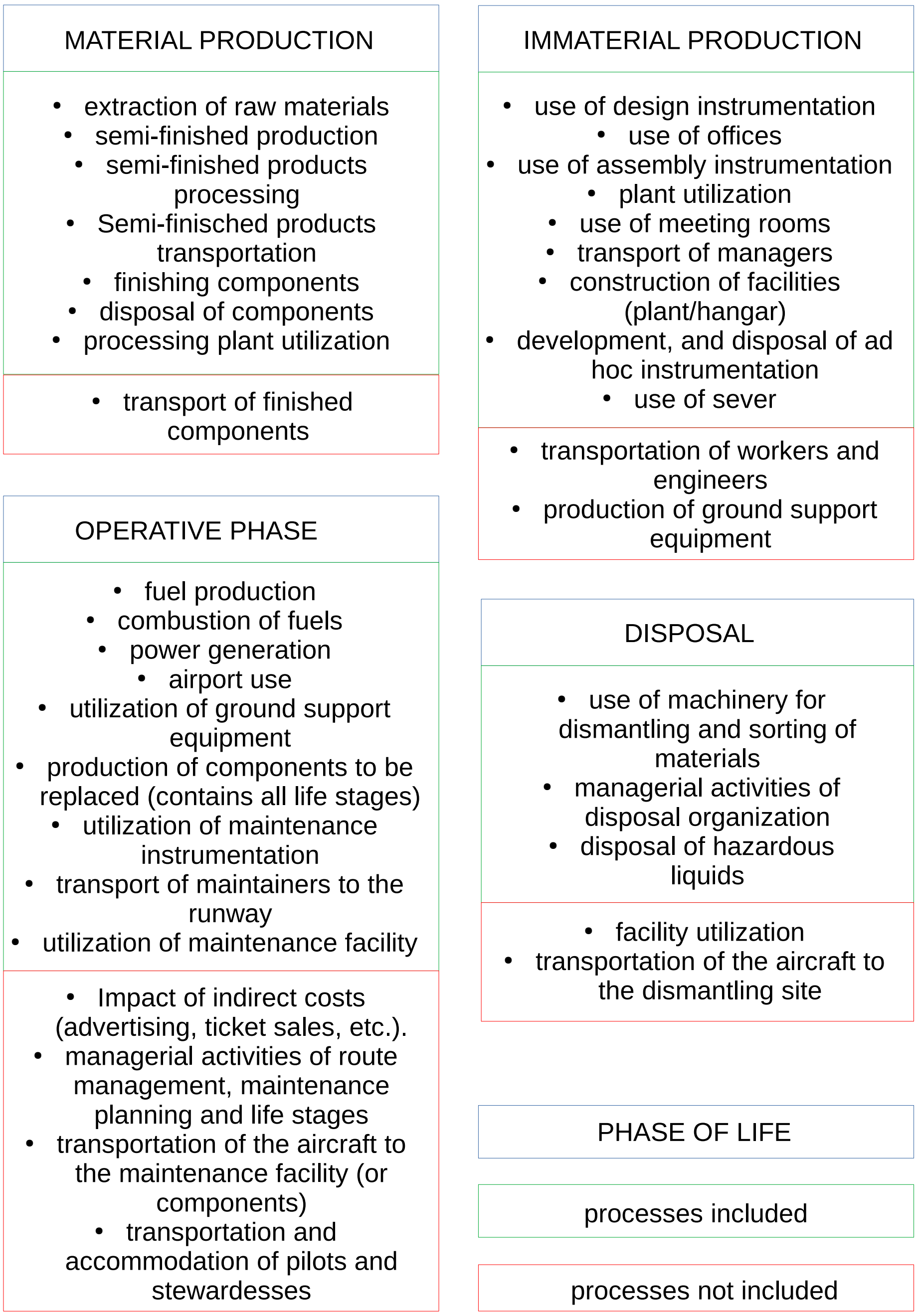
The entirety of **data used** are secondary data, which means that they are not directly collected into production sites but rather comes from databases, literature or patents. For this work the most important source of information has been *Ecoinvent v.3.8 database*, created by the *Ecoinvent Association* which is a not-for-profit organization dedicated to promoting and supporting the availability of environmental data worldwide. It is a Life Cycle Inventory database that supports various types of sustainability assessments covering more than 18’000 reliable life cycle inventory datasets, over a wide range of sectors. Datasets are provided as individual unit process data and comprehensive documentation for all aspects of the database is available. For more information [17] or to explore data quality guidelines [16]. Sometimes it has happened that no documentation could be find about some specific materials or processes or elaborate components. In these cases, information has been searched into some articles or studies that have deepen the life cycle assessment of these products. Where the process of searching into literature or patents for information has been followed, it has been clearly stated and works have been duly cited.

The **critical revision** of the work has been done by making a comparison with some others thesis that had the same scope. Data where compared at the end of ATR42 case study, taking into consideration that aircraft analyzed where different and that results needed to be scaled using some hypothesis accordingly.

System boundaries. As can be seen from figure 4.1, in order to achieve the objective, all life cycle phases have been taken into account and for each of them it has been considered to reach the highest possible degree of characterization. However, it is obviously impossible to account for every process, and the limitation is not so much a function of whether it is more or less impactful as it is a function of whether it is feasible to have reliable data about it and whether it is a general enough process that it can be modeled avoiding losing truthfulness. Thereby, processes excluded from the system boundaries are that, such as transportation of workers and engineer to the factory, that even if they have a relevant impact, are impossible to model in a general or average way. Another category of emissions that have been excluded are the ones that come from processes of the operative life of the aircraft and are not directly related to missions or maintenance, e.g. managerial activities of route management emissions. It has been thought that these kind of impact is difficult to account and at the same time negligible from the point of view of the thesis scope.

4.2 Economic Input-Output LCA

As a river flows to the ocean by many ways, in this paragraph it will be presented one of the attempts made to reach the scope of the thesis, which was the first one made thanks to its relatively simple approach. Nevertheless, it has been a great source of information that has been useful for the second, and more detailed, approach. It has been explained



MATERIAL PRODUCTION

- extraction of raw materials
- semi-finished production
- semi-finished products processing
- Semi-finisched products transportation
- finishing components
- disposal of components
- processing plant utilization

- transport of finished components

OPERATIVE PHASE

- fuel production
- combustion of fuels
- power generation
- airport use
- utilization of ground support equipment
- production of components to be replaced (contains all life stages)
- utilization of maintenance instrumentation
- transport of maintainers to the runway
- utilization of maintenance facility

- Impact of indirect costs (advertising, ticket sales, etc.).
- managerial activities of route management, maintenance planning and life stages
- transportation of the aircraft to the maintenance facility (or components)
- transportation and accommodation of pilots and stewardesses

IMMATERIAL PRODUCTION

- use of design instrumentation
- use of offices
- use of assembly instrumentation
- plant utilization
- use of meeting rooms
- transport of managers
- construction of facilities (plant/hangar)
- development, and disposal of ad hoc instrumentation
- use of sever

- transportation of workers and engineers
- production of ground support equipment

DISPOSAL

- use of machinery for dismantling and sorting of materials
- managerial activities of disposal organization
- disposal of hazardous liquids

- facility utilization
- transportation of the aircraft to the dismantling site

🟦 PHASE OF LIFE

🟩 processes included

🟥 processes not included

Figura 4.1: System boundaries

into the state-of-the-art description that EIO approach is based upon the economic value generated into the production of a good, in this case an aircraft, and it aims in correlating this value to the pollutants emitted in generating it. However, doing an EIO LCA just over one single product amplifies the approach weaknesses related to its low accuracy and reliability and, thereby, it has been tried to use it upon a relatively great number of aircraft, all having characteristics that fall into the determined range of regional aircraft. In this way, results gain reliability from comparison with each other. Into the following paragraphs the path followed to achieve the objective is explained.

4.2.1 Statistical analysis

The main purposes for which it was decided to do a statistical analysis are several:

- Firstly, to use the EIO LCA method, which is very fast though imprecise, to obtain values on the probable impact of the aircraft in the database so that it would be possible at a later time to use them as a starting point and as reference and comparison points for what will be the detailed analysis, presented in the next chapters. Moreover, statistical tools have been used to strengthen the assumption of using values deriving from EIO LCA impact assessment, despite the high uncertainty associated with them;

- Secondly, to do an analysis trying to relate the environmental impact of the production of traditional regional aircraft to their characteristics, dimensional and performance. Through a linear regression, it can be seen what the correlations are and how it is possible to obtain a mathematical law that can be implemented in the tool and that allows to make a quick estimate in a conceptual design phase, starting from a small number of data;

- Finally, results obtained from the analysis are not properly set values but probability distribution functions characterized by a mean and a variance. This fact is important because allows to make analysis on the frequency with which it is possible that the estimated value is actually equal to, or greater than, the real one, obtained at the end of the design and production phases. Such an analysis is very useful for the designer and is implemented within the tool, as will be better explained in the chapter 8.

The correlation found becomes useful when it is used to predict the impact of a new aircraft production but, in this case, it is limited due to the problem of having a statistical base constituted mainly by traditional aircraft, meaning that only traditional architectures can be analyzed with a good confidence. This fact can be seen as a limitation but by the point of view of a designer it gives the possibility to make a comparison between the new architecture he is designing and traditional ones.

4.2.2 Hypothesis and limitations

Into this assessment, a free tool provided by an American University has been used. Unfortunately, the site were this tool could be consulted is no more available, or at least it is not at the time this thesis is being written, so it can't be adequately cited. The site path was "http://www.eiolca.net/".

The first hypothesis made regard aircraft characteristics taken into account and environmental impact categories considered:

- As previously mentioned, characteristics considered are of two kinds, dimensional and performance ones. To take into account dimensions, that usually define the category which the aircraft belongs, the number of passenger that can be transported and the maximum take-off weight were chosen. The first one is the main value searched by airlines because it precisely define how the aircraft will be used while, into choosing the second one, it was initially considered to use the operational empty weight instead because it is independent from the payload and the fuel weights, values that are directly related to other characteristics considered. The reason for which Wmto was picked in the end is that it is a more practical chose since it is simpler to find it than the Woe. To account for performances, the parameters considered are the maximum range and the cruise speed. Both are strictly related to the type of engine used into the aircraft. At the end, another factor has been taken into account and it is the number of aircraft build supposing that the more efficient a process becomes thanks to the learning mechanism and the less it will be impactful from both an environmental and an economical point of view;

- Another data that is fundamental for the statistical analysis is the acquisition price of the aircraft into database. Values were mainly found into Jane's All the World Aircraft [32], the ones that could not be found into the book have been researched online, especially through Wikipedia information [63]. Obviously, to overcome the problem of aircraft being build in different periods all prices have been normalized to the values of the US dollar in a specified year, considering the inflation through US Consumer Price Index, before being used into the previously mentioned tool;

- Impact categories that has been considered are the main ones, being global warming effect due to CO2 equivalent, ozone formation through NOx equivalent and terrestrial acidification through SO2 equivalent. More impact categories could be added but only values from these three were taken before the site was disabled. Moreover, it would be not so useful to get values about a large set of impacts, being this analysis a preliminary one and knowing that uncertainties are really high at this level. The term emission equivalent has already appeared into chapter 3 and means that the number of pollutants that contribute to the final effect, for example global warming, is great and, in order to make the assessment easily understandable, they are proportioned to the main pollutant, in this case the CO2, and, all summed, give the final value. The proportioning factors vary a lot for different pollutants and they also vary between assessment methods but it has not been possible to understand which values have been taken for these analysis before the site was disabled.

Some more hypothesis have been necessary to overcome problems mainly arising from a general scarcity of data:

- The first hypothesis comes by the use of the tool because, as previously said, EIO LCA is based on the principle that the emissions of a product can be calculated as an economical allocation of the total industry emissions. This hypothesis is itself strong and also leads to the consequence that data are always from many years before the study because it needs a lot of time to gather all the information needed to make the economical allocation. Thereby, the tool uses data that came from the 2002 US aerospace sector and the database as been shaped accordingly;

- It is important to note that aircraft considered were designed in a period that goes from 60's to nowadays. That means that their price has been subject to variations due to the improvement of the technology, moreover some processes that have an high environmental impact are today heavily taxed. To overcome the problem of the building period, price values were normalized using the inflation and making the hypothesis that price has varied during time also for the taxes applied to impactful production processes. The hypothesis could seem a little simplistic but it is effective enough at this stage. Another problem is related to the production site, because these planes were build across the whole world meaning that their acquisition price is strictly related to the cost of the workforce, so if it costs less the aircraft can be sold at a lower price, and the taxation of the country where the manufacturer has its registered office. Fortunately, different nations production has not been deemed a big problem after the first analysis, noting that it has little impact on the linear regression and therefore its influence has been ignored.

Main limitation, as can be seen from the hypothesis made, is the quality of data used to do the statistical analysis and the impossibility of knowing and taking into account in the analysis all the parameters that are at stake. Nevertheless, results achieved can be easily used in a conceptual design phase where uncertainty is accepted to be high and values are used as a guiding light.

4.2.3 Database

Model	**# passengers**	**Wmto [kg]**	**2002 price [US MM]**	**V [Mach]**	**Range [km]**	**aircraft build**
CRJ700	72	34019,00	28,86	0,78	2593,00	330
CRJ900	83	38330,00	34,50	0,78	2871,00	487
CRJ1000	100	41640,00	36,75	0,78	3056,00	63
B717-200 basic	117	50000,00	35,63	0,77	2648,00	155
Fokker 100	110	44450,00	35,40	0,82	3170,00	283
Fokker 70	79	39915,00	23,60	0,77	3410,00	47
ERJ145	52	22000,00	30,00	0,78	2871,00	888
ARJ21	90	43500,00	26,60	0,78	3700,00	97
A220	127	63100,00	56,70	0,78	6390,00	480
AN 148	74	43700,00	20,16	0,78	4400,00	47
EMB 190	100	51800,00	37,35	0,78	4537,00	582
Sukhoi SUPERJET	100	38820,00	26,25	0,78	4578,00	176
CRJ100	50	24041,00	17,25	0,74	3056,00	1021
DC 9	90	41141,00	34,05	0,84	2400,00	976
Mitsubishi MRJ	88	42800,00	35,25	0,78	3770,00	203
HS 748	58	21092,00	10,21	0,40	1715,00	380
Fokker 50	50	20820,00	20,65	0,45	1700,00	213
ATR-42	48	18600,00	14,35	0,44	1259,00	484

Model	**# passengers**	**Wmto [kg]**	**2002 price [US MM]**	**V [Mach]**	**Range [km]**	**aircraft build**
ATR-72	74	21500,00	18,98	0,46	1528,00	1000
AN 140	52	19100,00	10,03	0,51	2100,00	35
Dash 8	50	19505,00	12,48	0,48	1711,00	1244
Dash 7	50	19958,00	10,85	0,37	1280,00	21
CASA C 212	26	8000,00	7,12	0,32	2680,00	583
CASA CN 235	51	16100,00	17,10	0,40	4355,00	285
Ilyushin IL 114	64	23500,00	11,09	0,42	5000,00	20
Xian MA 60	62	21800,00	16,72	0,39	1600,00	420
BAE ATP	64	22930,00	19,00	0,43	1825,00	64
Dornier 328	33	13990,00	7,12	0,56	1852,00	217
Saab 2000	58	22800,00	16,50	0,61	2869,00	63
Saab 340	34	13154,00	6,60	0,46	870,00	459

Table 4.1: Traditional aircraft database

Two more considerations, that were made to build the database, are the fact that, in case of aircraft families where only one plane was taken for the entire family, the number of aircraft build refers to the entire group because it was considered that learning effect is developed through all the aircraft thanks to their similarity. Least but not last, for the Mitsubishi MRJ, that is now being developed, price and number of aircraft build are those that have been prospected by the company. CO2eq. SO2eq. and NOxeq. values are derived thanks to the EIO LCA tool entering as input the price value of aircraft minus the part of the price that accounts for financial costs and profit, both a 10% of the acquisition price as can be found in acquisition costs breakdown made by Roskam in [46].

Model	**CO2 eq. [tons]**	**SO2 eq. [tons]**	**NOx eq. [tons]**
CRJ700	10317,00	27,12	22,45
CRJ900	12333,21	32,42	26,84
CRJ1000	13137,55	34,54	28,59
B717-200 basic	12735,38	33,48	27,72
Fokker 100	12654,95	33,27	27,54
Fokker 70	8436,63	22,18	18,36
ERJ145	10724,53	28,20	23,34
ARJ21	9509,09	25,00	20,69
A220	20269,37	53,29	44,11

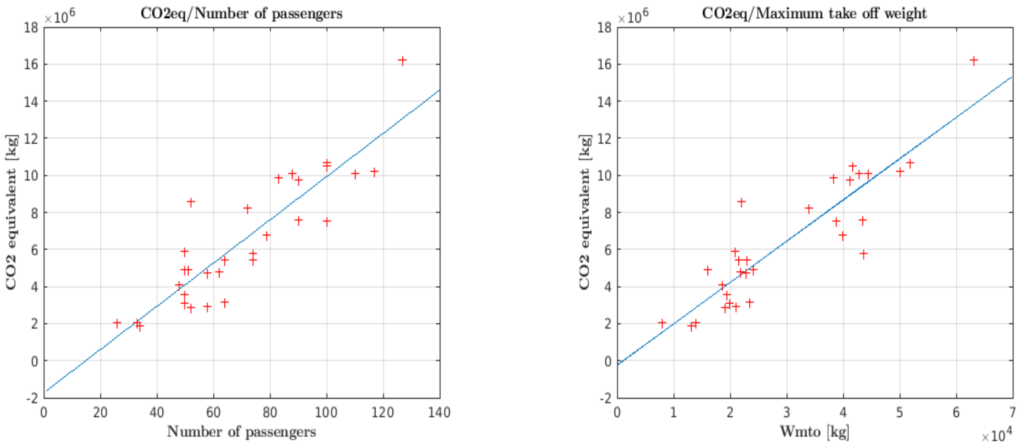
Model	CO2 eq. [tons]	SO2 eq. [tons]	NOx eq. [tons]
AN 148	7206,89	18,95	15,68
EMB 190	13352,04	35,10	29,06
Sukhoi SUPERJET	9383,97	24,67	20,42
CRJ100	6166,61	16,21	13,42
DC 9	12172,34	32,00	26,49
Mitsubishi MRJ	12601,33	33,13	27,42
HS 748	3649,20	9,59	7,94
Fokker 50	7382,05	19,41	16,07
ATR-42	5130,62	13,49	11,17
ATR-72	6785,05	17,84	14,77
AN 140	3586,28	9,43	7,80
Dash 8	4461,41	11,73	9,71
Dash 7	3877,28	10,19	8,44
CASA C 212	2545,29	6,69	5,54
CASA CN 235	6112,98	16,07	13,30
Ilyushin IL 114	3963,79	10,42	8,63
Xian MA 60	5977,14	15,71	13,01
BAE ATP	6792,20	17,86	14,78
Dornier 328	2545,29	6,69	5,54
Saab 2000	5898,49	15,51	12,84
Saab 340	2359,40	6,20	5,13

Table 4.2: Traditional aircraft impacts

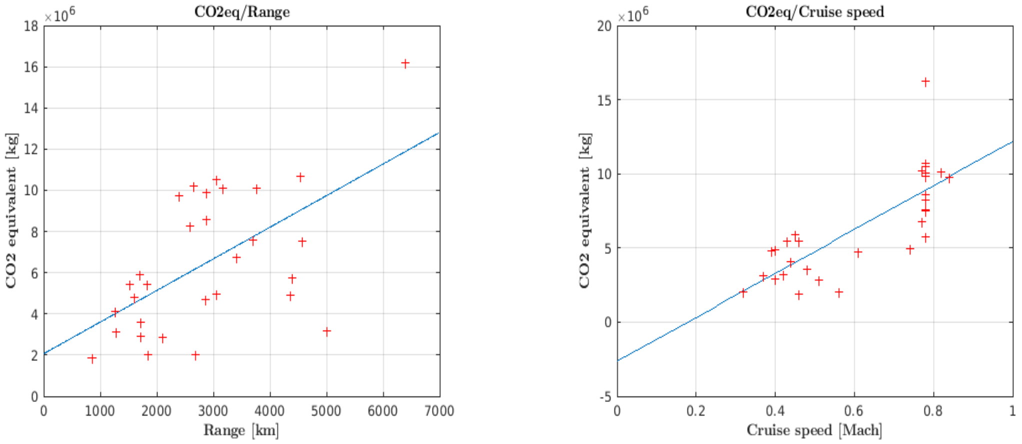
4.2.4 Linear regression process

Due to the fact that characteristics of aircraft considered have been preliminary chosen based on aerospace sector knowledge, since they are the parameters that guide conceptual design, the first step made has been trying to find real correlations between these variables and impact values. Thereby, hereafter graphs that puts in comparison independent variables with the CO2 equivalent value, taken as y-variable, have been reported. Obviously, the same way has been followed for the other impact categories. The scope of graphs is to visually show if there is a interrelation between x and y variables and to find if this interrelation is explicable through a linear regression.

What can be found it is that four out of five variables are closely related to CO2 equivalent fluctuations while cruise speed is common between aircraft with very different dimensions and performances and, as a consequence,

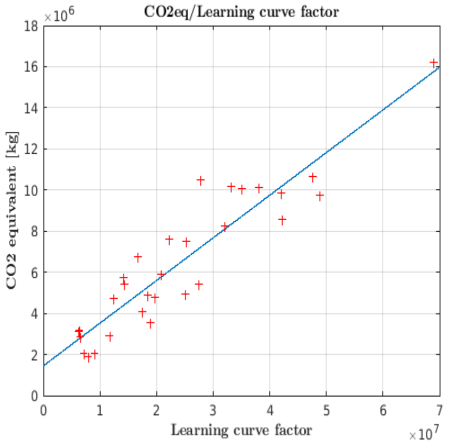


(a) CO2eq and number of passengers relation (b) CO2eq and maximum take-off weight relation



(a) CO2eq and maximum range relation (b) CO2eq and cruise speed relation

it is not to be taken into account in the following because it does not add any useful information. The absence of relationship could not be hypothesized from the beginning and it underlines how useful can be the correlation analysis. Hereafter, only number of passengers, maximum take off weight, maximum range and learning curve factor are used into the linear regression. LCF is calculated as price divided by the number of aircraft build elevated to a coefficient obtained considering a learning curve slope of 85%, usual value taken for aerospace industry.



(a) CO2eq and learning curve factor relation

$$\mathrm{LCF} = \frac{\mathrm{Price}}{(\text{Number of aircraft built})^{b}} \quad \text{where b} = \frac{\ln(\text{slope})}{\ln(2)} \tag{4.1}$$

The second step is to search for correlations between x variables. The coefficient of correlation r has been calculated and is shown into the table . Such an high correlation could be a problem and, usually, an expert in statistical analysis would suggests to take into

	N__pax	**Wmto**	**Range**	**LCF**
N__pax				
Wmto	0,95			
Range	0,59	0,65		
LCF	0,73	0,75	0,47	

consideration, as variables into the regression, also products, e.g. the number of passengers multiplied by the maximum take-off weight. However, products influence can only be explained from a mathematical point of view while it can be really difficult to find a physical explication of its effect. That being said, it was chosen to ignore the correlations to achieve a close relationship to the physical world at the expense of a less fitting model. Moreover, it is important to keep in mind that correlation is not the same as causation and that multicollinearity does not influence the predictions, precision of the predictions and the goodness-of-fit statistics [22]. This means that, primary goal being to make a prediction, it is not fundamental to understand the role of each variable.

Subsequently, linear regression has been done using the software MATLAB, which permits to the user to make it the same way used to solve a matrix equation, remembering that in this case the system of equations is overdetermined. This process permits to express the law in the following formulation $y_{\text{variable}} = [1\ N_{\text{pax}}\ W_{\text{mto}}\ R_{\text{max}}\ \text{LCF}] * a$ where a is a vector of coefficients that fit data using the least squares method. The principle is simple as it consists in minimizing the sum of the squares of the differences between the observed dependent variable in the input dataset and the output of the function of the independent variable. The only limitation that occurs using this approach is that data are all taken with the same "weight" meaning that they all influence coefficients the same way. The effect is that any training point that has a dependent value that differs a lot from the rest of the data will have a disproportionately large effect on the resulting constants that are being solved for.

Doing a linear regression using the ordinary least squares method the equations found are:

$$\begin{aligned} \text{CO2 equivalent} =& -7.03E^5 + 2.9E^4 \times N\text{pax} + 6.2E^1 \times W_{\text{mto}} \\ & + 6.1E^1 \times R_{\text{max}} + 3.6E^4 \times \text{LCF} \end{aligned} \tag{4.2}$$

$$\begin{aligned} \text{SO2 equivalent} =& -1.85E^3 + 7.71E^1 \times N\text{pax} + 2E^{-1} \times W_{\text{mto}} \\ & + 2E^{-1} \times R_{\text{max}} + 9.53E^1 \times \text{LCF} \end{aligned} \tag{4.3}$$

$$\begin{aligned} \text{NOx equivalent} =& -1.53E^3 + 6.38E^1 \times N_{\text{pax}} + 1.35E^{-1} \times W_{\text{mto}} \\ & + 1.33E^{-1} \times R_{\text{max}} + 7.89E^1 \times \text{LCF} \end{aligned} \tag{4.4}$$

All the impacts are given in terms of kilograms and the different order of magnitude of coefficients is due to the different order of magnitude of variables, as can be seen in table 4.1. Doing a check it can be found that most influential terms are the number of passengers and the number of aircraft build.

One could not find himself satisfied, at this point, because it has been said that CO2eq calculation was based on the price of the aircraft and now this value is newly indirectly used into the regression as one of the parameters. Maybe it could be more useful for a designer to estimate CO2eq emissions directly from price. However, it is impossible in the phase of conceptual design to have a precise idea of what the selling price will be. As a consequence, it was thought that using it as just one of many variables in the linear regression permits to find a more accurate curve explaining data with the help of the parameters that are more precisely known during designing. In this way, when the designer will use the equation, the price used as input can be only an initial idea of the market price band in which the product should be placed.

4.2.5 Goodness-of-fit coefficients of linear regression

Some goodness-of-fit coefficients have been calculated to show that the equation found is worth of using. Goodness-of-fit tests are important to understand how much equations found explain data trends and can be used to predict the future.

The first one calculated is obviously the coefficient of determination R2, in this case it was corrected in function of the number of variables considered. In fact, into multiple linear regression analysis adjusted R2 is used, otherwise its value will increase with the rise of the number of variables accounted without any physical reason. The formulation is 4.5, here written in terms CO2equivalent:

$$R_{\mathrm{sqCO_2}} = 1 - \frac{\sum (\mathrm{CO_2} - \mathrm{CO_2ex})^2}{\sum (\mathrm{CO_2} - \mathrm{mean}(\mathrm{CO_2}))^2} \tag{4.5}$$

$$\mathrm{SeeCO_2} = \frac{1}{\mathrm{length}(\mathrm{CO_2})} \sqrt{\sum \left(\frac{(\mathrm{CO_2} - \mathrm{CO_2ex})}{\mathrm{CO_2ex}} \cdot 100 \right)^2} \tag{4.6}$$

Adjusted R2 is equal to 0.9547, a relatively high value meaning that the linear regression explains data in a good way. Another coefficient that can be calculated is the standard error of estimate, SEE, 4.6 which is the measure of variation of an observation made around the computed regression line. In percentage terms, the SEE is equal to 2.2175%, meaning that the average percentage error is low and that the model optimally represents its own underlying data. The advantage of this coefficient is that it is more independent from how the database is constructed than the R2. The last coefficient calculated is the standard deviation σ. This parameter is very important for the point of view of the tool, as will be explained into user manual 8, , because it permits to define a probability density function for every estimated value and, thereby, to derive a confidence curve to give the opportunity to the designer of choosing a confidence leveled estimation. Sigmas vary between the three pollutants and their values are: 7.82e5 for CO2, 2.06e3 for SO2 and 1.70e3 for NOx. Read by themselves these numbers have little significance but they can be compared to database mean values for every pollutant. In this way, it can be said that averagely there is a 68.2% probability that the final impact falls into a range of ±12% around the estimated value, which is a consistent result for a preliminary analysis.

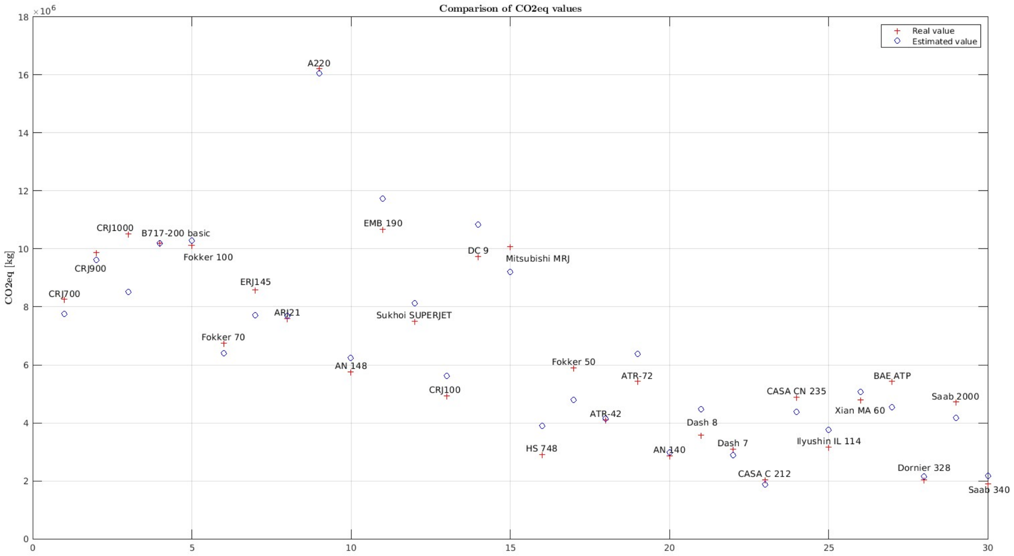


Figura 4.5: Comparison between real and estimated CO2eq values

4.3 Process based LCA

After following the path of Economic Input/Output LCA, it was decided that results were not consistent enough to be used in general term and, moreover, that it covers only production phase while operations phase is probably the most impactful. The natural consequence has been trying to make a process based analysis starting from the most important phase, considering that the scope and boundaries are the ones described previously, which is the inventory of all inputs necessary. In order to ease the work, it has been decided to subdivide the aircraft life into:

- `Material production`: all the impacts due to the production processes and materials used, in this phase it is possible to distinguish emissions correlated to each component and system;

- `Immaterial production`: here all the activities that are common to many systems and components, and their impact, are accounted, e.g. production site operation is a fundamental activity that has a big impact which need to be allocated over the entire aircraft or family of aircraft produced;

- `Operative life`: it comprehend all the emissions related to missions achievement, mainly due to fuel consumption, but also all the impacts that derive from the maintenance of the aircraft, which means the production of spare parts but also the work needed to change them;

- `Disposal`: this phase accounts for all the emissions that come from the dismantling of the aircraft and the recycling process of recyclable components or the disposal process of non-recoverable parts.

Into the following paragraphs, the breakdown of each of these phases is presented specifically.

4.4 Life Cycle Inventory - Material production

4.4.1 Breakdown of aircraft components

The first hypothesis made, necessary to easily analyze the environmental impact of the production phase, is to break down the aircraft system into six subsystems as can been seen in table 4.3.

1 STRUCTURE	1.1 WING
	1.2 FUSELAGE
	1.3 TAIL
	1.4 LANDING GEAR
	1.5 NACELLE AND STRUTS
2 POWER PLANT	2.1 EQUIPPED ENGINES AND PROPELLERS
	2.2 FUEL SYSTEM
3 SYSTEMS	3.1 HYDRAULIC GENERATION
	3.2 HYDRAULIC DISTRIBUTION
	3.3 ENVIRONMENTAL CONTROL SYSTEM
	3.4 THERMAL PROTECTION SYSTEM
	3.5 DE ICING
	3.6 FLIGHT CONTROL SYSTEM
	3.7 AVIONIC INSTRUMENTATIONS
	3.8 ELECTRICAL GENERATION
	3.9 ELECTRIC COMMON INSTALLATIONS
4 FURNISHING	4.1 THERMO ACOUSTIC INSULATION
	4.2 FURNISHING
	4.3 LIGHTING
5 OPERATOR ITEMS	5.1 OPERATIONAL ITEMS
	5.2 OPERATIONAL EQUIPMENT
6 SYSTEMS SOFTWARE	6.1 SOFTWARE

Table 4.3: Aircraft breakdown

This breakdown structure derives from the study of regional plane models already taken into account during the precedent phase of statistical analysis mixed with the usual breakdown used in program management. Some sub-subsystems have been grouped to simplify the structure, keeping in mind that the tool should be as user friendly as possible. An explanation of all hypothesis made to group little items into sub-systems will be provided in every paragraph while here there are general hypothesis made that regard the entire process:

- Assumption on weight ratios of different components over the sub-system weight will be thoroughly explained into the following paragraphs;
- Only component production is taken into account at this phase because assembly labor will be evaluated based on man working hours necessary for all subsystems integration;
- Not all the components of the aircraft are developed internally at the program but some are manufactured for many different airplanes and designer usually choose them off-the-shelf. Development impacts of these components are not taken into account considering that, due to high volumes of production, their allocation over the single component is low and that trying to detail them could be like draining the ocean with a bucket;
- The last general hypothesis is that all transport impact, generated by components moving between production site and assembly site, will be evaluated only where reliable data are available, mainly through a statistical analysis of *ATR* planes production and considering an overall impact, sum of all single components transportation.

4.4.2 1. Structure

Aircraft structure is made of many little structural components assembled together by mechanical junctions or by gluing. Thereby, many of them are here unified into main subsystems to ease the comprehension. However, into sub-systems, material and production processes are differentiated as it would be too sloppy and lacking in validity if different components were to be considered identically under the environmental impact profile, e.g. aluminium ingot production is far less impactful than carbon fibre composites production. The table 4.4 has been created to account for all the materials and processes that will be necessary to consider in order to make a good approximation. For every material, also the supply chain from mining of the mineral to the transport of the metallic ingot to the site were it will be processed, even if not directly specified into the possible process, will be considered. Many components, although composing different sub-subsystems, undergo the same processes but are here cataloged based on the sub-subsystem which they belong. Moreover, some components that go under the same nominal name can be produced with different methods, in particular aluminium ribs can be formed into stamps or milled from a block depending on the different function they will have to perform. For percentages of components produced with a technique rather than another it should take as a reference subdivision made into the last paragraph of this section while every process chosen from *Ecoinvent* database is into 5.

4.4.3 2. Engines and fuel system

Engines are usually produced by highly specialized companies while the aircraft manufacture usually just buys and assembles them over the aircraft. Nevertheless, the impact due to their manufacturing is here taken into account, making the approximate assumption that an engine is just an assembly of different metallic items. For the subdivision of engine weight between components one must refer to the last paragraph of this chapter, were values are chosen based on the opinions of some experts and upon average values from state-of-art engines. In facts, two different type of engines, turboprop and turbofan, can be chosen, the differences between the two consisting in little different weight proportions between components. Moreover, to consider hybrid propulsion aircraft, it was chosen to insert also electric powertrain production. Fuel system is all accounted as one

Possible Materials	**Possible processes**	**Typology of components**
1.1 WING		
Aluminium	milling	ribs
	sheet rolling and impact extrusion	ribs/panels
	casting	spars
Carbon fibre	layering	panels
1.2 FUSELAGE		
Aluminium	milling	load frames
	sheet rolling and impact extrusion	panels/frames/stringers
Carbon fibre	layering	panels
1.3 TAIL		
Carbon fibre	layering	panels
1.4 LANDING GEAR		
Steel	forging and milling	forged structure
	impact extrusion	brakes and wheel rim
1.5 NACELLE AND STRUTS		
Aluminium	milling	load frames
	sheet rolling and impact extrusion	panels/frames/stringers
Carbon fibre	layering	panels

Table 4.4: Structure breakdown

only sub-system made only by steel pipes that conduct fuel to the propellers. In this way, tanks are considered as if they were steel pipes. The approximation is made on the basis that the little weight of tanks compared to pipes system makes them negligible and in general that the little relative weight of this sub-system over the entire aircraft leads to the fact that detailed calculations would have very little effect on the production impact anyway. The only exception is in case there is a tank designed for containing liquid hydrogen at cryogenic temperature, in this eventuality the production of such a kind of tank is specifically considered but data about the component will be inserted as inputs into the *ELECTRICAL GENERATION* voice.

Possible Materials	**Possible processes**	**Typology of components**
2.1 EQUIPPED ENGINES AND PROPELLERS		
Aluminium	impact extrusion	exterior body
Steel	forging and milling	internal components
Titanium	forging and milling	turbines
Nickel-based superalloy	forging and milling	internal components
Copper and steel	electric powertrain production	electric engine
	control unit production	electric engine control unit
Carbon fibre	layering	propeller blades
2.2 FUEL SYSTEM		
Steel	pipes production	pipes
Aluminium	pipes production	pipes

Table 4.5: Engines and fuel system breakdown

4.4.4 3. Systems

This is the most compelling system because wrong hypothesis could give completely unrealistic results, data are difficult to find and yet making no assumption means that, to be consistent enough, the number of components needs to grow exponentially with the results that they cannot be adequately traced. In order to set boundaries to the analysis, many hypothesis were made:

- Hydraulic system is represented like a sum of pumps, pipes and expansion vessels because these elements are the heaviest;
- Environmental control system takes into account only air compressors and pipes. A milling process is also added to represent some valves and little elements whose require some machining;
- The thermal management system is needed in case of an hybrid electric configuration and it is modeled in the likeness of the TMS of electric automotive vehicles [65];
- De-icing system is constituted by a rubber membrane, as in traditional regional aircraft, but there is the possibility to implement a electric heating system or an aerothermal system, in case the designer chooses a more advanced configuration;

- Both mechanical and fly-by-wire controls are accounted to give the possibility to the designer to choose to insert a mechanical redundancy. It's not, indeed, strange to insert this type of redundancy on a traditional aircraft;
- To represent the avionic system a mix of active and passive electronic instrumentation and data cable is used, considering that the various instruments on board are not so different from a point of view of manufacturing;
- Electric system takes into account electricity generators, electric motors and cable, but there is the possibility of choosing between different type of batteries, a traditional Li-ion and a more advanced Li-sulphur. Moreover, fuel cell packs can be implemented in order to represent hybrid configurations and, to account for the need of liquid hydrogen on board in this situation, there is a tank production process associated.

Possible Materials	**Possible processes**	**Typology of components**
3.1 HYDRAULIC GENERATION		
Steel	pumps production	pumps
3.2 HYDRAULIC DISTRIBUTION		
Steel	pipes production	pipes
	expansion vessel production	expansion vessel
3.3 ENVIRONMENTAL CONTROL SYSTEM		
Steel	air compressor production	air compressor
	pipes production	pipes (both aluminium and steel)
	aluminium milling	mechanical components
3.4 THERMAL MANAGEMENT SYSTEM		
Aluminium	impact extrusion	fins
Steel	pipes production	pipes
Multiple materials	pumps production	pumps
	reservoir production	reservoir
	electronic instrumentation production	electronic instrumentation
	electric motor production	electric motor
	heating element production	electric resistance
3.4 DE ICING		
Plastic materials	polymer foaming	rubber membrane

Possible Materials	**Possible processes**	**Typology of components**
Multiple materials	heating element production	electric resistance
Aluminium	pipes production	pipes
3.5 FLIGHT CONTROL SYSTEM		
Steel	Forging and milling	mechanical flight controls
Copper	cable production	enhanced flight controls
Steel	hydraulic actuator production	hydraulic actuator
Multiple materials	electro hydraulic actuator production	electro hydraulic actuator
3.6 AVIONIC INSTRUMENTS		
Multiple materials	electronic instrumentation passive production	electronic instrumentation passive
	electronic instrumentation active production	electronic instrumentation active
	cable production	data cable
3.11 ELECTRICAL GENERATION		
Multiple materials	electric generator production	electric generator
	starter generator production	starter generator
	traditional electric motor production	traditional electric motor
	innovative electric motor production	innovative electric motor
	battery production	Li-ion battery
	battery production	Li-sulphur battery
	fuel cell production	SO fuel cell
	fuel cell production	PEM fuel cell
Aluminium and rubber	liquid hydrogen tank production	liquid hydrogen tank
3.8 ELECTRICS COMMON INSTALLATIONS		
Copper	cable production	conductive cables

Table 4.6: Systems breakdown

Due to the great possibility of production processes for every of the above mentioned components, here only the typology of item chosen is presented and the production process chosen will be explained in the last paragraph of this section while every process chosen from *Ecoinvent* database is into 5.

4.4.5 4. Furnishing

Components of this system are difficult to approximate due to the great variety of materials and processes needed. Furnishing, that takes into account both cockpit and cabin, is considered as if the majority of weight were to be plastic products and interior lining and, thus, their production is the only one considered. In order to account for all the various typologies of plastic present into the furnishing, two main categories have been used, the first one being polystyrene and the second one being polyvinyl chloride. This is a notable approximation of the reality but it is needed in order to limit the number of processes. For insulation panels and bulbs, values are taken from construction sector considering the affinity between different production methods of polystyrene foam.

Possible Materials	**Possible processes**	**Typology of components**
4.1 THERMO ACOUSTIC INSULATION		
Plastic materials	polystyrene foam production	insulation panels
4.2 FURNISHING		
Plastic materials	interior furnishing production	interior furnishing
4.3 LIGHTING		
Multiple materials	bulb production	bulbs

Table 4.7: Furnishing breakdown

4.4.6 5. Operator items

Possible Materials	**Possible processes**	**Typology of components**
5.1 OPERATIONAL ITEMS		
Multiple materials	seat production	seats
5.2 OPERATIONAL EQUIPMENT		
Multiple materials	galley equipments production	galley equipments
	toilet equipments production	toilet equipments

Table 4.8: Operator items breakdown

Within operational items group fall many elements that are necessary for the aircraft to flight but that are not usually provided by the manufacture company itself, e.g. fire extinguishers provided on board per legislation. Here they are divided into operational items and operational equipment. For the first ones, it was thought that the main voice of the ensemble could be passenger seats and, so, only their production is reported. Into the *Ecoinvent* database seat are not modeled, in order to overcome this obstacle they were modeled starting from basic product like aluminum skeleton and polyurethane foam. Operational equipment is constituted by all those items that compose an usual galley and those items necessary for toilets. Further information is reported in the last paragraph.

4.4.7 6. System Software

Possible Materials	Possible processes	Typology of components
6.1 SOFTWARE		
Immaterial	software development	systems software

Table 4.9: Software breakdown

Although software is not something material its production is no different from the previously presented components and it is therefore considered into this chapter. Moreover, in recent years software has become more and more important and its production, that is done working with a computer and so less impactful than industry processes, is no more negligible and undergoes strict legislation.

4.4.8 Components modeled

Turbofan and turboprop engines

Turbofan and turboprop engines were modeled taking the necessary information from some papers, in particular from the work [39], and asking the opinion of experts. In this way, proportions between different materials has been set as an average value. To account for machining processes, it has been considered that both steel alloys, titanium alloys and nickel-based superalloys needs to be heavily machined, passing through processes like milling, to reach the necessary perfection while aluminium pieces usually serve as enclosures and so the principal process is stamping. Into turboprop engine modeling it is also important to remember the presence of propellers, and the solution adopted has been to consider that these blades are made out of composites, especially carbon fibre reinforced plastic. The average proportion between their weight and that of the engine itself is 1:6.

	Turbofan Engine	Turboprop Engine
Nickel based superalloy	50,0%	50,0%
Titanium alloy	20,0%	20,0%
Steel alloy	10,0%	10,0%
Aluminium alloy	5,0%	5,0%
Composite	10,0%	5,0%
Alumina	2,5%	5,0%
Silicon carbide	2,5%	5,0%

Table 4.10: Turbofan and turboprop engines materials

Hydraulic and electro-hydraulic actuators

These two components are discussed together because the electro-hydraulic actuator is in principle much similar to the hydraulic one but it needs a little electric engine, which means that the power in input is an electric one and not an hydraulic one, and a pump to convert one power into the other, making use of a little reservoir associated with it. The hydraulic actuator has been modeled in the easiest possible way by considering that it is the sum of a perforated cylinder, obtained by extrusion and milling, and a metal arm sliding inside it, obtained by lathe machining. Quite similar is the composition of the

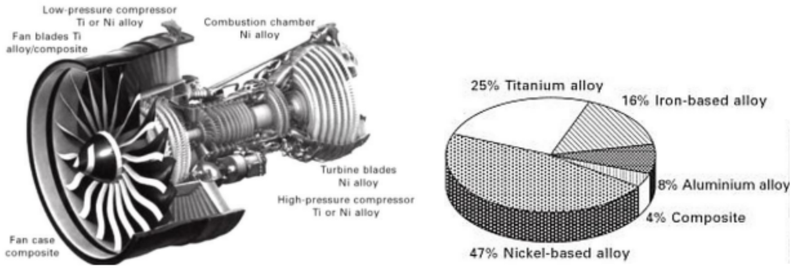


Figura 4.6: Cross-section of the GEnx engine and material distrubution

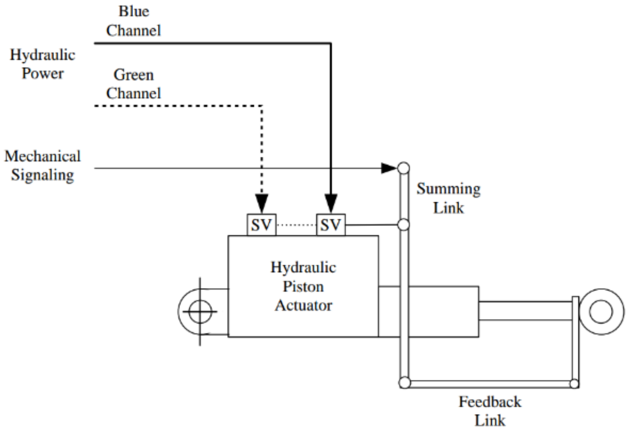


Figura 4.7: General scheme of an hydraulic actuator controlled by both a mechanical and an hydraulic line

electro-hydraulic jack, but in this case due to the need of the pump and the electric motor the percentages of weights are: 25% perforated cylinder, 25% electric motor, 25% metal arm and 25% hydraulic pump. Regarding the hydraulic oil used into both configuration, it is not modeled with the actuator because it needs to be changed many times during the life of the component and of the aircraft and so it has been thought that the easiest solution could have been to account for it only into the maintenance phase. In this way, it is possible to evaluate the impact of every life cycle of the oil, which means the production of new one and the treatment and disposal of the old one.

Liquid hydrogen cryogenic tank

This component has been modeled following the the work of D. Verstraete et al. [59], taking average values for ratio between the weight of aluminum walls and insulation panels. The use of aluminium derives from the evaluation that nowadays there is no composite that can resist the cryogenic temperatures needed to maintain the hydrogen into its liquid form. Thereby, the possibility of using plastic materials for this component will take with it new technologies of which even imagining how the assessment might be made is difficult. Processes to which the aluminium is subjected comprehend impact extrusion, milling and surface treatments. To account for the insulation material it has been chosen an elastomere which performances resembles the one of aerogel modernly used by NASA [21], in particular the important aspects are its density and the number of layers needed to obtain the desired effect of maintaining temperatures inside the tank at around 30 kelvin degrees.

Innovative electric motors and starter generators

Due to the fact that a generator and a motor differ only over the flow of the energy between mechanical and electrical one, the component modeled as starter generator is

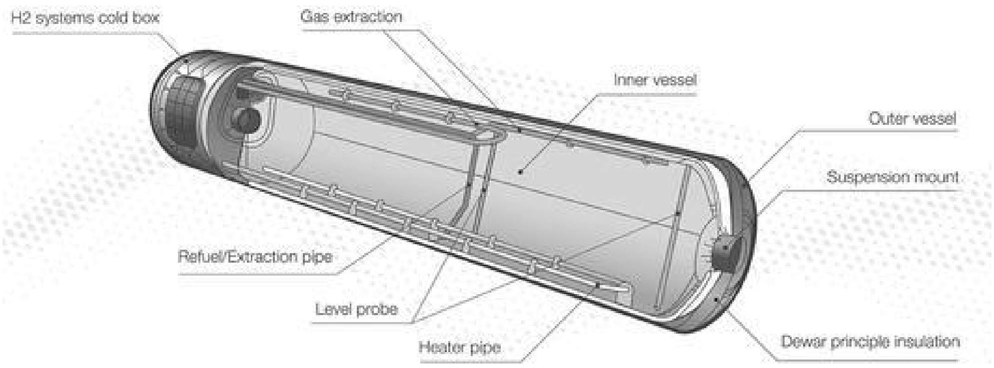


Figura 4.8: General scheme of an liquid hydrogen tank

the same used to account for high power density electric motors. The main difference from traditional generators lies in the increased use of permanent magnets and in the use of a brushless architecture. The advantages of a permanent magnet made rotor are that it reduces losses providing a more efficient source of magnetic fields compared to electromagnets, which require an electrical current to flow through them to create the magnetic field with the consequence of energy losses, it is easier to control thanks to a more stable and predictable magnetic field and the magnetic field provided is also stronger, which leads to more compact and lightweight starter generators. A typical brushless motor has permanent magnets that rotate around a fixed armature, eliminating problems associated with connecting current to the moving armature. An electronic controller replaces the commutator assembly of the brushed DC motor, which continually switches the phase to the windings to keep the motor turning. The controller performs similar timed power distribution by using a solid-state circuit rather than the commutator system. The composition is the one in 4.11.

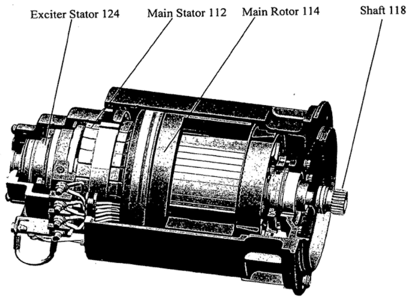


Figura 4.9: Innovative electric motors and electric generators

	STARTER GENERATOR
Permanent magnet	46,3%
Steel alloy	18,5%
Copper alloy	13,9%
Aluminium alloy	4,6%
Carbon fibre	4,6%
Synthetic rubber	4,6%
Control unit	7,4%

Table 4.11: Starter generator materials

4.5 Life Cycle Inventory - Immaterial production

4.5.1 Breakdown of aircraft immaterial production

The term immaterial production is used to describe the ensemble of all those processes that are strictly necessary for aircraft even if they are not linked with the material production of a component. To easily understand them, it may be useful to take a look at the table 4.12.

1 DEVELOPMENT AND MANUFACTURE	1.1 ENGINEERING 1.2 MANUFACTURING WORK 1.3 TOOLING 1.4 QUALITY CONTROL
2 PROGRAM MANAGEMENT	2.1 OFFICE WORK 2.2 TRAVELS
3 TEST AND EVALUATION	3.1 TEST AIRFRAMES AND PROTOTYPES 3.2 TESTING
4 DATA MANAGEMENT	4.1 SERVER OPERATION
5 PECULIAR SUPPORT EQUIPMENT	5.1 PECULIAR SUPPORT EQUIPMENT
6 COMMON SUPPORT EQUIPMENT	6.1 COMMON SUPPORT EQUIPMENT
7 SITE ACTIVATION/ OPERATION	7.1 SITE CONSTRUCTION 7.2 SITE OPERATION
8 INITIAL SPARES	8.1 INITIAL SPARES

Table 4.12: Immaterial production breakdown

First activities tabulated are those that involve personnel working over the whole project and, thereby, their impact cannot be allocated over a singe component but it is transversal to many systems, if not to the whole aircraft. It is important to note that here when the term "manufacturing work" is used it is referred to all that work, usually much manual and little automated, needed to assemble components into sub-systems, sub-systems into systems and so on until the assembly of the complete aircraft. A similar reasoning can be made about all the other activities listed, which are fundamental for every plane to be build and whose emissions needs to be distributed over the fleet of aircraft manufactured during the program life. As it will be clearly explained during the chapter, in order to obtain an estimation of the number of hours, and related cost, needed for these activities, it has been of great advantage the work made by Ian Roskam [46]. Analyzing data from existing aircraft development and production programs, many parametric equations have been derived which relate transversal processes cost, e.g. the number of hours necessary to design a new aircraft as a function of main system features. Equations taken into account for this work will be cited hereafter. Moreover, another tool, that can give the same output in terms of hours and costs, has been used and it is PRICE TruePlanning® software [55]. This has been made because this software is nowadays widely used within cost estimating offices and it is essential for implementing design-to-cost development methodologies. Using it is a first step into trying to link sustainability design and cost design. The reason of the choice of setting parameters so that they can work with both the tools is that this way there is the possibility to choose between two valid methods, one more connected with traditional architectures and one that permits to account for technology advances, and to develop sustainability analysis simultaneously with a cost analysis, in the optic of a more user friendly design process.

4.5.2 1.Development and manufacture

Possible phase	**Possible estimation relationship**	**Possible process**
1.1 ENGINEERING		
development	Roskam relationship	computer operation, active mode
	PRICE TruePlanning®	
production	Roskam relationship	computer operation, active mode
	PRICE TruePlanning®	
1.2 MANUFACTURING WORK		
development	PRICE TruePlanning®	electricity usage, low voltage
production	Roskam relationship	electricity usage, low voltage
	PRICE TruePlanning®	
1.3 TOOLING		
development	PRICE TruePlanning®	metal working machine production
production	Roskam relationship	metal working machine production
	PRICE TruePlanning®	

Possible phase	**Possible estimation relationship**	**Possible process**
1.4 QUALITY CONTROL		
development	PRICE TruePlanning®	computer operation, active mode
		electricity usage, low voltage
production	Roskam relationship	computer operation, active mode
	PRICE TruePlanning®	electricity usage, low voltage

Table 4.13: Development and manufacture breakdown

Development and manufacture are probably the most important phases of immaterial production, even if for two different reasons. In fact, engineering development require a long number of years and so it is responsible for quite a big environmental impact but this will be divided over the number of aircraft build at the end of the project. Production manufacture is, indeed, less time-consuming, if only the production of one aircraft is considered, but more energy-intensive and moreover its impact falls over the single unit produced. The last important process of immaterial production is test and evaluation, which will be discussed into one of the following paragraphs. Some hypothesis have been made to estimate these activities emissions:

- Processes that go under the name office work are varied and it would be difficult to account every one in a different way so they are grouped under an unique procedure considering that the main activity during development is computer working;
- Manufacturing needs tools and electricity to power them but it cannot be found into the database, or searching into literature, any information about the emission impact of hand or industrial tool production. Consequently, into manufacturing work only electricity consumed is considered and the quantity of energy used is calculated based on the consumption of an average electric production line machinery, multiplied for the number of man working hours necessary to assembly sub-systems and, at the end, the entire system;
- For tooling the reference value of the process of metal working machine production is one kilogram of machine produced, this is a little problem since for ground-based machine weight is not a characteristic feature. Thereby, to account for the impact of this phase, developing and manufacturing cost of every kg have been used to rescale the functional unit of the process and switch from weight to cost. This means, that passing through the output of Roskam equations, or PRICE TruePlanning® ones, that estimate total costs of this phase, it is possible to calculate its impact. It is not the most functional way imaginable but it has proved itself useful. Obviously, the cost per kg used is an average and it is of 2400 US dollars;
- For quality control phase, it has been adopted an assumption similar to the one used for manufacturing since also testing machine production is not tabulated into the database. Accordingly, an average value of electricity consumption, due to tool operation, will be considered and multiplied for the total number of hours necessary. Moreover, active computer operation process has been involved because nowadays quality control phase is highly computerized and it is useful to assess testing machines impact;

- Some of these assumptions regarding processes that reoccur in other phases have been maintained equal to themselves every time.

4.5.3 2. Program management

Possible phase	Possible estimation relationship	Possible process
2.1 OFFICE WORK		
entire program life	PRICE TruePlanning®	laptop operation with internet access
2.2 TRAVELS		
entire program life	PRICE TruePlanning®	transport, passenger car transport, passenger aircraft

Table 4.14: Program management breakdown

For program management it has been thought that the main task would be laptop work, where the process chosen from *Ecoinvent* database is different from the previously one used to describe computer aided design work because for management activities it is more important to have internet access, e.g. in order to complete task as video-conferences. While the main operative task is laptop work, it is useful to remember that management is an activity that requires continuing traveling between many sites, especially in aircraft manufacture. To consider the impact of this important process, it is necessary to insert also the emissions due to transport by passenger car and by passenger aircraft. The calculation of hours, or kilometers, traveled may pass through the estimation of their cost using PRICE TruePlanning®, or any life cycle cost software able to predict it, or through the assumption that a constant percentage of hours estimated for program management in the whole is spent traveling, and it is converted into emissions using the *Ecoinvent* processes of moving a person for a km, by air or by car. Impacts of using infrastructure during work hours is accounted into the site operations, here only direct impact of program management work is considered. This assumption is valid also for the development and manufacturing phases.

4.5.4 3. Tests and Evaluations

Test and evaluation procedures are both really time-consuming and energy-intensive since it is required to build prototypes and samples of the final system or subsystems and test them for a long time. The percentage of development cost associated to an aircraft that is due to this phase is estimated by Roskam to be around 44% which means that it occupies the biggest share among cost items. Here it was chosen to subdivide this phase into the manufacture of test airframes and prototypes and their testing. For manufacturing, tooling, quality control and laboratory testing assumption made are equal to the ones explained into previous paragraphs. New hypothesis made are:

- Material production of airframes and prototypes is calculated deriving it from the production of the complete aircraft considering that only some subsystems will be taken into account and tested from time to time;
- Simulation is a process similar to designing and thereby is calculated starting from the use of an operational computer multiplied for the number of hours needed for simulation. The number of hour needed can be obtained as an output from PRICE TruePlanning®;

Possible phase	**Possible estimation relationship**	**Possible process**
3.1 TEST AIRFRAMES AND PROTOTYPES		
production	Roskam relationship	electricity usage, low voltage
material production	Relationship implemented from data of complete aircraft	
tooling	Roskam relationship	metal working machine production
quality control	Roskam relationship	computer operation, active mode
		electricity usage, low voltage
3.2 TESTING		
laboratory testing	PRICE TruePlanning®	electricity usage, low voltage
simulation	PRICE TruePlanning®	operational, computer, desktop, with liquid display, office use
flight testing	PRICE TruePlanning®	transport, passenger aircraft

Table 4.15: Tests and Evaluations breakdown

- Last assumption is that flight testing is similar to flying the aircraft for an usual mission so transport consumption and emissions of a very short haul of a passenger aircraft are used to calculate it based on the number of flight hours. The only limitation related to the use of this dataset is that, during flying tests, passengers are obviously not present on board. However, considering the instrumentation boarded for monitoring it is possible to say that there is a little change into payload weight. This assumption is not completely true since even a small difference payload means different kerosene consumption but it is here hypothesized as negligible.

4.5.5 4. Data management

Possible phase	**Possible estimation relationship**	**Possible process**
4.1 SERVER OPERATION		
entire program life	PRICE TruePlanning®	data are taken from these two works [43] [8]

Table 4.16: Data management breakdown

During development, the volume of data created is so high that their management activity is strictly necessary to organize them. However, server manufacturing and operation are not tabulated into the database and it has been necessary to find some papers to account for their impact. Works found are the one made by S. Retegui et al. and the one made by J. Chang et al. [43] [8], the first one compare different methods of assessment while the second one is a more detailed analysis. In both cases, the entire life cycle of servers is valued, from cradle to grave. Accordingly, values from these papers will be implemented into the tool. Estimate how many hours of data management will be necessary through the whole life of the program, and even after whether data is supposed to be kept for a few years after its end with the purpose of keeping confidential information and eventual technological dominance intact, is not a simple task and even using PRICE TruePlanning®, or others estimation equations, it is possible to make errors. Nevertheless, their impact is little if compared to others activities and therefore errors into this task are negligible.

4.5.6 5. & 6. Peculiar and Common support equipment

For now these voices are neglected. Reasons behind this choice are that:

- Commons support equipment is used for a great number of different aircraft at airport and so their impact over a single plane is very little. Moreover, in operational phase there is a voice that add and take into account all the emission due to airport facilities use and consumption, so it is not useful to insert them at this point, also considering that the scope of the tool is mainly to compare different designs;
- Peculiar support equipment, instead, can be of much importance to account for hybrid aircraft that surely need new support equipment specifically designed. However, it is difficult at this time, during which this type of aircraft is in the early stages of development and different solutions are being tested, to know what kind of equipment will be necessary and how they will be produced.

Accordingly, the voice of support tools is left behind and not treated into this work, with the hope that, if this work should be expanded and refined into another thesis in the near future, it will be possible to implement them.

4.5.7 7. Site construction and operation

It is not a every time necessity the construction of new plants or shed but it may be a possibility in order to face technology improvements. In this case, emissions will be proportioned to the extent of the structure knowing that *Ecoinvent* processes have the production of a square meter of factory or shed as reference unit.

Possible phase	**Possible estimation relationship**	**Possible process**
7.1 SITE CONSTRUCTION		
factory construction	input given by the user PRICE TruePlanning®	factory construction
shed construction	input given by the user PRICE TruePlanning®	shed construction
7.2 SITE OPERATION		
factory operation	Roskam relationship for manufacturing work hours PRICE TruePlanning®	energy and auxiliary inputs

Table 4.17: Site construction and operation breakdown

Into site operation all inputs necessary for the plant to work are accounted, from electricity and heat consumption, for lighting and heating respectively, to wastewater disposal from toilets. In this way, it has been sought to consider all the activities that take place into the factory and that, even if not directly related to production, are unavoidable, e.g. conference room utilization for meetings or production plant heating during winter.

4.5.8 8. Initial spares

The approximation for initial spares is that they account for around the 15% of total aircraft components, predominantly some components over others, and so its impact will be derived from total impact of aircraft components manufacturing, after necessary proportioning.

4.5.9 Processes modeled

Energy and auxilliary inputs Into *Ecoinvent* database it is possible to find a process called "energy and auxilliary inputs, metal working factory" that has been created to consider all energetic, could they be heat or electricity, consumption related to the use of a production plant. However, the reference unit chosen, into the database, had been the kg of final products manufactured and this is not a reliable value since aircraft weight is an important parameter that designers tend to diminish when possible. In order to overcome the problem, a similar process has been modeled, this time with the number of hours of utilization of the plant. Values upon which it is based are:

Consumption of natural gas	7.54E-2 kWh/m2
Consumption of electricity	4.57E-3 kWh/m2
Consumption of water	4.8E-4 m3/m2

Table 4.18: Average plant consumption

and they are taken from [7], estimating the cumulative number of hours of utilization to be 2080 per year. This way, linking the consumption to the square meters of plant extension, it is possible to use this process both into production and into maintenance phases, while otherwise the enormous difference between these two type of facilities extension would have compromised it. In facts, for aircraft production plant the square footage assumed, as said before, will always be of 274 000 m2 while for maintenance facility it is assumed to be 2322 m2, value taken from [47] as representative of an average.

4.6 Life Cycle Inventory - Operative life

4.6.1 Breakdown of operative life phases

Airplanes produced in the last few years are designed to have an expected life of around two decades, during which they will undergo many activities. First of all, for an average regional aircraft, that is planned to flight for around 35000-40000 hours, the principal phase of operative life is the accomplishment of missions. Each flight can be divided into at least seven phases: taxi, take off, climb, cruise, approach, landing and taxi, during which it will use some kind of fuel to obtain the power needed to accomplish the phase, could it be kerosene in traditional architecture aircraft or electricity in hybrid electric configurations. The second phase for importance is the maintenance. All activities associated with it are fundamental if the airline wants to maintain the aircraft airworthiness and to continue flying. Maintenance operations are usually divided into three types: organizational maintenance, intermediate maintenance and depot maintenance. Differences between them will be explained into the following paragraphs.

These two are the only voices into operational life whose impact has been analyzed into this thesis. However, there would be many other activities associated with it that have a great relevance into a life cycle cost analysis. They can be divided into direct costs, such as ownership or “cost of operations”, which usually refers to pilots and flight assistants salaries or even charges, and indirect cost, that are all those activities needed to develop a profitable route e.g. advertising and promotion expenses. All these are important cost items but it has been thought that the emissions related could not be estimated in a reliable way and that they would have surely been negligible if compared to mission ones and so the conclusion, as previously said, is that only mission accomplishment and maintenance are assessed.

4.6.2 Mission Impact

Before talking about how mission impact has been evaluated and what processes have been chosen for its inventory, it is important to underline the fact that emissions have a different impact upon the environment depending on the height at which they are released into the atmosphere. 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, which can have negative effects on human health and the environment. On the other hand, emissions released at higher altitudes can have a more widespread impact, as they can be transported over longer distances by atmospheric winds and currents. This can lead to the formation of secondary pollutants such as ozone and particulate matter, which can also have negative effects on human health and the environment. Additionally, emissions at higher altitudes can also have a greater impact on climate change, as they can have a longer lifetime in the atmosphere and contribute to the greenhouse effect, e.g. emissions of carbon dioxide, CO2, at higher altitudes can have a greater warming effect than emissions at ground level, as the concentration of CO2 is already high near the surface and there is less atmospheric mixing at higher altitudes. However, the change in the impact is linked to a multitude of factors, such as atmospheric conditions and segment of the globe that is being flown over, in a way that accounting for it would be a really complex problem. Moreover, studies made to analyze these effects are now few and not always reliable. To overcome the problem, the great hypothesis made into the assessment of missions is that emissions have the same environmental impact, regardless the altitude they are emitted.

In recent years there has been an exponential growth of fuel types, all of which have arisen with the ultimate goal of making the aviation industry more eco-friendly. In this thesis, only four fuel types were used, and average values were assumed for these so that they could be representative of a wide range. Combustibles considered are:

- Kerosene based, such as Jet A-1 or Jet B, similar to diesel fuel, they can be used in either compression ignition engines or turbine engines. They are high-quality fuels, specifically treated to be used into aviation industry, see the fact that if they fail the purity and other quality tests for use on jet aircraft, they are sold to ground-based users with less demanding requirements;

- Biofuels, or sustainable aviation fuels, such as HEFA, Hydroprocessed Esters and Fatty Acids. Alternatives to conventional fossil-based aviation fuels, new fuels made via the biomass to liquid method, and certain straight vegetable oils, have the advantage that few or no modifications are necessary on the aircraft itself while they yield lower emissions of particles and GHGs [11] [58];

- Liquid hydrogen, it can be used largely free of carbon emissions, if it is produced with power from renewable energy sources. It can be burned without much changing of engines architectures or used into fuel cell to produce electricity. Hydrogen fuel cells do not produce CO2 or other emissions, besides water, while hydrogen combustion does produce NOx emissions. Hydrogen has a severe volumetric disadvantage if compared to hydrocarbon fuels, but future blended wing body aircraft designs might be able to accommodate this extra volume without greatly expanding the wetted area [29];
- Electricity, it also can be used free of carbon emissions if it is produced from renewable sources, but this degree of technological advance still need to be achieved. It may be used to power electric powertrains but there would be the necessity to change the whole architecture of aircraft because these engine are littler than internal combustion ones and this fact leads to different way to develop the needed thrust, such as distributed propulsion [33].

The assessment of fuel consumption has been evaluated following two different ways and thereby process chosen are of two types, as can be seen into table 4.19. It has also been chosen that, in addiction to fuel consumption emissions, into missions impact it is important to insert also emissions associated with airport usage.

FUEL CONSUMPTION		
	kerosene production and burning	kerosene_burning
	electricity production	electricity_production
	sustainable aviation fuel production and burning	SAF_burning
	liquid hydrogen production	LH_production
	average fuel consumption	transport_very_short_haul
		transport_short_haul
		transport_medium_haul
AIRPORT CONSUMPTION		
	airport construction	airport_construction

Table 4.19: Mission breakdown

Average fuel consumption is derived from statistics into the *Ecoinvent* database and represent the average fuel burned for passenger transported associated with a known distance range and so this first way does not need to know how much energy is needed for every km because it make reference to average values, subdivided between very short haul, short haul and medium haul flights. The assessment method implemented accordingly relies upon another statistical analysis, this time it has been made into the article [2] based on the data from [38] . This study shows the renewed interest about regional aircraft market, accordingly with the evolution of aircraft's technology toward an hybrid electrical mobility. From these data, it has been possible to derive a logarithmic normal

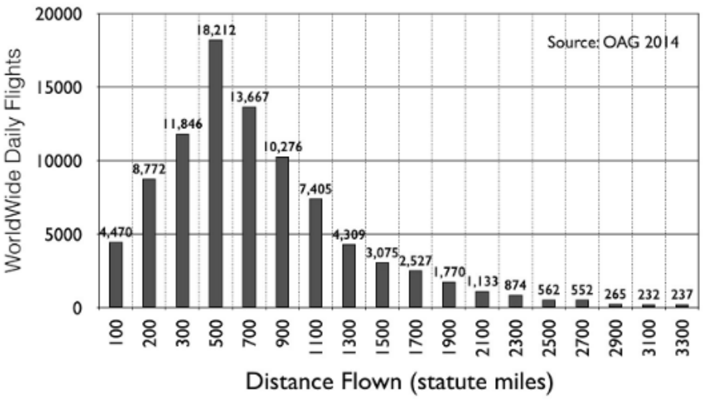


Figura 4.10: Daily flights density function

distribution of distances flown by regional aircraft and, thereby, it has been possible to obtain a mean value that can be considered as the range of a type mission. The assessment method derived from these data relies upon the product between the mean value of km traveled per flight, the average consumption per km, divided by aircraft category as said, and the number of flights that one want to analyze. Obviously, this method can be used only with traditional aircraft that burn kerosene because that is the fuel taken into consideration into the statistical analysis made by *Ecoinvent*. The possibility of using the mean range comes from the central limit theorem which establishes that, in many situations, for identically distributed independent samples, the standardized sample mean tends towards the standard normal distribution and, thereby, if used as an approximation for a finite number of observations, it provides a reasonable one only when close to the peak of the normal distribution. As a consequence, it requires a very large number of observations, flights to assess in this particular case, to stretch into the tails and this limitation lead to the fact that the maximum range, upon which average consumption is subdivided, and the number of flight to assess are also useful to verify if this method is reliable. This because if the maximum range is two little it could exclude many of the route taken into account into the statistical analysis and, thereby, the assessment could not be very precise. At the same time, to overcome the limitation posed by the statistical analysis, the number of flight to assess needs to be big enough to guarantee the validity of the calculations made. As it can be seen, however, this method is strictly linked to the state of the art of short to medium haul mobility. Fundamentally, the input it takes are the average number of passenger which is expected to flight with the aircraft taken into consideration, the range of a type mission, the maximum range it can fly and the number of flights to assess.

The second way of assessment, on the other hand, is based upon the knowledge of the impact of fuel production and burning emissions and, for the same reason, of electricity production. This means that if the consumption associated with every km traveled is known, it is possible to multiply the consumption per km for the kilometers flown and finally for the impact of fuel and the assessment is made. The result is that through this method it is possible to calculate the impact in a similar way to the first one, and so using the mean distance flown for the missions, or it may used to exclusively assess emissions due to the consumption of a known quantity of fuel.

The last important hypothesis made here is that for the secondary way the mission has been modeled as a black box where kerosene, biofuels, liquid hydrogen and electricity are given as input and the output are their emissions, not considering if during the flight part of the power generated by engines is used to produce more electric power or the other way round. In this way, only the effective consumption due to the flight have been taken into account.

4.6.3 Maintenance

Maintenance levels pertain to the division of functions and tasks for each area where maintenance is performed. Each level differs from the others due to tasks complexity, personnel skill-level requirements, frequency of occurrence, special facility needs, economic criteria, and so on, which all together dictate the specific functions to be accomplished at each phase. Maintenance levels are usually classified as:

- `Organizational maintenance`, which is accomplished on the prime elements of the system at the consumer's operational site. Usually, it includes tasks performed by the using organization by personnel usually involved with the operation, using its own equipment and having minimum time available for detailed system maintenance. Maintenance at this level is normally limited to periodic checks of equipment performance, visual inspections, cleaning of equipment, some servicing, external adjustment, and the removal and replacement of components, thereby skills required are very low;
- `Intermediate maintenance`, where tasks are performed by mobile, semi-mobile, and/or fixed specialized organizations and installations. At this level, end items broken from the operating system may be repaired through the removal and replacement of major modules, assemblies, and/or piece parts. Available maintenance personnel is usually more skilled and better equipped than those at organizational level and are responsible for accomplishing more detailed maintenance. Mobile or semi-mobile units are often assigned to provide close support to deployed operational elements of the system;
- `Depot maintenance`, depot level constitutes the highest type of maintenance and supports the accomplishment of tasks above and beyond the capabilities available at the intermediate level. Physically, this may be a specialized repair facility supporting a large number of systems/equipment/software in the inventory, or it may constitute the manufacturer's main plant. Depot facilities are fixed, and mobility is not a problem. Complex and bulky capital equipment, large quantities of spares, environmental control provisions, and so on can be made available if required.

ORGANIZATIONAL MAINTENANCE		
	electrical hand tool consumption	electricity_usage_low_voltage_FR
	mechanics and tools transportation	ground_support_transport
INTERMEDIATE MAINTENANCE		
	industrial electrical tool consumption	electricity_usage_low_voltage_FR
	factory operation	energy_and_auxilliary_inputs
	mechanics and tools transportation	ground_support_transport

DEPOT MAINTENANCE		
	industrial electrical tool consumption	electricity_usage_low_voltage_FR
	factory operation	energy_and_auxilliary_inputs
TIRES		
	tires substitution	tire_production
WHEELS		
	wheels substitution	wheel_production
BRAKES		
	brakes substitution	brake_production
ENGINES		
	power plant production	power_plant equipped_engine_and_propellers
APU		
	power plant production	power_plant equipped_engine_and_propellers
BATTERY		
	battery production	Li_ion_battery_production
		Li_S_battery_production
FUEL CELL SYSTEM		
	fuel cell production	PEM_fuel_cell_production
		SO_fuel_cell_production
HYDRAULIC OIL		
	hydraulic oil production	hydraulic_oil_production
	hydraulic oil treatment	hydraulic_oil_treatment
AVIONICS		
	avionic instruments production	systems avionic_instruments
FLIGHT CONTROL SYSTEM		
	flight control system production	systems flight_control_system_production
FUEL SYSTEM		
	fuel system production	power_plant fuel_system
HYDRAULIC SYSTEM		

	hydraulic generation production	systems hydraulic_generation
	hydraulic distribution production	systems hydraulic_distribution
ELECTRIC SYSTEM		
	electric common installations production	systems electric_common_installations
STRUCTURE		
	structure production	structure

Table 4.20: Maintenance breakdown

After seeing how the various maintenance tasks are subdivided, it will become more understandable how the method used for the analysis of this phase of the aircraft's life works. In fact, it was decided to distinguish impacts between the ones due to labor, which are directly attributable to the use of machinery, the transportation of personnel to the site of operation, and the use of a facility, and the ones related to the production, use and end of life of the various components that will be replaced, remanufactured, and disposed across the whole life. It is good to note that end-of-life operations are as important as production ones since, often, replaced components are usually made out of materials whose treatment is not always simple and low polluting, e.g. tires whose main material are plastic composites or batteries with their acids. Processes chosen also include disposal activities with the result that into maintenance emissions will be considered also end-of-life emissions of components replaced.

A somewhat separate discussion is about the assessment of repairs made to systems in its entirety, e.g. engine regeneration. This was done by going to the manufacturing stage and taking the processes required to create each component within the system in question and calculating the emissions accordingly, as can be seen from the table 4.20.

4.6.4 Components modeled

During the building of this inventory, it has been necessary to create some processes because of the lack of literature about these components life cycle assessment. The first process is the one about energy and auxilliary inputs but luckily this has already been modeled into the immaterial production paragraph and it is here used making the same hypothesis. Here three activities have been modeled in particular, even if they can be found also into material production inventory, that are: tire production, wheel production and brakes production.

Tire production

Tires are a highly wear-and-tear component that need to be changed every 120 to 400 landings [28] and the impact associated with them is linked both to production and disposal but also to wearing process during landings where the tire time after time releases multiple particles into the air. High wear and low replacement time, however, offer an opportunity since tires can be regenerated easily by molding a new tread layer. Thereby, it has been decided to consider that tire production impacts can be treated as the sum of production from basic materials and retread, with a percentage where 60% of times the tire is produced from new and 40% of the times is retreaded. For every kg of tire produced the breakdown of material used is the one in table 4.12:

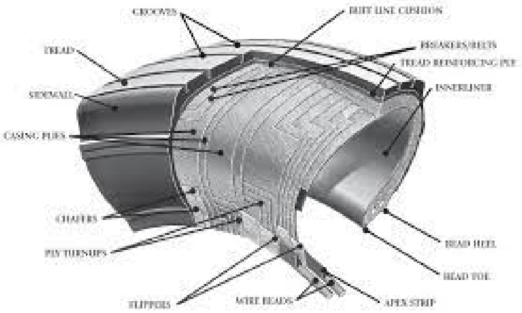


Figura 4.11: Aircraft tire

Material	Percentage
natural rubber	48,0%
carbon black	27,0%
steel alloy	10,0%
resin	9,0%
textile	6,0%

Figura 4.12: Tire breakdown

and plastic materials have been associated with thermoforming and calendering while steel is usually used under the form of wires. Moreover, the wearing process has been also considered into the production as if at the end of its life the tire has lost a quarter of its weight. The same materials and production processes have been used in case of retread tires, this time considering that only 250 grams every 1 kg of tire should be replaced, the same quantity lost before. The final market activity is constituted of 60% of new tire production and 40% of retread tire.

Wheel production The typical aircraft wheel is lightweight, strong, and made from aluminum and magnesium alloys. The typical modern two-piece aircraft wheel is cast or forged and the halves are bolted together and contain a groove at the mating surface for an o-ring. Wheel halves are not identical from the point of view of form but materials used are the same [3]. Landings have a huge impact over wheels, that as consequence need to be frequently inspected and overhauling usually take place every 2000-4000 landings [5]. Material used into the making of these components are the one in table 4.14, while the production processes associated to materials are forging and milling for magnesium and titanium alloys and impact extrusion for steel and aluminum alloys. Due to the fact that all materials are metals, it has been decided that wheels an the end of their life undergo a process of recycling and so their disposal has no impact.

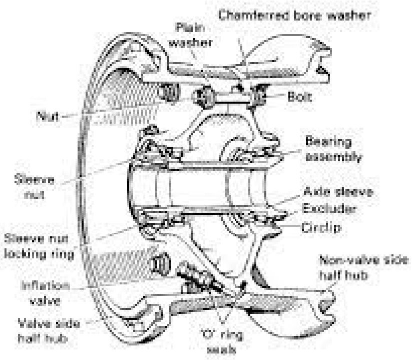


Figura 4.13: Aircraft wheel

Material	Percentage
magnesium alloy	60,0%
aluminium alloy	30,0%
steel alloy	5,0%
titanium alloy	5,0%

Figura 4.14: Wheel breakdown

Brake production

Modern aircraft typically use disc brakes. The disc rotates with the turning wheel assembly while a stationary caliper resists the rotation by causing friction against the disc when the brakes are applied. The size, weight, and landing speed of the aircraft influence the design and complexity of the disc brake system. Single, dual, and multiple disc brakes are common types of brakes. However, it can be said with a relatively good accuracy that material used and in general the production process is quite similar between different types. The difference is inherent into the weight that brake system will have into the aircraft. To model brakes, it has taken from the study made by K. Gradin and al. [56] where products considered are that usually used into the automobile industry. It is a strong hypothesis that cars and aircraft brakes are similar enough to take the impact of the first to be used also for the second. This choice has been made basing over two assumption, the first one is that literature on the subject of LCA is sparse and patchy and the second one is that the brake system described into the paper has been found similar enough to an average aircraft one. Also in this case, as in the case of tires, wearing process has been considered since its particulate emissions in the near airport space are significant.

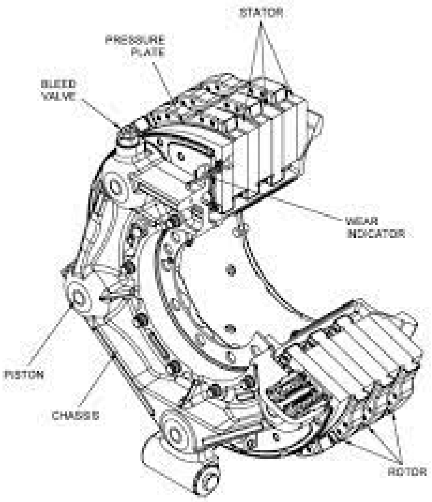


Figura 4.15: Aircraft brake

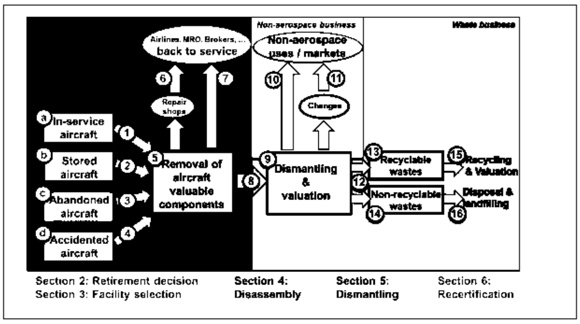


Figura 4.16: Disposal flow

4.7 Life Cycle Inventory - Disposal and treatment

4.7.1 Disposal scenario

Aircraft decommissioning and recycling is a multi disciplinary process, with environmental, operational, safety, legal and economic aspects. Past decades have seen a growing trend into aircraft production with the consequence that every year more and more of these marvelous machines need to undergo end-of-life processes, even if the average age of aircraft at retirement has also increased.

To better understand the importance of the process, it may be useful to analyze each phase it takes. The overall aircraft end-of-life process has been modeled by European project PAMELA [44] into three clearly separate phases:

- The first phase is the decommissioning, the aircraft is parked and stored attending for a decision from the owner airline;
- The second stage, which includes the processes up to the removal of parts for re-use in other aircraft, is part of the aviation domain and subject to the related regulations. During this phase, the retired aircraft is still certified;
- During the third phase, which comprises final dismantling and recycling, the retired aircraft has lost its certification and aviation regulations are no longer applicable.

Into a well-organized airline company end-of-life process is carried out as follows:

- After the owner's decision to disassemble and dismantle an aircraft, it will enter the disassembly process, the purpose of which is to remove the valuable components from the aircraft. The removed components, depending on their technical condition, will either return to the aviation market directly or need to be inspected and repaired or overhauled by an approved repair shop before returning to service. All these activities need to be performed by competent and authorized/certified actors in the aerospace sector because the aircraft is still considered an airworthy machine. It is worth mentioning that during this phase a particular attention is dedicated to fluids present on-board, which are usually highly harmful for both human operators and environment. Thereby, all operating liquids needs to be removed following safety procedures and can then be either re-sold for direct re-use or disposed in specific recovery channels;
- Once the aircraft has permanently lost its airworthiness, it will not be considered as an aircraft under the State of registry's responsibility anymore and begins to be considered as waste instead. Usually this occurs once all the valuable components

> and systems have been dismantled and re-entered into the aviation market and what remains of the aircraft has been sold to a company specialized into dismantling. Thereafter, it has become business waste. Through the process of dismantling, some parts of the aircraft can be re-used for non-aerospace applications, while the rest of the aircraft will be considered as waste and will be extracted and transferred for further treatment. Recyclable parts will be processed, and batches will be prepared for recycling, and the non-recyclable parts will be prepared for disposal.

Today, 85 per cent to 90 per cent 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 [1]. All the previous information has been taken from studies that give a snapshot of what is the end-of-life process at the state-of-art. Having a long history, metal industry has now a level of efficiency that is admirable and the consequence is that almost the entirety of metal parts into an aircraft after dismantling can go through a recycling process and be reused, taking down environmental costs associated with their production. However, the same cannot be said about plastic parts, whose recycling process is not very efficient. Into the production paragraph it has been shown that, excluding some minor components inside the furnishing of the aircraft, the major used plastic products are composited, e.g. wing and fuselage parts made out of carbon fibre panels. At the state-of-art it is difficult to recycle composites which means that landfill and incineration remain the most widely used methods of dealing with them. Nevertheless, many pilot projects are starting between major aircraft production companies and recycling industry, such as the five years agreement signed between the Boeing Co. and carbon fiber recycling specialist ELG Carbon Fibre Ltd. whereby Boeing will supply to ELG cured and uncured carbon fiber composites that will be converted by ELG into secondary products for use in other composites manufacturing applications. Making an hypothesis upon that basis it could be said that from now on the percentage of composites aircraft parts that will undergo a recycling process will increase steadily, optimistically to the same level of metal ones.

This short introduction to the theme of dismantling and disposal of aircraft was needed in order to easily understand all the hypothesis made into the work to treat the procedures and to extrapolate some data about their environmental impact. Considering all the peculiarities of aviation industry previously explained, the end-of-life has been modeled following the path presented in figure 4.16.

The basic idea is that if components are re-entered the market their impact cannot be allocated over the current aircraft and so will be allocated, at their end-of-life, over the aircraft they are mounted on. Following the same concept, it is possible to say that during the dismantling process, ascertained that it will be done in a meticulous way, all recyclable materials will be put aside differentiated on their material composition, which means that from that moment on they can enter the recycling process. The same can't be said of non recyclable materials, which will undergo disposal processes that have a non negligible impact which needs to be allocated over the aircraft. A particular attention is paid to hazardous fluid present on board, e.g. hydraulic fluid that works into the hydraulic system, that, similar to non recyclable materials, needs to be disposed but whose treatment is highly dangerous and involves specialized companies and it is regulated by competent authorities.

To sum up, the assessment of disposal processes is divided into three categories:

- Treatment and disposal of hazardous and non hazardous materials is treated into the production of components that involves these materials, thus the result is that their disposal is also accounted into the environmental impact of sub-system production;

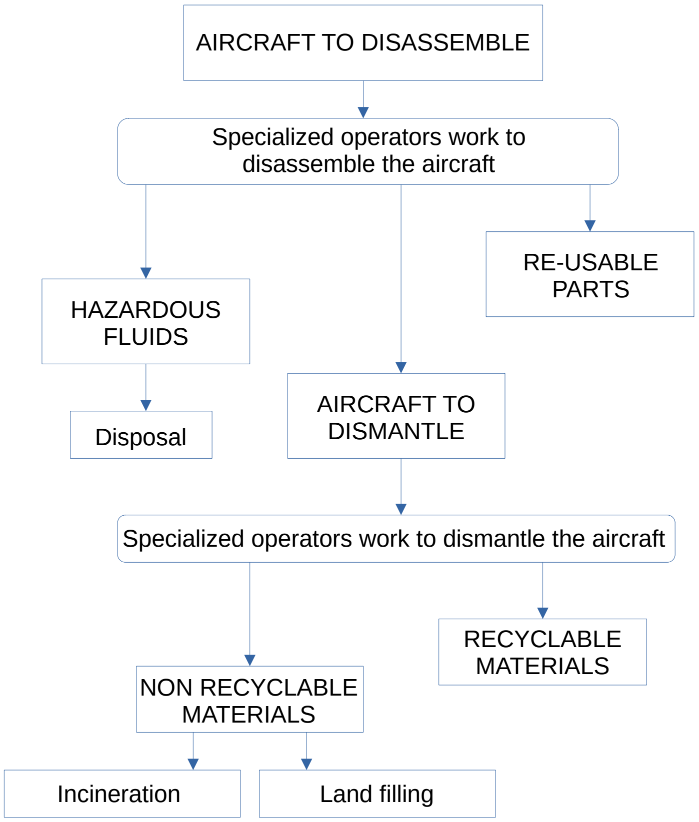


Figura 4.17: End-of-life flowchart

- For components that cannot be dismantled into their basic materials, e.g. batteries or bulbs, the end-of-life process is that modeled by *Ecoinvent* database, whose data comes from disposal industry;
- Dismantling of the whole aircraft system is considered as a separate voice into the life cycle impact assessment, that can be done or can be left aside, and its impact is evaluated as the impact of disassembling and dismantling work, i e. operators using electric tools.

From the point of view of the materials, all metallic ones are considered completely recyclable while for plastic ones the percentage of recycling is taken from European average values so that 32.5% is recycled while the rest is incinerated or landfilled, with a proportion of 2 to 1.

4.7.2 Processes inventory

The idea to assess the impact of these phases is to start from the number of hours that they takes and consider that the 90% of these hours are spent effectively working on the

Disposal program management	laptop operation with internet access
Dismantling and disassembling industrial work	electricity usage, low voltage

Table 4.21: Disposal breakdown

Hazardous fluids treatment	treatment of mineral oil-based fluids

Table 4.22: Hazardous fluids treatment

aircraft while the remaining 10% are due to the program management work needed to efficiently organize and perform the work. The *Ecoinvent* processes chosen for industrial and program management are the one into 4.21 Moreover, to transform the number of hours of industrial work into an energy consumption value in kWh it has been chosen to consider that the average consumption of an electrical working machine could be around 1.2 kW and so this number will be multiplied to the number of hours worked.

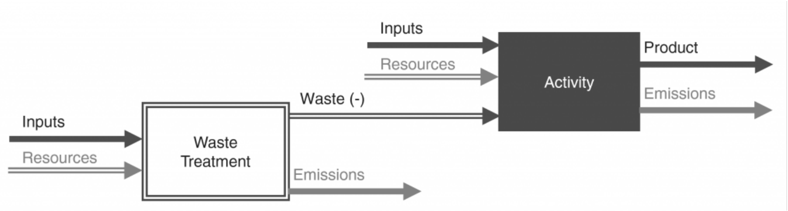
The hazardous fluids treatment process has been chosen keeping in mind that the major component of these fluids is the hydraulic system one, which usually are mineral oil-based fluids, so the process chosen is the one into table 4.22.

4.8 Cut-off allocation method

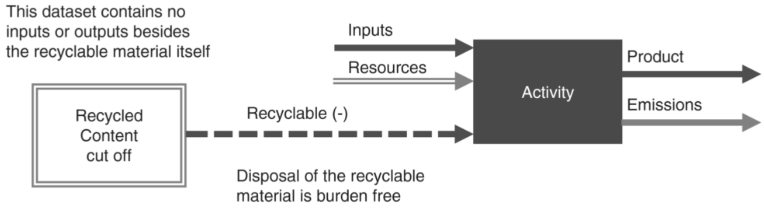
Allocation is the activity of dividing inputs or outputs flow of a process between the product system that is under study and other product systems. This is a problem since the beginning of LCA studies because there is no obvious solution to many impact allocation problems and as a consequence the ISO standards for life cycle assessment leave a large degree of freedom. The main problem is the allocation in case of recycling and multifunctional process for which there are multiple good methods based on different points of view. Here the allocation method used is the cut-off approach. The idea of this approach is that primary production impacts of a material are always allocated to the primary user of that material. This means that if a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary materials impact is affected only by the recycling processes. For example, recycled paper only bears the impacts of waste paper collection and the recycling process of turning waste paper into recycled paper. Forestry activities and processing required for the primary production are not allocated upon recycled paper.

At the database level, all intermediate exchanges within the technosphere are classified into either:

- `Allocatable products`: many production activities products more than one good, all products that are not the main good are ordinary by-products; they have economic value and therefore are included in the allocation, e.g. heat and electricity;
- `Recyclable materials`: these materials has no or little economic value but can serve as the input or resource for a recycling activity and, therefore, interest in their collection exists, e.g. metal scraps and waste paper;
- `Waste products`: waste products are materials with no economic value and whose collection needs to be compensated. The producer, therefore, generally has to pay to dispose of these materials; thus, he consumes the service of disposing of these materials, e.g. wastewater collection and treatments.



(a) Waste treatment



(b) Recycling

This classification is based on the perspective of the data provider and the judgment of the *Ecoinvent* experts and editors. The choice is made based on the use and fate of the product within the *Ecoinvent* database.

Waste by-products have to be treated, and the treatment burden is allocated completely to the waste-producing activity. In this way, wastes are linked as a negative input to the activity, representing the fact that the activity requires the service of waste disposal. Waste disposal is then provided by different treatment processes, which have inputs and emissions that add to the impact of the waste-producing activity.

Recyclable materials are cut off from their production activities through the use of special datasets, denoted as “product name, recycled content cut-off”. These datasets have no inputs or emissions and are therefore burden-free. In a production activity, the material is recorded as a negative input, as in the case of waste; however, the material is not linked to any treatment activity but simply to the empty process [62].

Chapter 5

Ecoinvent processes

After the analysis and explanation of all processes included into the `Life Cycle Inventory`, it is of much importance to show which *Ecoinvent* processes have been chosen to represent them. Usually, a life cycle assessment requires to the analyst to obtain data from direct study of the production site and of the production chain of a good, however in this case first hand data could not be retrieve both because no company has been contacted but most important because using these data would have had the result of losing generality in favor of reliability. As a consequence, only second hand data, coming from various databases, studies and patents, have been used into this thesis.

The most important database that has been used is Ecoinvent®, the most used life cycle assessment database around the world, created by the *Ecoinvent Association*, a not-for-profit organisation dedicated to promoting and supporting the availability of environmental data worldwide. Through many years of excellent work it has achieve the milestone of being the most consistent and transparent life cycle inventory database and of supporting environmental assessments of products and processes worldwide.

Here all processes chosen, all hypothesis made, all articles and patent consulted are reported, subdivided by life phase.

5.1 Material production processes

Main information contained into this paragraph are written into notes of the table below, thereby at the end of the paragraph only some specification will be reported just to complete the description of more complex processes or the ones that have needed more hypothesis in order to be used. To associate every process to the component it produce it is always necessary to consult tables in the previous chapter. Moreover, it is necessary to remember that, even if not specified, raw material production is always taken into consideration when talking about the manufacturing of components whose machining process is the only one reported into the table. In these cases, manufacture is considered as the sum of raw material production and basic working processes.

	***Ecoinvent* v3.8 process name**	**Notes**
RAW MATERIAL PRODUCTION		

	***Ecoinvent* v3.8 process name**	**Notes**
Aluminium	aluminium alloy production. AlLi | copper, cathode | Cutoff,S	primary aluminium slab percentage is up to 30%, aluminium used in aeronautical sector, Canada manufacture
Steel	steel production converter, low alloyed | steel, low-alloyed | Cutoff, S	primary low-alloyed steel produced in a basic oxygen furnace, Europe manufacture
	steel production electric low alloyed | steel, low-alloyed | Cutoff, S	secondary low-alloyed steel production from scrap, electric furnace, Canada manufacture
Titanium	titanium production | titanium | Cutoff, S	primary titanium production by the Kroll process, average values from Global production
Nickel-based superalloy	nickel-based superalloy production | nickel-based superalloy | Cutoff, S	the production of this raw material has been derived from an analysis of commercial nickel-based alloys composition, including the production of every material from cradle to grave, the composition is: 63.4% Ni, 16.6% Cr, 13.8% Co, 3.6% Mo, 2.6% Al, Global manufacture
Carbon fibre	carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded, Cutoff, S	production of carbon fibre reinforced plastic for use in aircraft manufacture, average values from Global production
BASIC PROCESSES		
Aluminium	aluminium milling, small parts | aluminium removed by milling, small parts | Cutoff, S	the reference is for 1kg of metal removed, average assumption is that 0.23kg of aluminium are removed for every kilogram of final product, Europe manufacture
	sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, S	rolling of aluminium ingots to a final thickness from 0.2mm to 6mm, Europe manufacture
	impact extrusion of aluminium, 2 strokes | impact extrusion of aluminium, 2 strokes | Cutoff, S	the final product is one kilogram of aluminium extruded, the process includes all upstream activities and in particular initial cold extrusion and heat treatment of the material,Europe manufacture
	casting, aluminium, lost-wax | casting, aluminium, lost-wax | Cutoff, S	sand casting is usually more common but this technique is used for small parts in aeronautical sector, Canada manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
	anodising, aluminium sheet | anodising, aluminium sheet | Cutoff, S	coating thickness up to 20μm, Canada manufacture
Steel	forging, steel, large open die | forging, steel | Cutoff, S	it includes forging processes, heat treatments, the machining processes (cutting and milling) and final testing, Canada manufacture
	impact extrusion of steel, cold, 2 strokes | impact extrusion of steel, cold, 2 strokes | Cutoff, S	it includes all the upstream activities as well as pre and post treatments, Europe manufacture
Titanium	titanium milling, average | Cutoff, S	reference value is 1kg of titanium removed, average assumption is that 0.23kg of titanium are removed for every 1kg of final product, this database derives from the one used for steel thanks to the use of the [14] work, Europe manufacture
	titanium forging, average | Cutoff, S	reference value is 1kg of titanium forged, it does not include any other process, this database derives from the one used for steel thanks to the use of the [50] work, Europe manufacture
Carbon fibre	layering	in this case processing of material is included into its production, see above

Table 5.1: Raw materials production and basic processes

	***Ecoinvent* v3.8 process name**	**Notes**
COMPONENT MANUFACTURING		
Pump	water pump production, 22kW | water pump, 22kW | Cutoff, S	water pump is taken instead of oil pump because the latter is not in the database, in this case instead of mass the reference value is the energy used by the pump, in calculation environmental impact will be proportioned to the necessary energy input value, Global manufacture
Steel pipe	drawing of pipe, steel | drawing of pipe, steel | Cutoff, S	reference value is 1kg of steel pipe, the process includes heating of the input, piercing, elongation, final rolling and heat treatment,average values of Europe manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
Aluminium pipe	impact extrusion of aluminium, 1 stroke | impact extrusion of aluminium, 1 stroke | Cutoff, S	comparing this process with the one needed to produce steel pipe inputs are similar enough to consider that aluminium pipes are produced in the way it describes, reference value is 1kg of aluminium pipe, the process includes heating of the input, deformation, initial surface treatment and tempering, Europe manufacture
Air compressor	air compressor production, screw type compressor, 300kW | air compressor, screw type compressor, 300kW | Cutoff, S	reference value is one air compressor unit of the weight of 4600kg, in calculation impact values will be proportioned to the weight input value, Europe manufacture
Turbofan engine	turbofan engine production | turbofan engine | Cutoff, S	the reference unit is 1 kg of turbofan engine, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global Manufacture see details about process into the modeled components
Turboprop engine	turboprop engine production | turboprop engine | Cutoff, S	the reference unit is 1 kg of turboprop engine, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global Manufacture see details about process into the modeled components
Traditional electric motor	electric motor production, vehicle | electric motor, vehicle | Cutoff, S	reference value is 1kg of final product, this dataset has been chosen because of affinity between electric motors, Europe manufacture
Innovative electric motor	starter-generator production, with permanent magnet | starter-generator, with permanent magnet | Cutoff, S	the reference unit is 1 kg of starter-generator, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global manufacture see details about process into the modeled components
Electric generator	generator production, 200kW electrical | generator, 200kW electrical | Cutoff, S	reference value is one generator used to produce 200kW of electric energy, in calculation impact values will be proportioned to the electric energy production input value, Europe manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
Starter generator	starter-generator production, with permanent magnet | starter-generator, with permanent magnet | Cutoff, S	the reference unit is 1 kg of starter-generator, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global manufacture see details about process into the modeled components
Powertrain	powertrain production, for electric passenger car | powertrain, for electric passenger car | Cutoff, S	the set is constituted by an electric motor, a converter, an inverter, an charger and a power distribution unit, as well as cables, the output is of 100kW, in calculation impact values will be proportioned to the electric energy production input value, Global manufacture
Control unit	electronic production, for control units | electronics, for control units | Cutoff, S	the reference value is 1kg of electronic for control units made of 46% steel, 32% plastic, 14% printed wiring boards and 8% cables, in calculation the environmental impact will be proportioned to the control unit weight input value, Europe manufacture
Li-ion battery	battery production, Li-ion, NMC111, rechargeable, prismatic | battery, Li-ion, NMC111, rechargeable, prismatic | Cutoff, S	the dataset represent the production of 1kg of Li-ion battery pack used in automotive industry, China manufacture
Li-Sulphur battery	battery production, Li-Sulphur | battery, Li-Sulphur | Cutoff, S	this dataset has been derived from the Li-ion NMC11 dataset thank to the work of G. Benveniste et al [6]
PEM Fuel cell pack	fuel cell production, stack polymer electrolyte membrane, 2kW electrical, future | fuel cell, stack polymer electrolyte membrane, 2kW electrical, future | Cutoff, S - CH	reference value is one pack of PEM fuel cell that produce 2kW of electric power, in calculation impact values will be proportioned to the electric power production input value, Switzerland manufacture
Solid oxide fuel cell pack	fuel cell production, stack solid oxide, 125kW electrical, future | fuel cell, stack solid oxide, 125kW electrical, future | Cutoff, S - CH	reference value is one pack of solid oxide fuel cell that produce 125kW of electric power, in calculation impact values will be proportioned to the electric power production input value, Switzerland manufacture
Conductive cable	cable production, three-conductor cable | cable, three-conductor cable | Cutoff, S	reference value is one meter of cable, in calculation cable length will be proportioned to weight with a linear density of 1.04 kg/m, Global manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
Bulb	compact fluorescent lamp production | compact fluorescent lamp | Cutoff, S	reference value is one fluorescent lamp of the weight of 75g, in calculation impact values will be proportioned with weight input values, Global manufacture
Insulation panel	polystyrene foam slab for perimeter insulation | polystyrene foam slab for insulation | Cutoff, S	reference value is the production on 1kg on insulation panel, density is 33kg/m3 and thermal conductivity is 0.033W/m*K, Switzerland manufacture
Data cable	cable production, data cable in infrastructure | cable, data cable in infrastructure | Cutoff, S	reference value is one meter of cable, in calculation cable length will be proportioned to weight with a linear density of 0.079 kg/m, the cable is a mixture (50:50) of metallic and metal-free glasfibre cable Global manufacture
Electronic instrumentation active	electronic component production, active, unspecified | electronic component, active, unspecified | Cutoff, S	reference value is 1kg of active electronic component, Global manufacture
Electronic instrumentation passive	electronic component production, passive, unspecified | electronic component, passive, unspecified | Cutoff, S	reference value is 1kg of passive electronic component, Global manufacture
Rubber membrane	synthetic rubber production | synthetic rubber | Cutoff, S	this module refers to the EPDM elastomer as it is used in technical products. The name "rubber" means only the unvulcanised polymer without any fillers. EPDM is one of many different rubbers and there are EPDM elastomers of many different compositions, here average values are taken, Europe manufacture
Electric resistance	auxiliary heating unit production, electric, 5kW | auxiliary heating unit, electric, 5kW | Cutoff, S	reference value is one heating unit that consume 5kW of electric power, in calculation impact values will be proportioned to the electric power consumption input value, Switzerland manufacture
Hydraulic actuator	hydraulic actuator production | hydraulic actuator | Cutoff, S	the reference unit is 1 kg of hydraulic actuator, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global manufacture see details about process into the modeled components

	***Ecoinvent* v3.8 process name**	**Notes**
Electro hydraulic actuator	electro hydraulic actuator production | electro hydraulic actuator | Cutoff, S	the reference unit is 1 kg of electro hydraulic actuator, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global manufacture see details about process into the modeled components
Seat production	metal working, average for aluminium product manufacturing | metal working, average for aluminium product manufacturing | Cutoff, S	values are taken doing a mean of environmental impact of European aluminium manufacture in its entirely
	mattress production, polyurethane foam | mattress | Cutoff, S	this dataset represent the production of one polyurethane foam mattress with a dimension of 1 m width, 2 m length and average height of 0.26 m while the density is taken as 50kg/m3, in calculation dimensions will be proportioned to weight input value through density, Global manufacture
Expansion vessel	expansion vessel production, 25l | expansion vessel, 25l | Cutoff, S	the reference value is one expansion vessel with a capacity of 25l, in calculation environmental impact will be proportioned to the volume input values, Switzerland manufacture
Reservoir	expansion vessel production, 25l | expansion vessel, 25l | Cutoff, S	the reference value is one expansion vessel with a capacity of 25l, in calculation environmental impact will be proportioned to the volume input values, Switzerland manufacture
Software	operation, computer, desktop, with liquid crystal display, active mode | operation, computer, desktop, active mode | Cutoff, S	the reference value is the impact of one hour of computer use including both the share of computer production and the energy consumption, as well as transport from factory to user, average values between different computer models, computer life assumed as 6 years, production mix applied for electricity consumption, Europe manufacture
Liquid hydrogen tank	cryogenic hydrogen aluminium tank production | cryogenic hydrogen aluminium tank | Cutoff, S	the reference unit is 1 kg of cryogenic aluminium tank, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global Manufacture see details about process into the modeled components

	***Ecoinvent* v3.8 process name**	**Notes**
Interior furnishing	polystyrene foam slab production, 45% recycled | polystyrene foam slab | Cutoff, S	combination of material and processing module, this process has as reference value the production of 1kg of EPS foam slab, Switzerland manufacture
	window frame production, poly vinyl chloride, U = 1.6 W/m2K | window frame, poly vinyl chloride, U = 1.6 W/m2K | Cutoff, S	the reference value is 1m2 of plastic window frame which weighs 94,5kg, in calculation the impact will be proportioned to the weight input value, Europe manufacture
	polyvinylchloride production, bulk polymerisation | polyvinylchloride, bulk polymerised | Cutoff, S	the reference value is 1kg of bulk PV. Data represent a mix of the two other types of PVC (suspension, emulsion PVC), according to their production volumes, Europe manufacture
	extrusion of plastic sheets and thermoforming, inline | extrusion of plastic sheets and thermoforming, inline | Cutoff, S	the reference unit is 1kg of plastic processed. For every kilogram of plastic in input the output is 94grams of plastic, meaning that the 6% of the input becomes waste and it treatment process is considered, France manufacture
Galley equipment	coffee maker production | coffee maker | Cutoff, S	the activity represents the production and disposal of an average coffee maker weighting 1.9kg, Asia manufacture
	dishwasher production | dishwasher | Cutoff, S	the activity represents the production and disposal of an average dishwasher weighting 50kg, Europe manufacture
	electric kettle production | electric kettle | Cutoff, S	the activity represents the production and disposal of an average electric kettle weighting 1.5kg, Europe manufacture
	microwave oven production | microwave oven | Cutoff, S	the activity represents the production and disposal of an average microwave oven weighting 10.6kg, Asia manufacture
	refrigerator production | refrigerator | Cutoff, S	the activity represents the production and disposal of an average refrigerator weighting 60kg, Asia manufacture
Toilet equipment	polyvinylchloride production, bulk polymerisation | polyvinylchloride, bulk polymerised | Cutoff, S	the reference value is 1kg of bulk PV. Data represent a mix of the two other types of PVC (suspension, emulsion PVC), according to their production volumes, Europe manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
	extrusion of plastic sheets and thermoforming, inline | extrusion of plastic sheets and thermoforming, inline | Cutoff, S	the reference unit is 1kg of plastic processed. For every kilogram of plastic in input the output is 94grams of plastic, meaning that the 6% of the input becomes waste and it treatment process is considered, France manufacture
	metal working, average for aluminium product manufacturing | metal working, average for aluminium product manufacturing | Cutoff, S	values are taken doing a mean of environmental impact of European aluminium manufacture in its entirely

Table 5.2: Material production processes

Here a list of hypothesis made, and not already specified, is presented:

- Where not explicit clarified reference value is always the weight of the component, specifically processes refers to the production of one kilogram of final product;
- Even if not specifically mentioned every component production process also account for the emissions due to its disposal at the end of life, even for components whose production is not already modeled into the database;
- In aluminum production the ratio between primary material and recycled one is 70:30, this ratio is recommended by *Ecoinvent* dataset itself;
- For steel production it has been considered that final product were to be made of primary and secondary processed material in a ratio of 60:40, this is a value usual for the category [12];
- Nickel-based superalloy proportion between different raw metals has been selected as an average between some state-of-art superalloy commonly used upon aircraft, the only limitation is that no information was retrievable about the process of "mixing" all the components together and so only their pure production has been used;
- Carbon fiber reinforced plastic production, as already mentioned, also contains the processing needed to reach the final product, as explicated by the database;
- Even if not explicit clarified when a process remove some material the ratio between removed material weight and final product weight is 23:100, this value is often recommended by *Ecoinvent* database itself;
- Even if not explicit clarified aluminum is always considered as anodized. This hypothesis is used to consider all superficial treatments that aluminum components undergo before assembly;
- In aerospace industry aluminum usually undergo some chemical treatment, such as chemical milling, used to remove material in a not homogeneous way. Unfortunately, none of these processes is present into the database and so they cannot be accounted, even if their emissions are logically high;

- For aluminum molding the process impact extrusion 2 strokes is chosen because the differences between different impact extrusion manufacturing in terms of environmental impact is relatively small and this seemed as a good average value;

- For aluminum casting the only process found into *Ecoinvent* database was lost wax, that is a relatively obsolete technique and is not usually used except in a few cases, but the weight of components made through casting over aircraft weight is really small so the influence is limited;

- For titanium manufacturing, due to the problem that into the database it could not be find a process for this material, the process taken into account is based on steel milling. In this case, values have been changed accordingly to the work [14], that is a comparative analysis between the manufacturing of these two metallic materials;

- It was not possible to find hydraulic pump production in the database so water pump production has been considered similar enough to be used in place of oil one;

- An average value for electronic component production is used to represent all the different equipment present into the avionic system. Ratio between electronic instruments and data cables in terms of mass is the one in 5.3;

- Electric powertrain and fuel cell production is taken to give the possibility to the user to made some changes of the traditional aircraft configuration toward an hybrid electric configuration, values of this innovative technologies are derived from automotive sector;

- Between different fuel cell technologies proton membrane exchange and solid oxide are the ones chosen because they are the ones that has the most attractive features, accordingly to the work Zehua D. et al. [13]. Here it is proved that fuel cell technology could also be used to compare the substitution of an internal combustion engine APU with a PEMFC APU;

- Reservoir in thermal management system is counted as an expansion vessel considering that the configuration of these two components is similar enough;

- Seat production is synthesized considering the production of the aluminum body and the polyurethane padding. Every seat is valued to weight around 7 to 10 kilograms and references about its constitution have been taken from [4];

- Interior furnishing is evaluated to be a mix of foam panels and rigid plastic internal lining. The confidence over values accuracy is not high but for the scope of the tool to compare different aircraft configurations the accuracy over furnishing is relatively negligible. If this work will be continued, this aspect is surely one to be deepened;

- Operational equipment accounts for galley equipment and toilets. First assumption is that toilet and galley facilities have the same weight, meaning that if there are two toilets and one galley into an aircraft operational equipment weight will be divided into three equal parts. The second assumption is that galley is constituted by these electric devices tabulated above, and its production emissions, as a consequence, would be an average value of them. In the meanwhile, toilets are modeled as made by aluminum components and some rigid plastic items.

electronic instrumentation active	10.0%
electronic instrumentation passive	45,0%
data cable	45,0%

Table 5.3: Electronic component breakdown

5.2 Immaterial production processes

	***Ecoinvent* v3.8 process name**	**Notes**
computer operation, active mode	operation, computer, desktop, with liquid crystal display, active mode | operation, computer, desktop, active mode | Cutoff, S	the reference value is the impact of one hour of computer use including both the share of computer production and the energy consumption, as well as transport from factory to user, average values between different computer models, computer life assumed as 6 years, production mix applied for electricity consumption, Europe manufacture
laptop operation with internet access	operation, computer, laptop, 68% active work with internet access 0.2 Mbit/s | operation, computer, laptop, 68% active work with internet access 0.2 Mbit/s | Cutoff, S	the reference value is the average impact of one hour of work using a laptop computer and broadband access to company server, it includes both the consumption of hardware (laptop and internet devices) and energy, production mix applied for electricity consumption, Canada manufacture
metal working machine production	metal working machine production, unspecified | metal working machine, unspecified | Cutoff, S	1kg of this process is needed for 1kg of metal working machine, *Ecoinvent* database also contains a price associated with this product and it will be used as reference value to re-scale the impact of this process, Europe manufacture
electricity usage, low voltage	market for electricity, high voltage | electricity, high voltage | Cutoff, S	this is a market activity which represents the consumption mix of a product in a given geography, connecting suppliers with consumers, it starts with the production of 1kWh of electricity fed into the high voltage transmission network and ends with the transport of 1 kWh of high voltage electricity in the transmission network over aerial lines and cables, France manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
transport, passenger aircraft, very short	transport, passenger aircraft, very short haul | transport, passenger aircraft, very short haul | Cutoff, S	the dataset represents the transport of one passenger over a distance of less than 800 km in an average passenger aircraft, and for an average over all passenger classes (economy, business and first). The dataset represents the entire transport life cycle including the production of the aircraft and the construction and operation of the airport, Global operations
factory construction	metal working factory construction | metal working factory, Cutoff, S	4.58E-10 units of this process are needed to produce 1kg of final product, it includes all upstream activities and all infrastructure needed for a metal working factory, Europe manufacture
energy and auxiliary inputs	energy and auxiliary inputs, metal working factory, with heating from natural gas | energy and auxiliary inputs, metal working factory | Cutoff, S	1kg of this process is needed for every 1kg of the final product, based on the average consumption of factories for ancillary processes, these encompass electricity for lighting and general water consumption, as well as heating, Europe manufacture
shed construction	building construction, hall, steel construction | building, hall, steel construction | Cutoff, S	the reference value is the construction of 1m2 of a hall made out of concrete and steel, it also includes maintenance operations and demolition after a life of 50 years, Switzerland manufacture
transport, passenger car	transport, passenger car | transport, passenger car | Cutoff, S	this activity provides an average transport in a passenger car, by linking specific "transport, passenger car", both with internal combustion engine and electric, into a generic product, Europe manufacture
transport, passenger aircraft, short	transport, passenger aircraft, short haul | transport, passenger aircraft, very short haul | Cutoff, S	the dataset represents the transport of one passenger over a distance between 800 and 1500 km in an average passenger aircraft, and for an average over all passenger classes (economy, business and first). The dataset represents the entire transport life cycle including the production of the aircraft and the construction and operation of the airport, Global operations
passenger aircraft, very short	aircraft production, passenger aircraft, very short haul | aircraft, passenger, very short haul | Cutoff, S	the dataset represents the production of a passenger aircraft used for very short haul flights (<800 km), average values, Global manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
passenger aircraft, short	aircraft production, passenger aircraft, short haul | aircraft, passenger, short haul | Cutoff, S	the dataset represents the production of a passenger aircraft used for short haul flights (800< <1500 km), average values, Global manufacture

Table 5.4: Immaterial production processes

Notes into 5.4 have been derived from databases description to ease the understanding of which process have been chosen for every good needed and how data about it is elaborated. Obviously, a consideration is necessary from the beginning, since tools and infrastructures chosen have a predetermined life. This means that, into calculations, as often as the number of hours of use of an asset exceeds the lifetime of the asset itself, then all emissions related to the disposal of the old good and the production of the new one are added, as if upon crossing this fictitious barrier the product was replaced. Additional hypothesis are:

- Electricity is considered as produced and consumed in France which means that French electricity mix is the one taken into account. This assumption poses a limitation due to the fact that French electricity mainly come from nuclear plants. However, the reason behind this choice is that, through all the thesis, production processes coming from Europe were predominantly chosen and the biggest European aircraft manufacture is sited into France, so this electricity mix could be the more representative. Moreover, it is written that this process account for low voltage energy consumption but the process taken from *Ecoinvent* database is for high voltage consumption. This is not really a problem since to consider the conversion form high to low voltage a factor 0.96 may be used, derived from the conversion efficiency of primary and secondary cabins;

- The dataset for “transport, passenger aircraft” also consider the emissions share due to aircraft production and, thereby, in calculation it will be necessary to eliminate this share to have only the impact of using a portion of airport life and of consuming kerosene;

- Factory construction is modeled into *Ecoinvent* considering that 4.58E-10 units of this process are needed to produce 1 kg of final product, which means that plant construction emissions are put into relation with the kg of product manufactured within it. This has been considered not to be the best possible way and so the impact has been linked to its extent considering that an average plant of *Ecoinvent* proportionally could occupy 274 000 m2. This values derives from the comparison to some of USA most important production plant, such as Boeing’s Everett plant in Washington state, which covers over 400000 square, or the Airbus plant in Mobile, Alabama, which covers approximately 270000 square meters and is used for the final assembly of Airbus A320;

- Shed construction database is not properly build into *Ecoinvent* and only some type of shed are accounted, for which the main construction material is wood. This, however, cannot be the case of an aircraft shed so it has been chosen to use hall construction instead. Reasons behind this choice are that, first of all, both the shed and the hall are build in concrete and steel, so there is no difference from the point of view of materials, and secondly the reference unit is one square meter of structure and so it is not necessary to make further assumptions but real values from shed that will be build for the project can be used directly;

- Differences between very short and short haul aircraft is that the first process will be used to calculate emissions due to test flights that are usually not so long, while the second one is needed to consider all the air travels that take place during program management work.

5.3 Operative life processes

	***Ecoinvent* v3.8 process name**	**Notes**
electricity_production	electricity, high voltage, production mix | electricity, high voltage | Cutoff, S - GE	the reference unit is the production of 1kWh of electricity, production technologies used are the one currently used in Germany, its production mix has been taken as an average value for European countries, German manufacture
kerosene_burning	heat and power co-generation, kerosene burning | Cutoff, S – CH	the reference unit is the burning of 0.00835kg of kerosene into a heat and power co-generation unit, it includes all upstream activities i.e. petroleum extraction and kerosene production, into calculation its impact will be proportioned to kerosene consumption, Europe manufacture
SAF_burning	heat and power co-generation, kerosene burning | Cutoff, S – CH	the dataset has been derived from the kerosene_burning one, the reference unit here is the burning of 0.00835kg on an average sustainable aviation fuel, average values of impact has been derived from statistic and are 1/3 of kerosene ones, Europe manufacture
LH_production	market for hydrogen, liquid | hydrogen, liquid | Cutoff, S – ReR	this is a market activity which represents the consumption mix of liquid hydrogen in Europe, connecting suppliers with consumers, it also accounts for transport to the consumer and for the losses during that process, when relevant, Europe manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
airport_construction	market for airport | airport | Cutoff, S - GLO	the dataset represents the construction, the maintenance and land use and the disposal of airport infrastructure of one entire airport. The data represents the airport in Zurich. The dataset of the maintenance and land use represents the maintenance and land use of one entire airport, Switzerland manufacture
transport_very_short_haul	transport, passenger aircraft, very short haul (without aircraft) | transport, passenger aircraft, very short haul | Cutoff, S - GLO	the dataset represents the transport of one passenger over a distance of less than 800 km in an average passenger aircraft, and for an average over all passenger classes (economy, business and first). The dataset represents the entire transport life cycle including the production of the aircraft and the construction and operation of the airport, Global operations
transport_short_haul	transport, passenger aircraft, short haul (without aircraft) | transport, passenger aircraft, short haul | Cutoff, S - GLO	the dataset represents the transport of one passenger over a distance between 800 and 1500 km in an average passenger aircraft, and for an average over all passenger classes (economy, business and first). The dataset represents the entire transport life cycle including the production of the aircraft and the construction and operation of the airport, Global operations
transport_medium_haul	transport, passenger aircraft, medium haul (without aircraft) | transport, passenger aircraft, medium haul | Cutoff, S - GLO	the dataset represents the transport of one passenger over a distance between 1500 and 4000 km in an average passenger aircraft, and for an average over all passenger classes (economy, business and first). The dataset represents the entire transport life cycle including the production of the aircraft and the construction and operation of the airport, Global operations

Table 5.5: Mission processes

	***Ecoinvent* v3.8 process name**	**Notes**
ground_support_transport	transport, regular bus | transport, regular bus | Cutoff, S	reference unit is one passenger for one kilometer traveled, dataset represents the entire transport life cycle, including road infrastructure, expenditures and environmental interventions due to construction of roads, energy use and combustion emissions data represents average data for the operation of an average Swiss regular bus
electricity_usage_low_voltage FR	market for electricity, high voltage | electricity, high voltage | Cutoff, S – FR	this is a market activity which represents the consumption mix of a product in a given geography, connecting suppliers with consumers, it starts with the production of 1kWh of electricity fed into the high voltage transmission network and ends with the transport of 1 kWh of high voltage electricity in the transmission network over aerial lines and cables, France manufacture
energy_and_auxilliary_inputs	energy and auxilliary inputs, metal working factory, with heating from natural gas | energy and auxilliary inputs, metal working factory | Cutoff, S	the reference unit is one hour of facility auxilliary energy consumption, based on the average consumption of factories for ancillary processes, these encompass electricity for lighting and general water consumption, as well as heating, Europe manufacture
Li_ion_battery_production	battery production, Li-ion, NMC111, rechargeable, prismatic | battery, Li-ion, NMC111, rechargeable, prismatic | Cutoff, S	the dataset represent the production of 1kg of Li-ion battery pack used in automotive industry, China manufacture
Li_S_battery_production	battery production, Li-Sulphur | battery, Li-Sulphur | Cutoff, S	this dataset has been derived from the Li-ion NMC11 dataset thank to the work of G. Benveniste et al. [6]
PEM_fuel_cell_production	fuel cell production, stack polymer electrolyte membrane, 2kW electrical, future | fuel cell, stack polymer electrolyte membrane, 2kW electrical, future | Cutoff, S	reference value is one pack of PEM fuel cell that produce 2kW of electric power, in calculation impact values will be proportioned to the electric power production input value, Switzerland manufacture

	***Ecoinvent* v3.8 process name**	**Notes**
SO_fuel_cell_production	fuel cell production, stack solid oxide, 125kW electrical, future | fuel cell, stack solid oxide, 125kW electrical, future | Cutoff, S	reference value is one pack of solid oxide fuel cell that produce 125kW of electric power, in calculation impact values will be proportioned to the electric power production input value, Switzerland manufacture
hydraulic_oil_production	lubricating oil production | lubricating oil | Cutoff, S	dataset represents the production of 1 kg of liquid lubricating oil, including additives, used into internal combustion engines, vehicle and industrial gearboxes, compressors, turbines, or hydraulic systems, mineral oil components is the most important ingredients of lubricants, Europe manufacture
hydraulic_oil_treatment	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, S	the treatment process in this case includes only the incineration of these fluids, that are highly dangerous, in order to produce electricity and heat, Europe manufacture
tire_production	market for aircraft tyre production | aircraft tyre production | Cutoff, S	the reference unit is 1 kg of aircraft tire, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global Manufacture see details about process into the modeled components
wheel_production	aircraft wheel production | aircraft wheels | Cutoff, S	the reference unit is 1 kg of aircraft wheel, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global Manufacture see details about process into the modeled components
brake_production	disc brake production, use and disposal | disk brake | Cutoff, S	the reference unit is 1 kg of aircraft disk brake, the final product has been assembled starting from raw material production and adding some transformation process to account for raw materials forming, Global Manufacture see details about process into the modeled components

Table 5.6: Maintenance processes

Hypothesis:

- To account for ground support equipment transport, where units usually used may include vans, trucks, or portable shelters containing some test and support equipment and spare parts, it has been chosen to use the process of transportation by bus. The reference unit in this case is in person × km traveled and so the hypothesis made to assess its impact is that every working man-hour is associated with a travel of 5km, it can be seen as if the workers and the roving maintenance vehicle are deployed from the airport hangar to an airplane parked at a commercial airline terminal gate and needing extended maintenance;

- Electricity consumed into the various tasks is not always the same. In facts, it has been thought that France production mix could be more suitable to account for the consumption associated with the industrial machines during production while Germany production mix is utilized to represent average European values into production of electric energy used into the flight by hybrid electric architectures;

- Energy and auxilliary inputs associated with the use of a facility during intermediate or depot maintenance undergo the same hypothesis exposed into the production processes inventory. Briefly, it has been derived from consumption data about European industry that average values for every square root of a plant are 0.075 kWh of heat derived from natural gas burning and 0.0046 kWh of electricity [47]. Obviously, they are associated only to auxiliary utilities, e.g., lighting or heating of spaces;

- “SAF_burning” process is derived from “kerosene_burning” process. This is due to the fact that these two fuels differ from the point of view of production but are really similar into their use. They both can be burned into internal-combustion engines and their specific energy is quite similar. However, as said, they differ in production with biofuels that derive from sintering of vegetable oils or animal fats. According to work made by Katja Oehmichen et al. [37], SAF can have very different characteristics across typologies. It has been chosen to represent them by averaging over the percentage reduction in emissions compared to kerosene. The conclusion is that “SAF_burning” process emissions are one third of the kerosene ones [40] [41];

- To take into account NOx emissions into the process “LH_production” due to hydrogen combustion to the entries “Ozone formation, Terrestrial ecosystems” and “Ozone formation, Human health” were added 1.2e-2kg of NOxeq for each kg of hydrogen. This value has been derived from the work of B.Fumey and al. [23], where tests have show a maximum emission of 0.366 mg of NOx for every 1 kWh of hydrogen. Due conversions have been made considering that hydrogen has 33 kWh of potential energy for every kg.

5.4 Dismantling and disposal processes

No more hypothesis were needed for the disposal process, in addiction to the ones made into the previous chapter, and so here only *Ecoinvent* processes chosen are reported.

	***Ecoinvent* v3.8 process name**	**Notes**
Laptop operation with internet access	operation, computer, laptop, 68% active work with internet access 0.2 Mbit/s | operation, computer, laptop, 68% active work with internet access 0.2 Mbit/s | Cutoff, S	the reference value is the average impact of one hour of work using a laptop computer and broadband access to company server, it includes both the consumption of hardware (laptop and internet devices) and energy, production mix applied for electricity consumption, Canada manufacture
Electricity usage, low voltage	market for electricity, high voltage | electricity, high voltage | Cutoff, S	this is a market activity which represents the consumption mix of a product in a given geography, connecting suppliers with consumers, it starts with the production of 1kWh of electricity fed into the high voltage transmission network and ends with the transport of 1 kWh of high voltage electricity in the transmission network over aerial lines and cables, France manufacture
Treatment of mineral oil-based fluids	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, S	the treatment process in this case includes only the incineration of these fluids, that are highly dangerous, in order to produce electricity and heat, Europe manufacture

Table 5.7: Disposal processes

Chapter 6

Cases study

After the detailed description of the complete inventory, and associated hypothesis, that has been assembled to consider all the process that takes place both into the production and the operation of an aircraft it is now the moment of using it to study some real cases. Main cases study comes all from the ATR family, where they have been used firstly to calibrate the ALiCIA tool and, secondly, to validate results. Into the following the first aircraft proposed will be the ATR42 and results about it will be taken as a mile stone to compare others models, a bigger one that is the ATR72 and a similar ATR42 hybrid-electric distributed propulsion one. For all the case study it has been chosen to assess the fuel consumption impact over the same route which range is of 200 NM and the number of flights is 37500, approximately considering around 1875 flights per year for a life of 20 years.

6.1 ATR42

The ATR 42 is a regional airliner produced by Franco-Italian manufacturer ATR, with final assembly in Toulouse, France. On 4 November 1981, the aircraft was launched with ATR, as a joint venture between French Aérospatiale, now Airbus, and Aeritalia, now Leonardo S.p.A.. The one taken into account is the model 300 that has the following characteristics:

Maximum number of passenger	48	
Maximum take off weight	16700	Kg
Maximum range	1259	Km
Number of aircraft to build	497	
Price	14.35	Million US 2002 dollars

Table 6.1: ATR42 initial data

Weights of systems have been taken by the Jane's all the world aircraft [32] and from ATR family training manual, most important values are here reported.

The decision about most important impact categories has been of showing and commenting results only over three midpoint categories: global warming, terrestrial acidification and ozone formation, which have been extensively explained into chapter 3.

Material production

Here only emissions directly connected with the production processes of components, as already stated, are considered. Some hypothesis have been necessary to get a complete analysis and have been derived both from maintenance manuals and experience:

- The propeller system weight is of around 200 kg, as the sum of both engines ones;
- The `electrical generation` subsystem is composed of an electrical generator which produces 16 kW in power, a starter generator, due to the absence of the APU, which produces 12 kW in power and an Nickel Cadmium battery of nominal energy of 1kWh;
- Fuel consumed is kerosene and during type mission the total consumption is of 540,78 kg.

The results of the analysis are:

	kg CO2eq.	**kg SO2eq.**	**kg NOxeq.**
WING	6,88E+04	2,94E+02	1,81E+02
FUSELAGE	4,36E+04	2,74E+02	1,37E+02
TAIL	4,00E+04	1,51E+02	8,41E+01
LANDING GEAR	9,88E+03	3,28E+01	2,48E+01
NACELLE AND STRUCTS	2,37E+04	9,80E+01	5,34E+01
EQUIPPED ENGINES AND PROPELLERS	5,44E+04	8,34E+02	1,46E+02
FUEL SYSTEM	6,32E+02	4,49E+00	2,21E+00
HYDRAULIC GENERATION	3,81E+02	4,87E+00	1,39E+00
HYDRAULIC DISTRIBUTION	1,30E+02	4,96E-01	3,23E-01
ENVIRONMENTAL CONTROL SYSTEM	2,30E+03	1,76E+01	7,98E+00
THERMAL MANAGEMENT SYSTEM	0,00E+00	0,00E+00	0,00E+00
DE ICING	1,48E+03	8,44E+00	4,34E+00
FLIGHT CONTROL SYSTEM	8,56E+02	3,14E+00	2,06E+00
AVIONIC INSTRUMENTS	4,72E+04	2,37E+02	1,57E+02
ELECTRICAL GENERATION	1,67E+04	4,62E+02	8,88E+01
ELECTRIC COMMON INSTALLATIONS	5,46E+03	2,29E+01	1,26E+01
THERMO ACOUSTIC INSULATION	4,09E+02	9,76E-01	7,66E-01
FURNISHING	3,42E+03	8,35E+00	5,29E+00
LIGHTING	4,49E+03	2,57E+01	1,53E+01
OPERATIONAL ITEMS	5,67E+03	2,79E+01	1,68E+01
OPERATIONAL EQUIPMENT	2,87E+03	1,72E+01	8,00E+00
SYSTEMS SOFTWARE	1,47E+02	6,85E-01	4,18E-01
TOTAL	3,33E+05	2,52E+03	9,49E+02

Table 6.2: ATR42 material production impacts

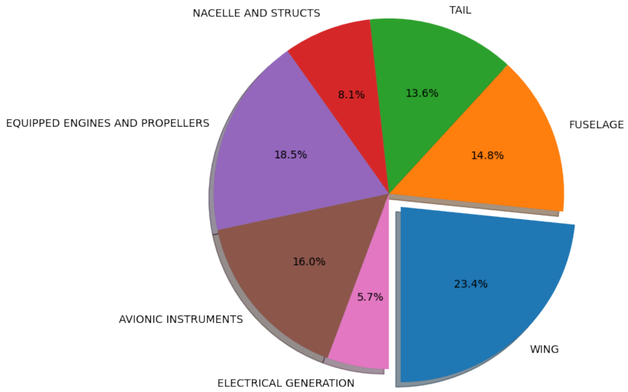


Figura 6.1: Most impactful components - Global Warming

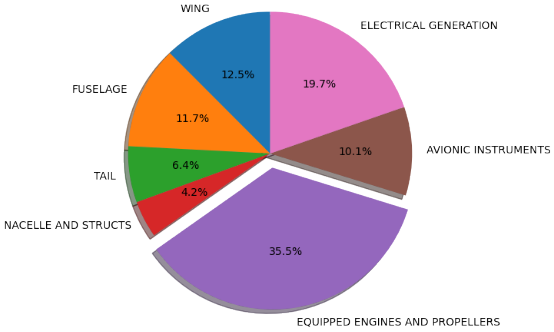


Figura 6.2: Most impactful components - Terrestrial Acidification

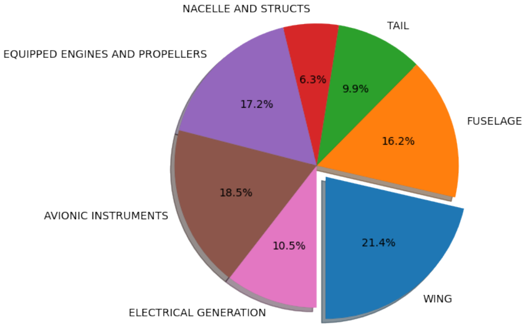


Figura 6.3: Most impactful components - Ozone formation

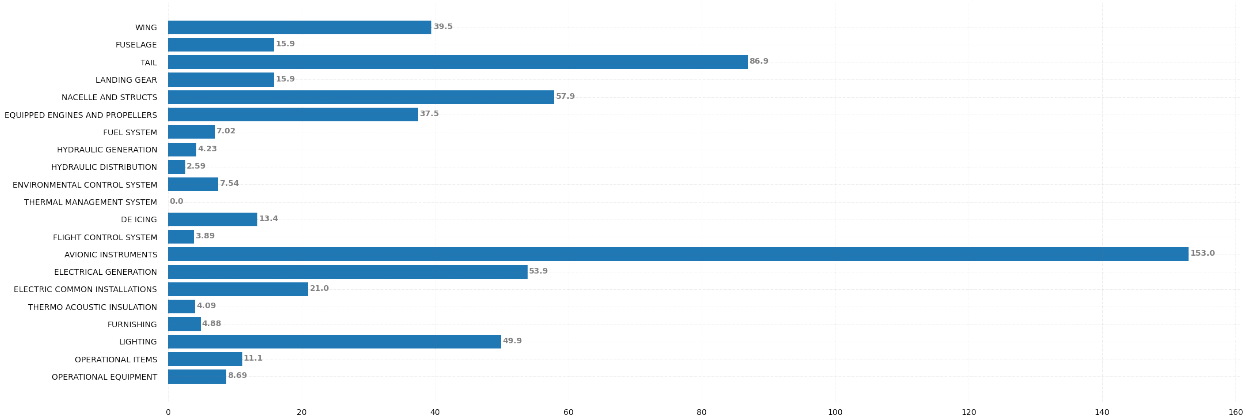


Figura 6.4: Material production breakdown - normalized CO2eq emissions

As can be seen from these graphs, most impactful categories are the same for both CO2eq, SO2eq and NOxeq emissions and they are those that weight more, like structure, but also that need more processes to be manufactured, like engines. Proceeding by order, between structure components it is possible to notice that wing is always more impactful than fuselage, even if fuselage weight is quite the double. This result can be related to a greater use of composite within the wing. A similar approach must be used for the tail, whose weight is about one-fifth of that of the fuselage but where the high percentage of composite, much greater than in the fuselage since the tail is almost entirely composed of this material, makes the impact of the two components comparable. On the other hand, engines are made out of metal material but requires many manufacturing processes and so, despite their relatively little weight, their impact can be compared to structures one. Most important is to notice that their production determines many SO2eq emission, due both to processes used but also to the heavy use of nickel based alloys. The last impactful typology of components are avionic instruments. This is the result of the use of valuable materials, such as rare earths, very specialized manufacturing processes, and also, a factor not to be underestimated, by the limited ability, at the state of the art, to recover these components at their end of life. All these reasons translate themselves into a great total impact.

It is now of use to show the results after a normalization of emissions through the weight of each component. Via the graph 6.4, where weight is no more an impact factor, it is possible to really understand how much emissions of component are related to materials they are composed of and to processes they need to undergo. From this point of view, avionic instruments are much more impactful, and so it is the tail, while engines or the wing are downsized. Another typology of components rises to prominence, the lighting system. In fact, its weight is very very little, around 90 kg, but emissions of CO2eq. per kilogram are really high due to the use of rare materials and complex production processes.

Immaterial production

Values into table 6.3 are the ones used into immaterial production assessment, they are all in man-hours except for tooling that, as said into the 5, is in US dollars and the initial spares that are given as a percentage of the whole aircraft. Data necessary to fill

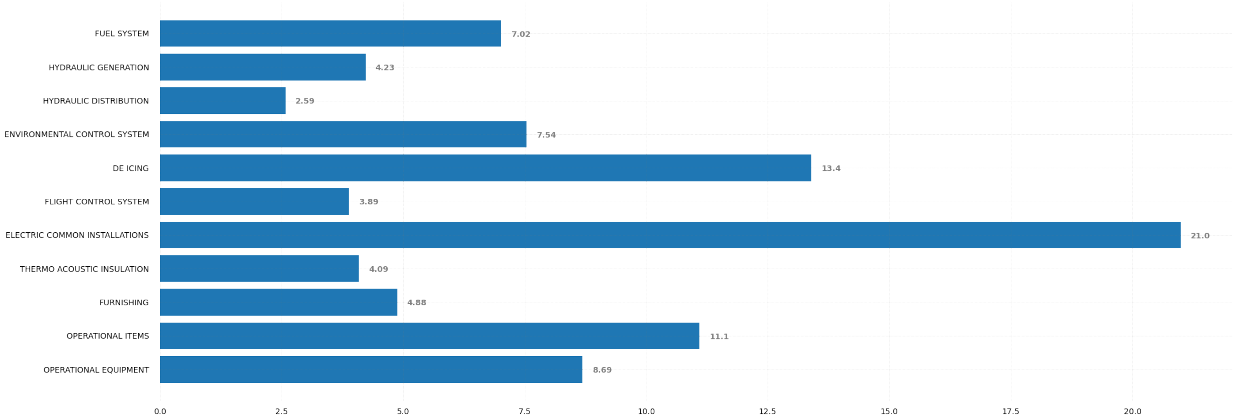


Figura 6.5: Less impactful components - normalized CO2eq emissions

DEVELOPMENT AND MANUFACTURING	
engineering	1,36E+04
manufacturing work	1,32E+05
tooling	7,45E+06
quality control	4,59E+03
PROGRAM MANAGEMENT	1,33E+04
TEST AND EVALUATIONS	
prototypes production	3/497
testing	3,48E+04
DATA MANAGEMENT	4,76E+02
SITE OPERATION	1,81E+01
INITIAL SPARES	15,00%

Table 6.3: ATR42 immaterial production

the immaterial production table of the software are derived from a simulation made with the life cycle cost design software PRICE TruePlanning®, data are reported into table 6.3. Hypothesis are that it has been considered 150 hours of flight testing, that is the minimum the normative accepts for aircraft that mount already widely used engines [15], that data management is necessary for all the life of the program, 24 hours over 24 hours, 365 days per year and, last but not least, that all aircraft have been build into two years, which means that the plant have been used 730 days in total, considered a work-shift of 8 hours a day. It is possible to see that most impactful voices remain always pretty the same through different emissions. Nevertheless, some processes are more important under one point of view and others under another one. Initial spares, deriving directly from the material production of the aircraft, is the most important voice for both CO2eq, SO2eq and NOxeq emissions. However, due to the fact that the last two have an impact localized only to the place where they are emitted, it is a little difficult to understand the real consequences. The discourses changes when the pollutant analyzes is the CO2eq

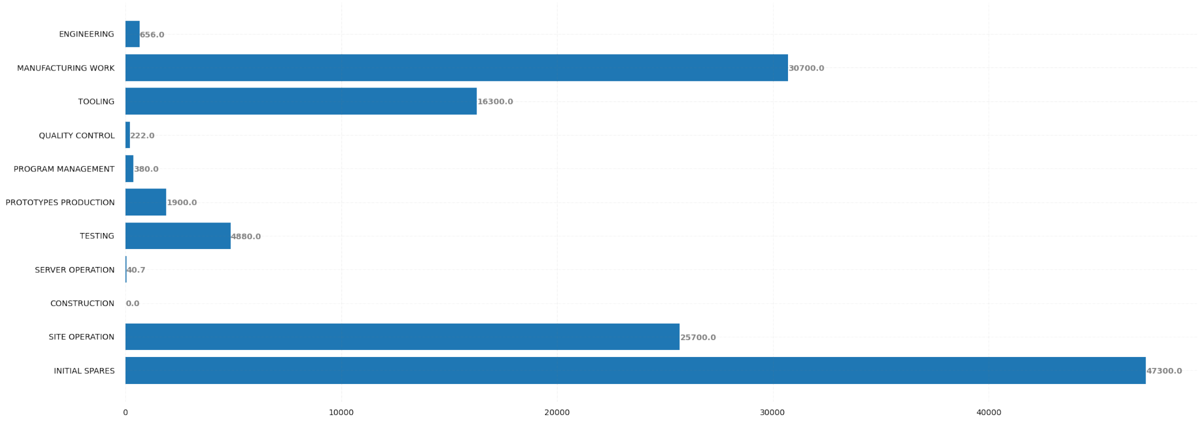


Figura 6.6: Immaterial production breakdown - Global Warming

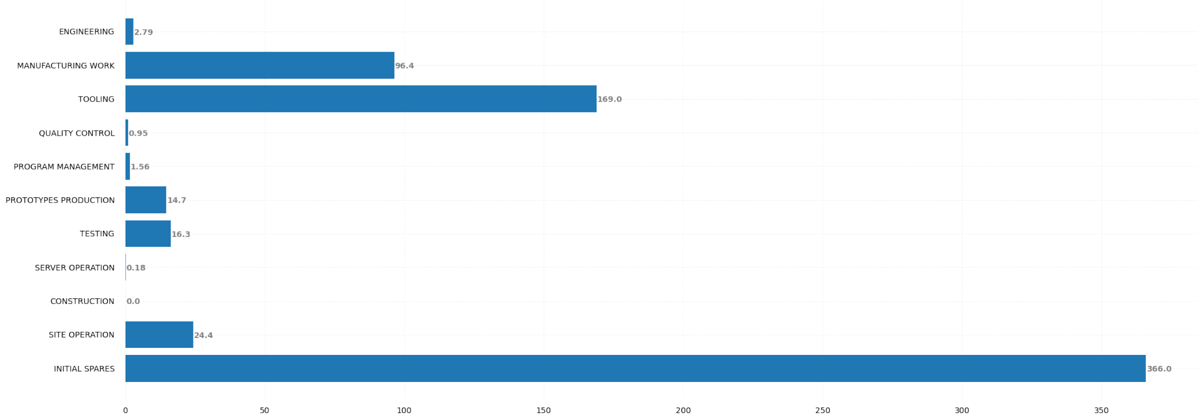


Figura 6.7: Immaterial production breakdown - Terrestrial Acidification

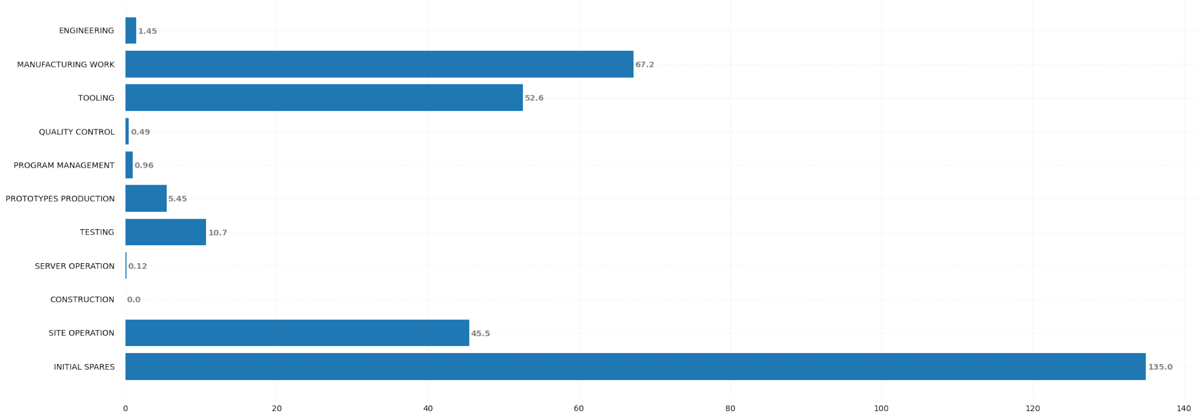


Figura 6.8: Immaterial production breakdown - Ozone formation

because in this case consequences, that are global, can be understood better. Others important voices are manufacturing work, due to the high requirement of working hours and of electrical energy to power all the instrumentation needed for the assembly of subsystems, systems and finally aircraft, and tooling, which is a fundamental voice since the production of a new aircraft brings with it the need to create dedicated machinery and a specific production line for the new product. Moreover, for the cost estimation analysis, it was assumed that basis for the project were null and so all equipment need to be build from new.

Maintenance

Maintenance phase has been treated considering the following assumptions:

- Tires need to be changed every 250 flights;
- Wheels and brakes need to be changed every 2500 flights;
- Batteries and hydraulic oil need to be substituted every 2500 hours of flight;
- The replacement percentage during life of engines and avionics is 120% while for other components is 40% or 30%;
- Direct maintenance operations man-hours have been estimated from statistics considering the number and type of checks the aircraft will undergo during its life and their duration.

In absolute values, these are the results for this phase 6.4.

	kg CO2eq.	**kg SO2eq.**	**kg NOxeq.**
ORGANIZATIONAL MAINTENANCE	4,49E+03	2,08E+01	4,42E+01
INTERMEDIATE MAINTENANCE	3,11E+04	5,01E+01	5,91E+01
DEPOT MAINTENANCE	3,17E+04	7,25E+01	6,43E+01
TIRES	1,39E+04	5,54E+01	9,47E+01
WHEELS	9,17E+04	2,91E+02	2,35E+02
BRAKES	4,25E+03	2,83E+01	9,44E+00
BATTERY	8,29E+03	2,20E+02	2,59E+01
FUEL CELL SYSTEM	0,00E+00	0,00E+00	0,00E+00
HYDRAULIC OIL	1,09E+04	1,72E+01	2,67E+01
ENGINES	6,53E+04	1,00E+03	1,76E+02
AVIONICS	5,67E+04	2,84E+02	1,88E+02
FUEL SYSTEM	2,53E+02	1,80E+00	8,83E-01
HYDRAULIC SYSTEM	2,04E+02	2,15E+00	6,86E-01
ELECTRIC SYSTEM	4,36E+03	1,83E+01	1,01E+01
STRUCTURE	5,58E+04	2,55E+02	1,44E+02
TOTAL	3,79E+05	2,32E+03	1,08E+03

Table 6.4: ATR42 maintenance impacts

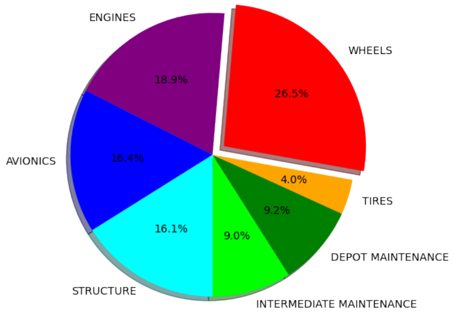


Figura 6.9: Most impactful components - Global Warming

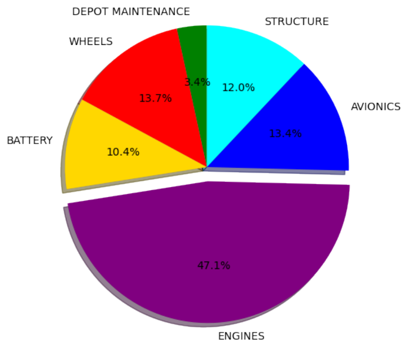


Figura 6.10: Most impactful components - Terrestrial Acidification

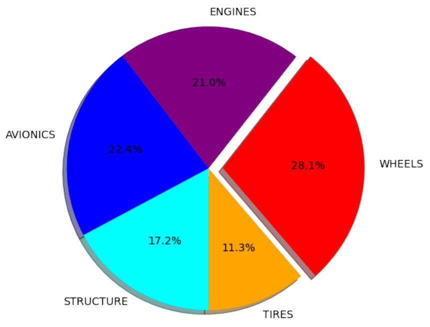


Figura 6.11: Most impactful components - Ozone formation

Unlike immaterial production phase, in maintenance phase as the impact category changes the most important impact items change. Components that always show up are:

- Engines, which have a very relevant impact into terrestrial acidification process, as already seen into the production;
- Structure, whose components are not substituted many times during the life of the aircraft but their number is extremely high and moreover they are relatively impactful;
- Wheels, which are not so impactful being produced from metal materials and through standard procedures but that need to be changed an high number of times;
- Avionics, which, unlike structure, requires a lot of components to be substituted, in addiction to the fact that they are a great number and of much impact.

Fuel consumption

It has been said into the beginning of this chapter that for each aircraft it has been considered a type mission of 200NM and the number of flights to evaluate is approximately the one an average regional airplane will make during its entire life. The ATR42, being a very traditional aircraft, burns kerosene based fuels and the total average consumption for mission is the one reported into table 6.5. The impact of operative life, despite being the most important under all the points of view, is relatively very simple to calculate and these are the results for an ATR42:

Kerosene burned in kg	540,784
Number of flights to evaluate	37500

Table 6.5: ATR42 missions characteristics

	kg CO2eq.	**kg SO2eq.**	**kg NOxeq.**
FUEL CONSUMPTION	7,54E+07	1,33E+05	1,16E+05

Table 6.6: ATR42 fuel consumption

Total

After the assessment of every phase taken alone, it is important to make a comparison between phases impact to understand which are the most impactful and how this issue can be limited or solved into design phase. These are the results and even if impacts are all summed together it can be seen how the order of magnitude is the same of the fuel combustion one, anticipating what is the real conclusion. These pie charts make it clear that the conclusion can be only one: despite all the arrangements that can be made

	kg CO2eq.	**kg SO2eq.**	**kg NOxeq.**
TOTAL	7,62E+07	1,38E+05	1,18E+05

Table 6.7: ATR42 Total impact

	kg CO2eq.	CO2 percentage	kg SO2eq.	SO2 percentage	kg NOxeq.	NOx percentage
MATERIAL PRODUCTION	3,33E+05	0,44%	2,52E+03	1,83%	3,20E+02	0,27%
IMMATERIAL PRODUCTION	1,28E+05	0,17%	6,93E+02	0,50%	3,20E+02	0,27%
FUEL CONSUMPTION	7,54E+07	98,90%	1,33E+05	95,99%	1,16E+05	98,54%
MAINTENANCE	3,79E+05	0,50%	2,32E+03	1,68%	1,08E+03	0,92%
DISPOSAL	1,26E+03	0,00%	2,90E+00	0,00%	2,04E+00	0,00%

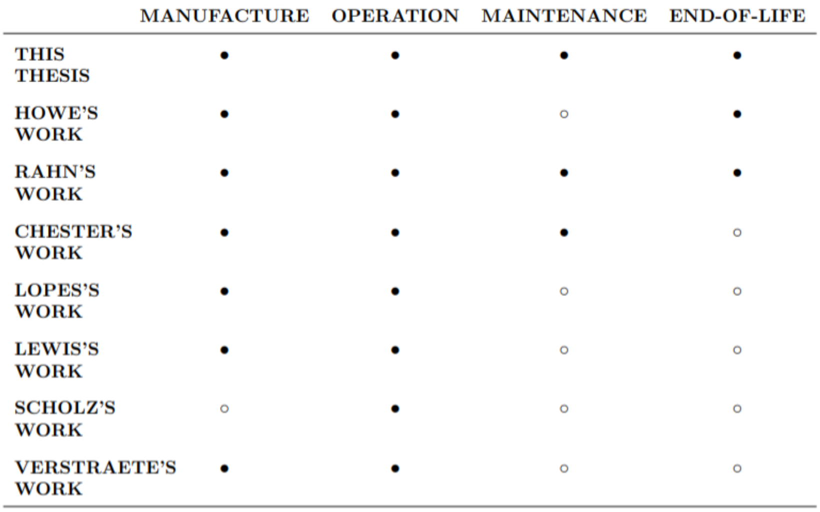
Table 6.8: ATR42 Comparison between phases impact

in development and production phases, in the end most of the impact related to the life cycle of an aircraft comes from its fuel consumption. This means that the main target of designer should be trying to reduce the need of fuel, and it can be achieved through many different ways that can be grouped under two main groups: rising the efficiency of the aircraft making it needing less fuel for the same route or changing the propulsion system trying to use less impactful fuels. These two ways are the one that will be presented into the following paragraphs.

6.2 Comparison with published studies

Before proceeding to the presentation of the cases studied, it was thought to insert this paragraph where a short comparison between the present study and some published work is made. The objectives of this comparison are two:

- Firstly, to credit the results obtained by showing how these values are in line with studies conducted. Articles and paper about this argument that have tried to eviscerate it with the target of achieving a punctual assessment are very few, the main being:
    - o the work made by Howe S. [27];
    - o the work made by Rahn A. et al. [42];
    - o the work made by Chester M.V. [9];
    - o the work made by Lopes J.V. [36];
    - o for hybrid electric aircraft, the work made by Scholz A.E. et al. [49];
    - o the work made by Lewis T. [35];
    - o the work made by Vestraete J. [60].
- Second, to better show the novelties introduced by this thesis, which, by maintaining its generality considering all the possibles architectures nowadays aircraft can have, has the gift of freedom. In facts, the software created can be modeled upon quite every design just making few arrangements, keeping in mind that the scope is to guide the developer into the choice of the better architecture, thanks to the hypothesis and simplifications made. This is quite a complete revolution from previous studies, which instead evaluated in more details just one or two configurations. Moreover,



	MANUFACTURE	OPERATION	MAINTENANCE	END-OF-LIFE
THIS THESIS	●	●	●	●
HOWE'S WORK	●	●	○	●
RAHN'S WORK	●	●	●	●
CHESTER'S WORK	●	●	●	○
LOPES'S WORK	●	●	○	○
LEWIS'S WORK	●	●	○	○
SCHOLZ'S WORK	○	●	○	○
VERSTRAETE'S WORK	●	●	○	○

Figura 6.12: Comparison between life phases considered

previous articles usually evaluated just few phases of the life and not the entire circle, inevitably losing important information that, on the contrary, was not lost in this thesis.

S.Howe

S. Howe into his thesis aimed to identify the key challenges relating to environmental efficiency within the aviation industry by both examining routing strategies, analyzing the viability of alternative fuels and conducting a holistic life cycle assessment of a commercial airliner, the Airbus A320, trying to determine environmental impacts associated with all stages of the aircraft life. The aircraft that he considered is, however, way bigger if compared to the ATR42, as a consequence results have been normalized by the maximum take off weight in order to ease the comparison. Another important factor is that absolute values into Howe work are difficult to extrapolate and so this comparison is pretty qualitative.

A. Rahn et al.

The study aimed to use discrete-event simulation in according 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 and its main advantage is the ability to simulate complex systems wherein inputs and variables can be quickly exchanged to gain insight into their significance. The main aircraft characteristics, which are especially necessary for the environmental assessment and the simulation of the life cycle, are hereby taken from project Central Reference Aircraft data System [45], and derive from an Airbus A320 type of aircraft. The use of the same impact assessment method, i.e. ReCiPe midpoint H, makes it very easy to do a comparison between Rahn work and the one made into this thesis.

T. Lewis

The methods employed by Lewis, to analyze the environmental impacts of commercial air transport, are two different, the first being a process-based LCA utilizing the Ecoinvent database, the second being an Economic Input-Output Life Cycle Assessment. This is a great similarity with the work made into this thesis, however he did not made any statistical study. He considered only manufacturing and operations of three Airbus aircraft, the A320, A330 and A380, which are way different from ATRs and still results are quite comparable.

J. Verstraete

Into his thesis, Vestraete tried to perform a comprehensive life-cycle assessment of an aircraft production and operation phases, and it results clear that his basis has been the work made by Chester [9]. Accordingly, he made use of EIO-LCA to evaluate life phases focusing over the mission accomplishment, mission that have been divided into sub-phases each individually analyzed. Due to the different method used, his results, even if the study has been conducted over an A320 like in other works, cannot be easily compared.

	This study	**Howe/Verstaete/Lewis**	**Lewis**	**Lewis**	**Rahn**
	ATR42	**A320**	**A330**	**A380**	**CeRAS**
Passengers	48	180	406	853	150
Maximum take off weight	16.9 ton	78 ton	242 ton	510 ton	78 ton
Operative empty weight	10.29 ton	42.6 ton	120.6 ton	277 ton	42 ton
Mission range	200 NM	755 NM			522 NM
Number of flights	37500	45330			45330
Fuel consumed per mission	540,78 kg	5663 kg			3166 kg

Table 6.9: Aircraft characteristics comparison

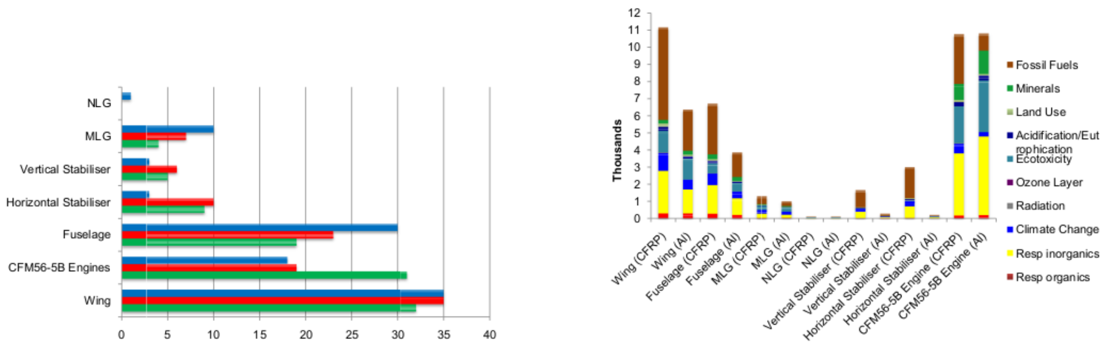
Comparison over material production

The first comparison is with Lewis, Rahn and Verstraete studies, mainly because they report absolute values that can be easily read. Here data have been normalized both through maximum passenger number and maximum take off weight.

	This study	**Verstraete A320**	**Lewis A330**	**Lewis A380**	**Rahn CeRAS**
kg CO2eq normalized by MTOW	2,73E+01	3,29E+02	8,26E+00	9,61E+00	1,80E+01
kg CO2eq normalized by passengers	9,60E+03	1,42E+05	4,93E+03	5,74E+03	9,34E+03

Table 6.10: Material production emissions comparison

From these values two reasoning can be made, the first being that EIO-LCA results are so different from process based LCA that it is impossible to compare them, always keeping in mind that the first method is comprehensive of all possible processes that take



(a) Howe study results

(b) Howe comparison between components

place during production, even workers meals and transport to the plant, because they all fall into the cost of the final product and so it logically gives higher results than the second method. The second reasoning is that it can be seen that even into environmental assessment we witness the fact that scale production factor has a non-negligible effect. In facts, bigger aircraft, that have higher production volumes, have a littler global warming impact. The comparison with Howe work needs to be qualitative due to the fact that he used others environmental impact indicators. However, for the table 6.11 it can be seen that, proportionally, different components are comparable between the two studies. The little difference between engines impact can be attributed to the fact that the A320 mounts turbofan engines that does not need big propellers made out of carbon fibre, which determine many emissions.

	Howe	**This thesis**
wing	35,00%	28,60%
fuselage	24,00%	18,15%
engines	18,00%	22,64%
tail	16,00%	16,62%
land gear	7,00%	4,11%

Table 6.11: Howe production impacts comparison

Moreover, Howe study shows the influence of composites over impact, verifying what has been found into this thesis, i.e. composited materials production determines much more emissions than metallic materials one, but can also determine a reduction into weight that means a reduction into fuel combustion during operative life.

Comparison over missions achievement impact

This time the comparison begins normalizing values by three factors: the number of passenger, the maximum take off weigh and the passenger for nautical miles traveled during the whole life, results are reported into table 6.12.

The third choice of normalization comes from the observation that the number of passenger and the MTOW are not so relevant if compared with the mission type and the number of missions that have been hypothesized into the study. A similar comparison is the one made with Lewis results for operative life, this time instead of nautical miles the range unit are kilometers. The graph 6.14 newly shows the influence of the scale factor presented previously, with bigger aircraft determining littler normalized impact. Making

	This study	Verstraete A320	Rahn CeRAS
kg CO2eq normalized by MTOW	4,46E+03	8,69E+03	9,41E+03
kg CO2eq normalized by passengers	1,57E+06	3,77E+06	4,89E+06
kg CO2eq normalized by (passengers*range*number of flights)	2,09E-01	1,10E-01	2,07E-01

Table 6.12: Mission achievement emissions comparison

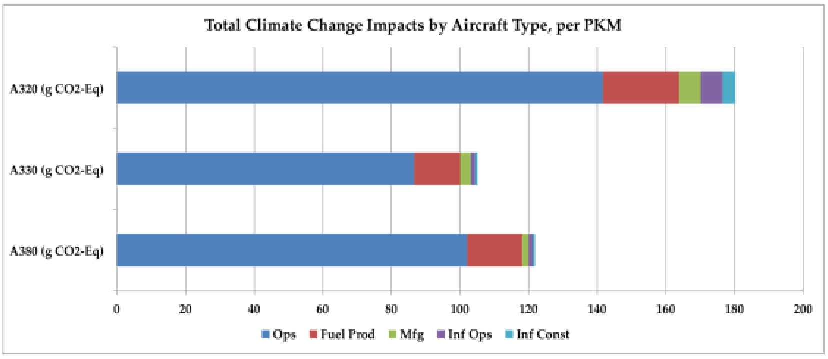


Figure 17 Total Climate Change Impacts, PKM

Figura 6.14: Lewis missions impacts - passenger per km

the same calculations, the value that comes out of the ATR42 study is of 113g CO2eq per PKM, which make perfectly sense with Lewis results.

After comparing different studies, it can be concluded that the results obtained into this thesis have relative truthfulness. It may seems a foregone conclusion but it should be remembered that these values have been taken out from a tool, ALiCIA, which point of strength is the generality and the fact that it can assess many different architectures while other analysis have been perfectly fitted over just one single aircraft or a little group. **Verifying that ALiCIA results are reliable enough is a fundamental passage that can be said to conclude the thesis that at this point achieves the purpose set at the beginning of the work.**

6.3 ATR42 hybrid-electric comparison with ATR42

The design hybrid-electric aircraft taken into account has been developed during IRON program. The IRON program is a research and innovation project within Clean Sky 2, aimed at developing a new, more efficient turboprop aircraft. The project is led by Leonardo S.p.A., an Italian aerospace company, and involves a consortium of industry partners and research institutions from across Europe. Its focus is on developing a new turboprop engine and aircraft design that will offer significant improvements in fuel efficiency, emissions, and noise reduction compared to current turboprop aircraft. The program also aims to develop new technologies and materials to reduce the weight of the aircraft and improve its aerodynamic performance. Thanks to these characteristics and to the fact that the starting point of the project is exactly the ATR family, it seems like the ideal candidate to make a comparison over environmental performances. Values into table 6.13 are the initial

Maximum number of passenger	48
Maximum take off weight	23.65 ton
Kerosene burned	390,5 kg
Electricity consumed	840 kWh

Table 6.13: ATR42 hybrid-electric characteristics

design data of the aircraft, and it is already possible to notice that, even if the number of passenger transported is the same, the maximum take off weight is much bigger than 16.8 tons of ATR42 and this is a consequence of the use of hybrid-electric propulsion. In facts, its main peculiarity comes from the fact that propulsion is distributed along the wing, with two internal combustion engines and many littler electric engines, all endowed with propellers.

In addiction to the change into the propulsion system, the hybrid-electric aircraft necessitate of an electric generation and distribution system completely different from the ATR42 case, accordingly with the increase in electric power consumed. Moreover, to accumulate a part of all the power needed it also presents a battery system which is around a thousand times bigger than the traditional one.

The results that outcome from its analysis through ALiCIA software are the following 6.14. Remembering global warming impact of ATR42, it is immediately apparent that here there is a significative reduction into CO2eq. emissions. However, it is also clear that maintenance phase is taking a more important role into this case, due to two factors:

	CO2eq. kg
Material production	6,31E+5
Fuel consumption	5,77E+7
Maintenance	2,08E+6
Total	6,04E+7

Table 6.14: ATR42 hybrid-electric impacts

- Firstly, as said, the battery system is much heavier even if technologies used on board have an energy densities that cannot be compared with traditional ones;
- The second point is the hypothesis, based upon IRON program discoveries, that there is the necessity to substitute the battery around every 1500 flights, which mean a littler more than one battery used for year, with its production and disposal environmental impacts.

Comparison over material production

Since not all data are of public domain, components weights and results will be presented as a percentage difference with the traditional turboprop.

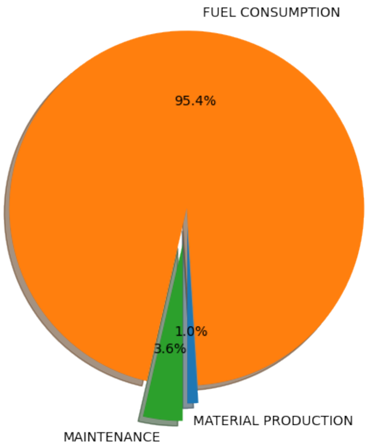


Figura 6.15: ATR42 hybrid-electric comparison between life phases

	ATR42Hybr	**ATR42**
STRUCTURE		
WING	-10,69%	-
FUSELAGE	0,98%	-
TAIL	-3,70%	-
LANDING GEAR	13,06%	-
NACELLE AND STRUCTS	-0,73%	-
POWER PLANT		
EQUIPPED ENGINES AND PROPELLERS	53,10%	-
SYSTEMS		
HYDRAULIC GENERATION	-100,00%	-
HYDRAULIC DISTRIBUTION	-100,00%	-
ENVIRONMENTAL CONTROL SYSTEM	63,93%	-
FLIGHT CONTROL SYSTEM	56,36%	-
AVIONIC INSTRUMENTS	299,68%	-
ELECTRICAL GENERATION	792,58%	-
ELECTRIC COMMON INSTALLATIONS	401,14%	-
FURNISHING		
THERMO ACOUSTIC INSULATION	90,50%	-

Figura 6.16: ATR42 hybrid-electric

	ATR42Hybr	ATR42
FURNISHING	7,71%	-

Table 6.15: ATR42Hybr comparison over sub-system weights

There are no major differences from the point of view of structures, the only one being a stronger landing gear in order to accomplish the landing with an heavier aircraft.

Differences start coming out starting from engines, where the weight is 1.5 bigger, but the real revolution of the hybrid-electric configuration resides into the electric generation and common installations, where looking at the weight percentage difference itself, it is clear how many more components are needed. The same can be said about avionics, whose need for more instruments comes both from the technological advance and from the necessity to manage all the control units of generators, electric engines, propellers and other electrical installations. The last observation that can be made over this architecture is that, through the electrification of systems, the necessity for an hydraulic system has completely vanished, thus allowing a reduction on the emissions generated by the hydraulic oil production and end-of-life treatment. Into the graph 6.17 only major changes into components and sub-systems impact have been presented. In fact, as said, the weights of structure items has not changed a lot and so production technologies or materials. The first thing that immediately becomes apparent is that every sub-system presents an increase into its emissions, apart from hydraulic ones. This means that producing an hybrid-electric aircraft is much more impactful than manufacturing a traditional one. However, the conclusion which the calculations over the ATR42 lead, if there is one only, is that it is not important how you build your product but how much it will consume during its operative life.

The same argument shown previously for avionics and electric systems weight found here its counterbalance, with impacts risen more than three to four times. However, it is curious to notice that electric common installations and electrical generation systems have alternated roles, having the former a smaller percentage increase in weight than the latter but a larger percentage increase in CO2eq emission. This is due to at least three factors:

- First of all, the technological advance had much more effect over generation, with machines that have higher power densities. The advance has also taken production

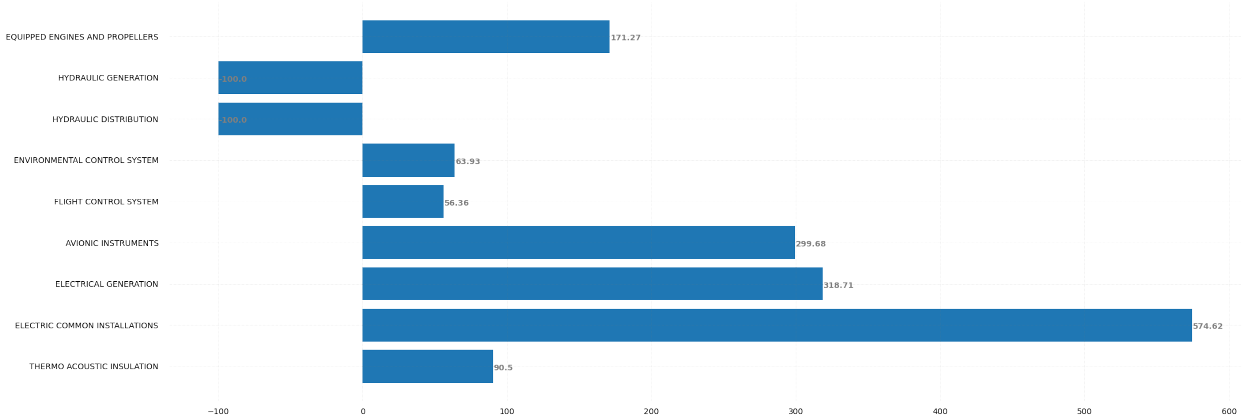


Figura 6.17: ATR42Hybr CO2eq percent different over production

processes that are less impactful;

- Secondly, ATR family aircraft presented an already quite developed generation system, if compared to the electric installations, due to the fact that the starting of engines is not done through the pneumatic system but it is based over a starter generator. This means that the biggest part of difference between the two architectures into this sub-system resides into the battery, where there was the most technological advance, with a change into accumulation system and chemicals used to less impactful ones;

- The last reasons is that percentage values should always taken with the proper arrangements since they can lead to erroneous conclusions. Here, absolute values shows how the generation system impact is more than the double of the electric common installation one, taking back to their right role these two sub-systems.

At the end, simple sub-systems change is properly proportionate to from weight to emissions, but this cannot be true for complex sub-systems where many factors vary at the same time determining a very high non-linearity of laws behind the calculation.

Until this point only Global Warming effect has been taken into account, since the change in SO2eq and NOxeq emissions follow pretty much the change in weights. However, it seem important to report changes into two items 6.16. From these values, it is possible to understand how the change into propulsion system influence the state of quality of air into production plants, where SO2eq and NOxeq high concentration could lead to respiratory problems for workers. The good news is that the technological advance lead to impacts that are littler than if they strictly follow the increase in weight.

	SO2eq	**NOxeq**
EQUIPPED ENGINES AND PROPELLERS	16,11%	125,79%
ELECTRICAL GENERATION	146,95%	212,59%

Table 6.16: Terrestrial Acidification & Ozone formation focus on

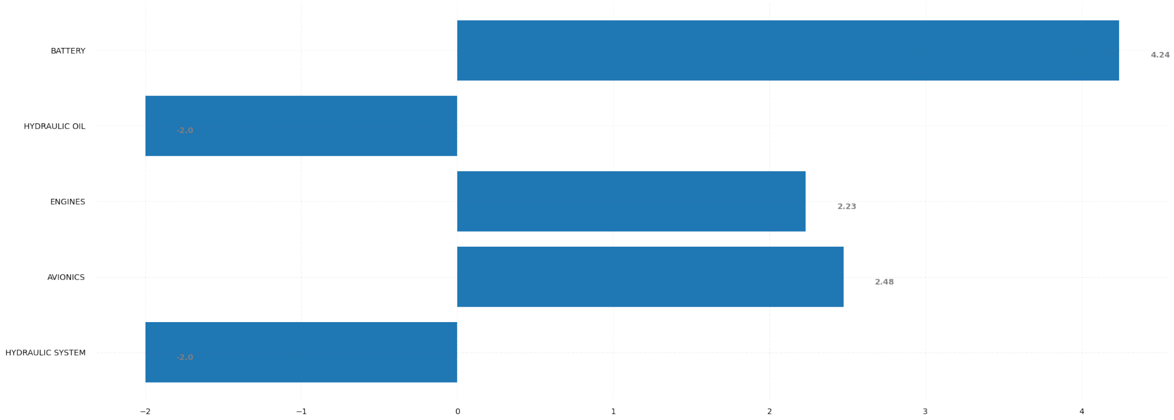


Figura 6.18: ATR42Hybr CO2eq percent different over maintenance

Comparison over maintenance

From the point of view of sub-systems that undergone little changes into technology, maintenance impacts arise following the major weight. As a consequence, these variations are of little interest and alone would not constitute an acquaintance useful to compare hybrid-electric configurations. However, if we take a look at what happens for the electrical system and the battery, it is clear that the increase in complexity, weight, and especially replacement rate, this reason being valid for the latter, have an enormous impact. The increase into battery substitution emissions in terms of CO2eq. is so high that it makes it look as if the ATR did not mount any type of power accumulation. And the change into technologies used, from a NiCd battery to a Li-ion one has a limited effect. The sum of these two effects makes the maintenance phase increase its impacts of 5.68 times, overall.

	CO2eq	**SO2eq**	**NOxeq**
BATTERY	17487,04%	5919,82%	17291,50%
ELECTRIC SYSTEM	911,92%	911,92%	911,92%

Table 6.17: Maintenance impacts focus on

Analogous to the reasoning made for production, looking at Terrestrial acidification and Photochemical smog formation effects, the only relevant voice appears to be the battery one. Here the change into technology used becomes more evident since increase in acidification is littler than how it could have been, while ozone formation increase is pretty the same of global warming impact.

Comparison over fuel consumption and cumulative impact

It has been said that comparison over missions impact would have been made over a typical mission of 200NM repeated for 37500 times, simulating a 20 years life of 1875 flights a year, these are average values. Consumption hypothesized for the hybrid-electric configuration are of four hundred kilograms of kerosene and eight hundred kilowatts of electric power. The results are the following 6.18. The reduction percentage is quite similar for every impact category and it is a very significant reduction if absolute values, and the great

	Global Warming	**Terrestrial acidification**	**Photochemical smog**
FUEL CONSUMPTION	-23,43%	-26,36%	-24,94%

Table 6.18: ATR42Hybr fuel consumption impacts comparison

difference between production, or maintenance, impacts compared to fuel consumption ones, are kept in mind. At this point, traces can be found of what will be the conclusion of this comparative study between the two architectures. Indeed, the starting idea was to demonstrate that a hybrid-electric configuration, through a change in propulsion, leads to an environmental benefit. However, from a manufacturing and maintenance point of view this results cannot be achieved, but it finally comes through the net reduction in emissions during operation.

	Global Warming	**Terrestrial acidification**	**Photochemical smog**
MATERIAL PRODUCTION	99,00%	66,88%	100,04%
FUEL CONSUMPTION	-23,43%	-26,36%	-24,94%
MAINTENANCE	568,26%	653,54%	587,93%
TOTAL	-20,49%	-13,94%	-19,25%

Table 6.19: ATR42Hybr life phases impacts comparison

It is possible to make now a recap of all results obtained into the analysis. The environmental benefit is achieved through the innovative configuration but the decrease seems little. Indeed, if you think that the objective of Europe is to achieve net zero emissions in 2050 this may turn out to be too small a step. Maybe, further increase into technologies could give better results but, and this is the personal opinion of the writer of the thesis, the solution can resides both into a change into propulsion but also into a more efficient design, capable of consuming less fuel per passenger transported, and more efficient way of traveling, through the use of artificial intelligence to optimize routes. The following analysis, a comparison between ATR42 and ATR72, better shows what an efficient design and use of the machine can achieve.

6.4 ATR72 comparison with ATR42

The ATR72 is a twin-engine turboprop, short-haul regional airliner developed and produced in France and Italy by aircraft manufacturer ATR. It was developed during the mid-80s, when the ATR consortium sought to introduce a larger airliner with increased capacity over its earlier product. This new regional airliner was directly developed from the earlier ATR42 and had much in common with it, the principal difference between the two being an increase in the maximum seating capacity from 48 to 78 passengers. This was principally achieved by stretching the fuselage by 4.5 m, along with an increase of the wingspan, the use of more powerful engines, and increased fuel capacity by about 10%.

Its development has been followed by a bigger success than its predecessor, since it is still produced at present and until now the number of aircraft build has overcome the one thousand units. For this aircraft characteristics, reference values have been taken from Jane's all the world aircraft [32], and the main motive it was decided to make a comparison between these two planes, both taken from the same family and the same manufacturer, is because the 72 was developed already knowing all critical aspects of its predecessor and how to solve them in order to achieve a more efficient machine.

Main characteristics

Maximum number of passenger	72	
Maximum take off weight	23000	Kg
Maximum range	1528	Km
Price	18.98	Million US 2002 dollars

Table 6.20: ATR72 main characteristics

It has been long said by experts that the 42 is a little too over-dimensioned for the number of passengers it transports, and this can be easily noticed by any, even inexperienced, observant looking at its fuselage. On the other hand, the 72, by stretching dimensions, has reached a perfect equilibrium and maybe designers went too far on the other way creating a little under-dimensioned aircraft.

It has been hypothesized that, apart from the structure, which has increased its weight of around a 16%, and from engines, that are PW127 instead of PW120 of the previous case, the remaining part of the aircraft is very similar to the 42, always keeping in mind that an increase in weight is physiological. Accordingly, the electric generation system is basically unchanged, thus generators, starter generators and batteries give the same power and have the same power or energy densities.

Material production

	kg CO2eq	**kg SO2eq**	**kg NOxeq**
STRUCTURE	2,10E+05	9,70E+02	5,48E+02
POWER PLANT	5,50E+04	8,38E+02	1,48E+02
SYSTEMS	7,38E+04	7,53E+02	2,72E+02
FURNISHING	1,10E+04	4,40E+01	2,70E+01
OPERATOR ITEMS	1,15E+04	6,04E+01	3,34E+01
TOTAL	3,61E+05	2,66E+03	1,03E+03

Table 6.21: ATR72 material production impacts

The first thing that can be immediately seen is that even for the 72 the most impactful systems is the structure, covering more than the fifty percent of emissions of CO2eq. However, looking at terrestrial acidification effect, it can be noticed that also engines and systems have a relevant impact, and a similar path is followed into NOxeq emissions. All these values, nevertheless, do not take into account the different weights of these systems, and consequently, if a normalization is applied over results according to the weight of the individual components then values would be quite different, as shown by the graphs 6.20 6.21. Having ascertained that in absolute values the trends are very similar to those seen previously for the 42, it is now possible to make a comparison between the two models. Obviously, it would be misleading to compare the values directly without taking

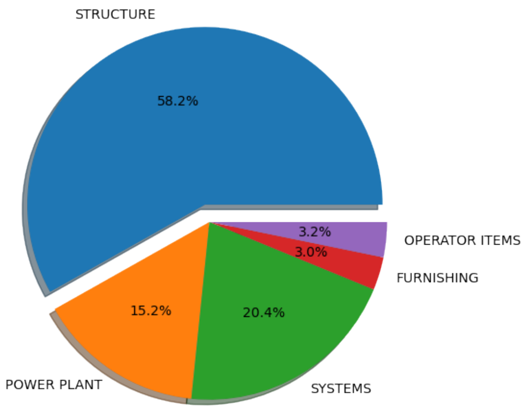


Figura 6.19: ATR72 subsystems production CO2eq emissions comparison

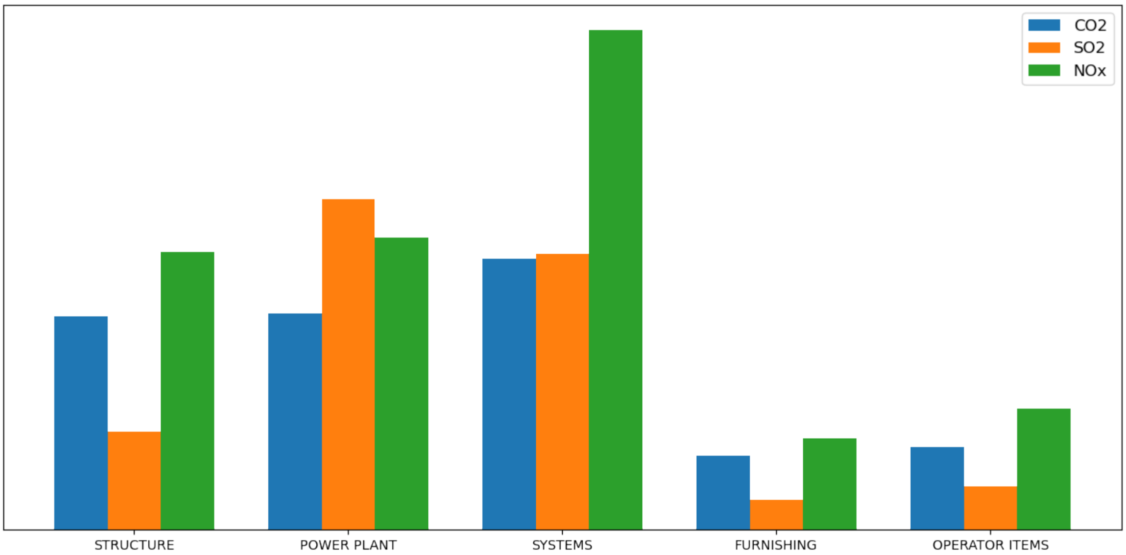


Figura 6.20: ATR72 subsystems production normalized impacts comparison

into account the change in weight and number of passengers. In choosing between which normalization factor to use, the choice fell on the latter since emissions are often expressed as per passenger carried per kilometer traveled (p*km).

	CO2eq emissions difference
STRUCTURE	
WING	-20,00%
FUSELAGE	-18,74%
TAIL	-33,48%
LANDING GEAR	-27,42%
NACELLE AND STRUCTS	-33,50%
POWER PLANT	
EQUIPPED ENGINES AND PROPELLERS	-33,43%
FUEL SYSTEM	-29,63%
SYSTEMS	
HYDRAULIC GENERATION	-34,07%
HYDRAULIC DISTRIBUTION	-33,33%
ENVIRONMENTAL CONTROL SYSTEM	-29,84%
DE ICING	-25,46%
FLIGHT CONTROL SYSTEM	-35,76%
AVIONIC INSTRUMENTS	-34,41%
ELECTRICAL GENERATION	-33,33%
ELECTRIC COMMON INSTALLATIONS	-35,64%
FURNISHING	
THERMO ACOUSTIC INSULATION	26,67%
FURNISHING	-3,62%
LIGHTING	-22,22%
OPERATIONAL ITEMS	-7,71%
OPERATIONAL EQUIPMENT	-15,15%

Table 6.22: ATR72 material production percent difference - normalized Global Warming

It can be seen that among all the components the percent reduction into CO2eq emissions is around a 30%, the only exceptions being:

- The wing and fuselage, that have been redesigned during development and have been sized over the new configuration. Despite the redesign, the reduction is still visible and allows you to understand that they have become more efficient;

- Furnishing and operator items needed to be re-sized because of the increase in the number of passengers, thereby impacts are not so different in percentage;

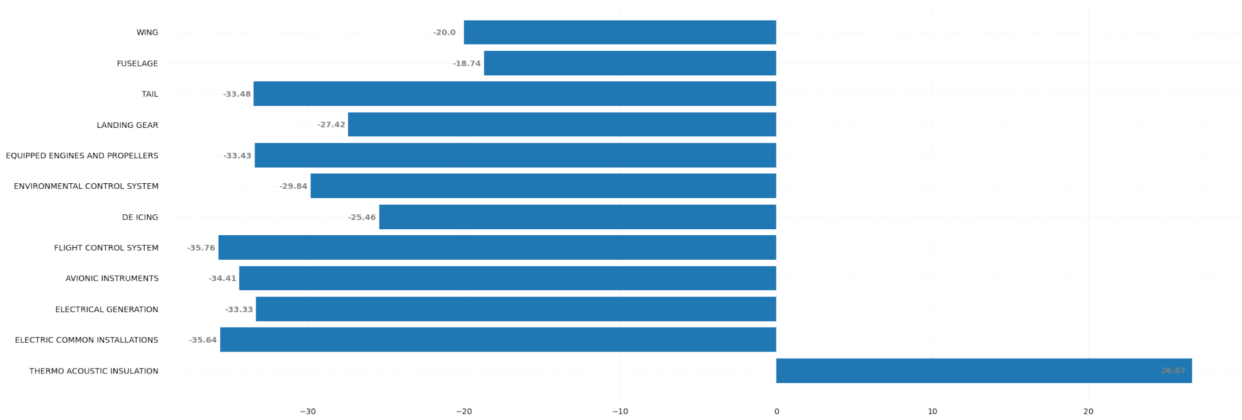


Figura 6.21: ATR72 CO2eq percent difference over material production

- The only positive voice is the thermo-acoustic isolation, it is difficult to hypothesize the reason behind it, possibly being the fact that a bigger aircraft needs thicker layer of insulation due to the bigger surface exposed to the atmosphere.

Immaterial production and Maintenance

DEVELOPMENT AND MANUFACTURING	
engineering	6,87E+03
manufacturing work	1,20E+05
tooling	7,30E+06
quality control	3,62E+03
PROGRAM MANAGEMENT	1,05E+04
TEST AND EVALUATIONS	
prototypes production	3/1000
testing	3,48E+04
DATA MANAGEMENT	2,37E+02
SITE OPERATION	1,81E+01
INITIAL SPARES	15,00%

Table 6.23: ATR72 immaterial production input values

Both immaterial production and maintenance phases are not of major interest due to the fact that technologies are the same and, thereby, impacts follow the trend well underlined into material production. Considerations about the decrease of passengers proportionate weight are true also when talking about maintenance, where the average reduction is around the thirty percent. The analysis made for immaterial production is a littler different, the reason being that it can be made following two ideas:

- It can be considered that the 72 was developed as if starting from zero without any previous knowledge, to see the difference into values due to a production volume that has doubled;

- It can be considered that all knowledge acquainted with 42 has been transmitted, and that as a consequence all activities of developing required much less time.

These are the result of the first way 6.24.

	kg CO2eq	**kg SO2eq**	**kg NOxeq**
ENGINEERING	3,32E+02	1,42E+00	7,34E-01
MANUFACTURING WORK	2,79E+04	8,75E+01	6,10E+01
TOOLING	1,59E+04	1,66E+02	5,15E+01
QUALITY CONTROL	1,75E+02	7,44E-01	3,86E-01
PROGRAM MANAGEMENT	3,00E+02	1,23E+00	7,59E-01
PROTOTYPES PRODUCTION	9,69E+02	6,35E+00	2,65E+00
TESTING	4,40E+03	1,46E+01	9,64E+00
SERVER OPERATION	2,02E+01	8,71E-02	6,00E-02
CONSTRUCTION	0,00E+00	0,00E+00	0,00E+00
OPERATION	3,82E+04	3,64E+01	6,79E+01
INITIAL SPARES	4,84E+04	3,18E+02	1,32E+02
TOTAL	1,37E+05	6,32E+02	3,27E+02

Table 6.24: ATR72 immaterial production impacts

Obviously, all amounts that have been taken from the simulation made through PRICE TruePlanning® software have been divided by 1000 units. It can be seen this way that both manufacturing work and site operation assumes similar values to the ATR42 simulation, and it is implicit that these voices cannot change a lot, even if the second idea were to be followed. This reasoning cannot be applied to others voices, e.g. tooling is a process that required quite the same amount of expense following the first idea but that instead would indeed decrease a lot if previous knowledge were to be maintained. One could get to the same conclusions when looking at the table 6.25 noticing that, apart from the fact that a bigger number of unit build physiologically decrease some impacts over the single plane, most impactful categories have not decreased a lot but instead some have increase, like the site operation impact. The last thing that can be said, accordingly, is that the difference between the two path into immaterial production impact calculation is more theoretical than practical and that the total emissions would not change by a significant amount.

Fuel consumption

The average consumption of an ATR72 over a route of 200NM has been estimated to be 616,81 kilograms. This means that in percentage the 72 consumes a 24% less than its predecessor per passenger. This increased efficiency is to be searched into its minor percentage weight and into the stretching of the fuselage, that increased cruise efficiency. Keeping in mind Breguet formulation 6.1, it is possible to easily understand the effect of

	kg CO2eq	kg SO2eq	kg NOxeq
ENGINEERING	-49,34%	-49,34%	-49,34%
MANUFACTURING WORK	-9,21%	-9,21%	-9,21%
TOOLING	-2,05%	-2,05%	-2,05%
QUALITY CONTROL	-21,28%	-21,28%	-21,28%
PROGRAM MANAGEMENT	-21,07%	-21,07%	-21,07%
PROTOTYPES PRODUCTION	-49,14%	-56,92%	-51,40%
TESTING	-9,87%	-9,87%	-9,91%
SERVER OPERATION	-50,30%	-50,30%	-50,30%
CONSTRUCTION			
OPERATION	49,10%	49,10%	49,10%
INITIAL SPARES	2,33%	-13,31%	-2,21%
TOTAL	6,75%	-8,82%	2,24%

Table 6.25: Percent difference over immaterial production

these two changes.

$$R = \frac{V}{C} \cdot \frac{L}{D} \cdot \ln\left(\frac{W_i}{W_f}\right) \tag{6.1}$$

It is possible to hypothesize that specific fuel consumption of engines mounted is quite the same, being the same series of products, and also cruise speed is the same so the only variables into the fuel consumption are exactly the aircraft weight and its efficiency. The results are the following:

	kg CO2eq	kg SO2eq	kg NOxeq
MISSIONS IMPACT	-23,96%	-23,96%	-23,96%

Table 6.26: ATR72 mission achievment impact

Total

Summarizing what have been said into the previous paragraphs, here 6.27 there are the percentage reductions for every life phase.

	kg CO2eq	kg SO2eq	kg NOxeq
MATERIAL PRODUCTION	-28.07%	-29.61%	-27.74%
FUEL CONSUMPTION	-23.96%	-23.96%	-23.96%
MAINTENANCE	-29.95%	-31.40%	-29.90%
TOTAL	-24.00%	-24.18%	-24.04%

Table 6.27: ATR72 life phases impacts - percent difference

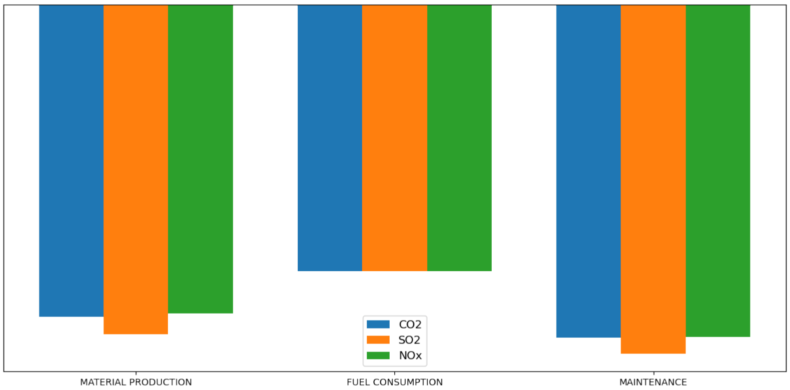


Figura 6.22: ATR72 impacts percentage reduction between life phases

Reductions are perfectly in line with what it has been said in the introduction. The natural conclusion of this analysis is quite in counter trend with the vision of last years but it underline an important truth. Wanting to express the concept in the form of a logical syllogism:

- The change into propulsion made into the hybrid-electric ATR42 reduced CO2eq emissions of around 20%;
- The ATR72 overall impact is littler than base line of around 24%;

The conclusion cannot be anything different from this: the increase into the efficiency and the configuration optimization made an aircraft developed nearly four decades ago less impactful than a modern day innovative architecture.

Surely the innovation into propulsion is a great step toward a greener aviation and should be pursued, however it cannot be a motive to develop configuration that are not an optimum. Indeed, if a new version of ATR72 should be developed following the same way of the hybrid 42 it could be predicted that its reduction into emissions could be at least up to a 40%, surely much more in line with European Union goals.

6.5 Parametric analysis over electrification

After making some analysis with both traditional and hybrid configurations, it was decided to do a study over the degree of electrification of an aircraft. The main reason behind it is that, through others simulations, it was possible to see that an higher degree of electrification means both minor emissions due to fuel consumption but at the same time greater impact due to an heavier battery and electric propulsion system. This trend suggests that increasing the level of electrification is possible up to a certain point with consumption benefits but that beyond a certain level the complications associated with the electric system are such that further electrification is unnecessary, if not harmful. The following are the assumptions made and how the analysis was conducted until an unexpected conclusion was reached.

The chosen starting architecture is that of an ATR42, as usual, whose components have all been kept unchanged except for the battery. An electrification of the aircraft implies that it will be necessary to add electric motors and to completely change the electric system in order to supply all the utilities; in this case, the hybrid aircraft was considered to have distributed propulsion.

Figura 6.23: Hybrid configuration

Obviously, accounting for the change of one single component is a simplification because it will usually lead to a renew into the architecture, and for each level of electrification systems would be different to fully take advantage of electric propulsion possibilities. However, these are the hypothesis made to streamline the analysis:

- The electrification level is calculated dividing the energy supplied under electric from by the total demand of energy, this way it is not linearly correlated to the change into the electric system configuration, thus being representative only of different energy consumption;
- The only component that is directly modified at the rising of electrification degree is the battery;
- To account for others changes into the architecture, it was chosen to consider that there is an increment in weight of 0.42% for each additional 1% of electrification, this value was obtained studying the hybrid-electric version of ATR42;
- From the same hybrid architecture, it was derived that the usual mission depth of discharge is of 80% while the number of cycle after which it is necessary to change the battery is of 1500, these values has been set as constant;
- Operative life considered is of 20 years with an average number of flight of 1875 per year;
- It was hypothesized that battery used are Li-ion batteries with an energy density of 0.5 kW/kg and that there is just one battery even when the size is so high that practically there would be more than one;
- Conversion efficiency of internal combustion engines has been set to 0.45 while for batteries it has been considered as 1;
- The last hypothesis is related to energy needed for every flight. It was considered to use the Breguet equation for range $R = \frac{V}{C} \cdot \frac{L}{D} \cdot \ln\left(\frac{W_i}{W_f}\right)$ to calculate the equivalent fuel for a mission of 200 NM. Due to the complexity of handling consequences of changing SFC or L/D or V for different architectures it has been chosen to set this terms as constant after calculating them for a typical ATR42 mission. This way the equation has assumed the form of $W_{fuel} = a \cdot W_i$ where a is a constant and its value is 0.03. This way is possible to calculate the equivalent kilograms of kerosene needed for the mission. Transforming these from kilograms to kilowatts-hour, assuming that

energy density of kerosene is 12 kWh/kg, it is possible to calculate the total energy demand of each mission. From this point dividing energy between electricity and kerosene is simple and it is a function of the electrification degree.

The objective of the study is to find a qualitative trend into emissions which are linked to the electrification level.

Procedure

The first part of the analysis has been dedicated to calculating the amount of electricity and kerosene needed for a mission as a function of the electrification level. The process followed has been iterative, implemented over MATLAB, since it is impossible to calculate the necessary values directly:

- Fist of all, it is necessary to set the electrification level required;
- From the EL is possible to calculate the first iteration weight of the aircraft as $W = 0.42 \cdot EL + 1 \cdot W_{trad}$;
- After that, the equivalent fuel needed is calculated multiplying the weight for 0.03;
- At this point fuel is converted into energy and the factor 0.45 of internal combustion engines is used;
- Finally, it is possible to calculate the required battery energy as $Batt_{energy} = EL \cdot \frac{energy}{0.8}$, where 0.8 is the DOD.

These calculations has been repeated into an iterative way every time using the found battery energy as the new values to be used into the equation of aircraft weight $W = 0.42 \cdot \mathrm{EL} + 1 \cdot W_{trad} + \frac{Batt_{energy}}{0.5}$. After some iterations it is possible to reach a value for new battery energy similar enough to the previous one to call the iterations off. Knowing how much energy is provided by the battery it is simple to calculate the kerosene required.

This way, values for 6 levels of electrification, 0%, 20%, 40%, 60%, 80% and 100%, has been obtained and then simulations through ALiCIA software were conducted with the following results.

battery size [kg]	**electricity needed [kWh]**	**kerosene burned [kg]**
0.00E+00	0.00E+00	5.46E+02
8.95E+02	7.16E+02	5.16E+02
2.12E+03	1.70E+03	4.58E+02
3.79E+03	3.03E+03	3.64E+02
6.06E+03	4.84E+03	2.18E+02
9.15E+03	7.32E+03	0.00E+00

Table 6.28: Electrification levels

Results

As it have been shown into previous paragraphs, both production and maintenance phases are always relatively less impactful than fuel consumption. The following graphs shows trends into production and maintenance emissions of C02eq. As it was imagined, trend is

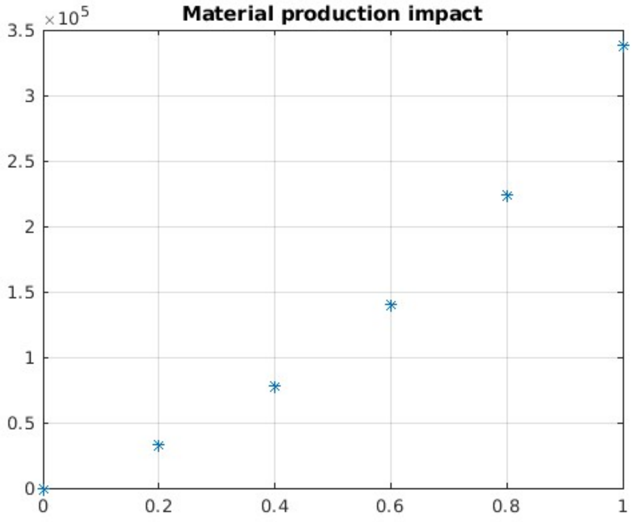


Figura 6.24: Material production impact trend

exponential and perfectly follow the increase of battery size, of which it is a proportional function. However, even this time, when these impacts increase exponentially, they never reach a value fully comparable to fuel consumption ones. Moreover, the difference between battery production and maintenance, that for low degree of electrification is little, becomes more and more evident at the increase of the level. However, their trend is not the same of the cumulative impact, as said the major part is due to fuel consumption, and in particular of kerosene burning. And for higher degree of electrification kerosene needed decreases until it disappear. From the trend of fuel consumption impact 6.26, it is possible to see how great is the difference between electricity, which has been considered with the production mix that characterize the present world without considering benefits from a greater use of renewable sources into the following years, and kerosene burning impacts. At last, here there is a bar graph 6.27 that visually shows the cumulative trend due to a greater level of electrification. It is completely different from what it was imagined at the beginning of the analysis, which leads one to think that maybe it would be always useful to base opinions over studies more than over instinct. The trend shows a maximum for low electrification levels and than it decreases moderately until a minimum in correspondence of the fully electric propulsion. The formula is:

$$\mathrm{CO_2eq} = -3.97 \times 10^7 \cdot \mathrm{EL}^2 + 1.96 \times 10^7 \cdot \mathrm{EL} + 7.54 \times 10^7 \tag{6.2}$$

and it allows us to make some observations that are completely different from the idea with which the analysis began:

- The first one is that maintaining the same base architecture changing only the size of the battery in order to allow a more electrical configuration leads to impacts that does not change so much, the all-electric aircraft differs from the conventional one by only 25 percent of the total impact. This could be a consequence of simplifications introduced which allow one to make a streamlined analysis and show a trend that is the real one but only qualitatively;

- As a consequence of the first observation, the advice is that a more electric configuration should take advantage of the electric system to improve its efficiency and further increase the gap with traditional architectures. Limitations of electrical propulsion,

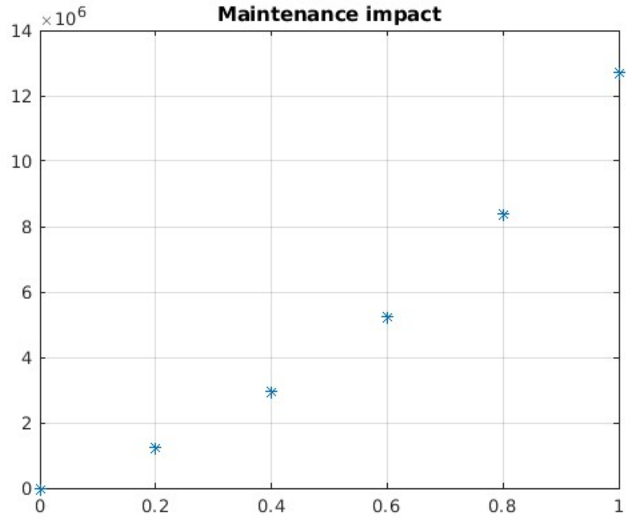


Figura 6.25: Maintenance impact trend

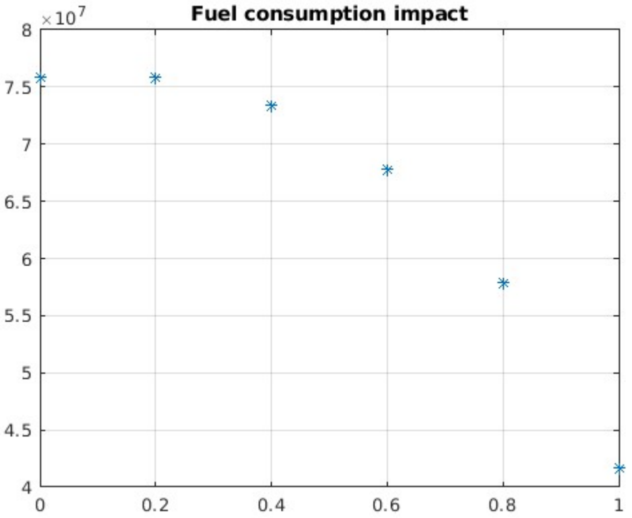


Figura 6.26: Fuel consumption impact trend

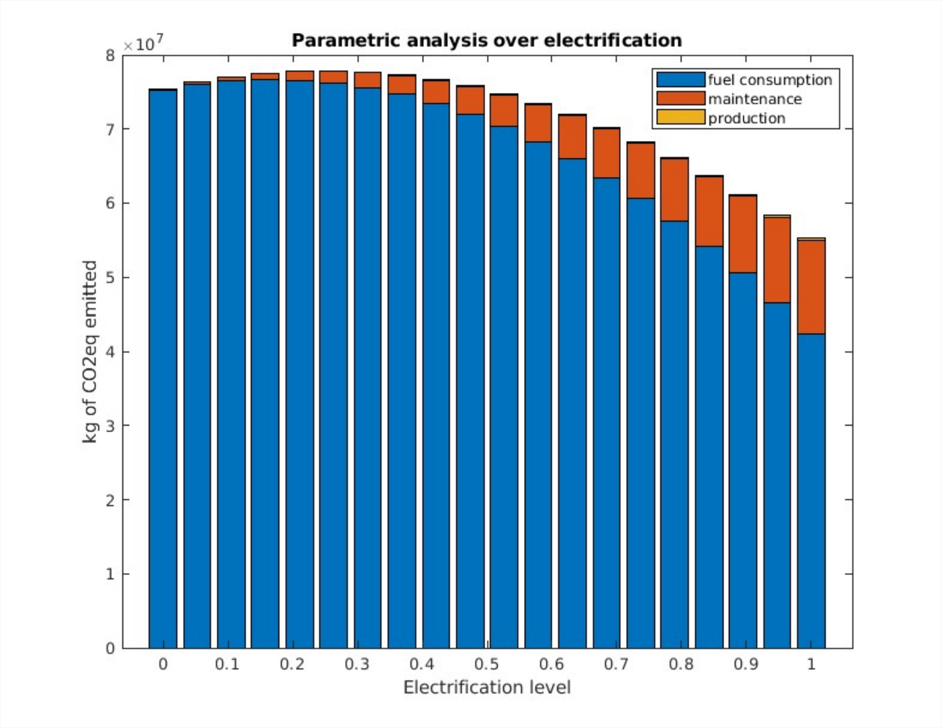


Figura 6.27: Parametric analysis results

in fact, make impossible to reach very high degree of electrification and so the range of possibilities is littler and any opportunity to reach a smarter architecture should be followed;

- However, the most important conclusion that can be extracted from this graph is that a low level of electrification can be more impactful than a zero electrification, because the weight of the battery leads to a bigger consumption not immediately compensated by electric propulsion. These results may be a reminder to try to develop electric mobility so as to achieve a degree of electrification that, while remaining within the range of possibilities given by electrical systems limitations, can leads to a real decrease of the total impact, not only being smoke and mirrors.

Chapter 7

Two additional cases study

When the work was already done and the ALiCIA software was already well calibrated and its results were found reliable enough if compared to other studies, the possibility of applying the tool over two additional cases study has appeared. The two aircraft analyzed are very different one from the other but the comparison between their configuration and, more specifically, between their environmental impacts has been found of great stimulus to see the aviation under a different point of view.

The planes taken into account are: an hybrid-electric regional aircraft (HETP) and a commuter aircraft. Here there is what has been discovered from their analysis.

7.1 Main characteristics comparison

	HETP	**Commuter**
Number of passengers	80	17
Maximum take off weight	32500	5670
Route type	Short Haul (800/1500 km)	Very Short Haul (0/800km)
Development scope	Regional flights	Business flights

Table 7.1: Main characteristics

FAR 23.3 defines a commuter category aircraft as:

> The commuter category is limited to propeller-driven, multi-engine airplanes that have a seating configuration, excluding pilot seats, of 19 or less, and a maximum certificated takeoff weight of 19,000 pound or less. The commuter category operation is limited to any maneuver incident to normal flying, stalls (except whip stalls), and steep turns, in which the angle of bank is not more than 60 degrees.

This definition means that commuter aircraft are not usually used for commercial route since their main scope is to transport a little group between two localities that are not so far from each other, usually for business purposes, reducing travel time which others means of transportation would require.

On the other hand, the regional aircraft is an airliner build to transport a larger number of passengers, but still under the one hundred seats, over short haul routes. As it as already been said, it is usually used from multiple purpose:

- Providing passenger air service to communities that lack sufficient demand for major airline service;

- Providing linking between two cities into the same state with many flights per day;

- Feeding larger carriers' airline hubs from small markets;

For these reasons, regional aircraft have become more and more important into U.S. aviation market, also because without them there would be hundreds of U.S. cities without flights.

The commercial use is not the only difference between the two. In facts, the first one, as its name says, has an hybrid electric propulsion system while the second one, instead of using a traditional configuration has abandoned hydraulic systems in order to be a more electric aircraft, which means that all its systems onboard are powered by electric energy while hydraulic and pneumatic power are relegated to a marginal role. Proceeding by order:

- The structure of the HETP is mainly formed of composites material, specially carbon fibre. In particular, the wing is quite totally composed by them, and the same can be said about the tail, while the fuselage still contains an high percentage of aluminium. The commuter itself, instead, has a more common design where aluminium still has the upper hand and this difference makes itself strictly evident into the environmental impact;

- The second important difference resides obviously into the propulsion system. While the commuter derives its power from two turboprop engines that burn kerosene based fuel, the HETP derives power from many different sources. It mounts both internal combustion and electric engines, the last receiving power from both a battery and a fuel cell systems. The use of different sources means that onboard there will be the necessity for both: a kerosene based fuel tank, batteries that need to be recharged before every flight and a liquid hydrogen tank, which probably presents the most difficult-to-overcome obstacle since it will require a big volume to carry enough LH2 [59]. However, by using electricity and hydrogen into fuel cells, the hybrid-electric aircraft can cut down on fossil fuels consumption;

- The last difference to be noted concerns the systems. The more electric configuration of the commuter aircraft reduces the potential difference, should it mount conventional systems, however, the need for electrical installations, from batteries to motors, is much greater in the HETP. Moreover, this change takes with itself the problem of maintaining electric devices at the right temperature and so the hybrid-electric aircraft also mounts a thermal management system. It can be noted that the change is very high and sill it could be higher should HETP not mount devices that have power and energy densities that are the best ones of state-of-the-art.

	HETP	**Commuter**
Electrical generation	4673,1 kg	76 kg
Electric common installations	412,5 kg	48 kg
TMS	720 kg	0 kg

Table 7.2: Electric system characteristics

7.2 Material production comparison

After the description of both aircraft and of their differences, it is now time to look at results coming from ALiCIA tool. The percent difference means that every kg of HETP component has an impact that is equal to the impact of a kg of commuter plus the percent difference multiplied per the kg of commuter impact.

		HETP	Commuter	Percent difference
Wing	GWP [kg CO2eq.]	2,44e5	2,07e4	+105,37%
	TAP [kg SO2eq.]	9,2e2	8,85e1	+81,49%
	EOFP [kg NOxeq.]	5,13e2	5,45e1	+64,29%
Fuselage	GWP [kg CO2eq.]	6,53e4	9,09e3	+25,39%
	TAP [kg SO2eq.]	4,1e2	5,7e1	+25,39%
	EOFP [kg NOxeq.]	2,05e2	2,85e1	+25,39%
Structure total	GWP [kg CO2eq.]	4,55e5	4,84e4	+64,09%
	TAP [kg SO2eq.]	1,89e3	2,16e2	+52,46%
	EOFP [kg NOxeq.]	1,04e3	1,24e2	+46,66%

Table 7.3: Structure production results

$$\text{HETP kg impact} = \text{commuter kg impact} + \text{percent difference} \times \text{commuter kg impact}$$

When talking about equipped engines and propellers it has been chosen to analyze under this name only the impact of internal combustion engines, fuel control units and propellers. The obvious consequence is that there is little difference between the two aircraft, both of which mount turboprop engines that it is hypothesized are produced with the same technology. It could be see looking at the difference of impact for kg of power plant system, where the values differ for a 4/5%.

		HETP	Commuter
Engines and propellers	GWP [kg CO2eq.]	4,70e4	1,92e4
	TAP [kg SO2eq.]	6,38e2	2,95e2
	EOFP [kg NOxeq.]	1,25e2	5,16e1

Table 7.4: Power plant production results

The great configuration difference shows itself into the following table 7.5. Here, electric powertrains, electric generators, the battery systems and the fuel cell system all go under the name Electric generation. One only has to look at the order of magnitude to understand what using an hybrid-electric propulsion means when it comes to produce all the necessary devices. The environmental loading is so high that it may, kept alone, induce into the error of considering this configuration not sustainable.

		HETP	Commuter
Electric gen.	GWP [kg CO2eq.]	5,41e5	5,87e2
	TAP [kg SO2eq.]	1,56e4	8,16e0
	EOFP [kg NOxeq.]	4,59e3	1,77e0
Electric comm. inst.	GWP [kg CO2eq.]	1,04e4	1,01e3
	TAP [kg SO2eq.]	4,36e1	4,22e0
	EOFP [kg NOxeq.]	2,41e1	2,33e0
TMS	GWP [kg CO2eq.]	4,81e4	0
	TAP [kg SO2eq.]	2,09e2	0
	EOFP [kg NOxeq.]	1,47e2	0

Table 7.5: Most important systems production results

7.3 Operative life comparison

The main observation, upon which it is important to evaluate if the innovative architecture is effectively a better choice in terms of environmental sustainability, cannot be but the fuel consumption impact for missions achievement. Here it has been decided to consider a very short haul, the same used into the previous chapter, of 370,4 km, while knowing that both the aircraft have an ideal route that goes from 700 km to 1000 km.

		HETP	Commuter
Fuel combustion	GWP [kg CO2eq.]	5,02e7	5,62e7
	TAP [kg SO2eq.]	8,93e4	9,89e4
	EOFP [kg NOxeq.]	7,73e4	8,65e4
Energy needed	[kWh]	9805,25	2176

Table 7.6: Fuel combustion results

Results in this case can leave you speechless.

The energy required per single flight is, indeed, much more for the HETP than for the commuter, even if a better cruise efficiency made it not linearly proportional to the increase in weight. But the real difference comes if it is considered that:

- The energy density of kerosene based fuels is always around 12 kWh/kg and the internal combustion engines efficiency can be at maximum around 45%;
- The efficiency of the battery system can be considered between 85% and 90% while for the fuel system it has been taken a value of 60% [13];
- The energy density of liquid hydrogen is of 33.33 kWh, much bigger than kerosene one.

All these factors make the HETP impact less than the commuter over the same route, not a big change in absolute value but an enormous change into passenger per kilometer impact, since it can transport 80 passengers and not only 17.

7.4 Total impact comparison and conclusions

The life considered is of 20 year and 37500 flights for both the aircraft. It is not properly typical for both of them but it is very useful to make an easily understandable comparison.

		HETP	**Commuter**
Total impact	GWP [kg CO2eq.]	5,14e7	5,63e7
	TAP [kg SO2eq.]	1,08e5	9,95e4
	EOFP [kg NOxeq.]	8,36e4	8,68e4

Table 7.7: Total impact results

At the end, all productions emissions are but a little part of the total and it is evident from the fact that, as shown, producing an hybrid-electric aircraft takes with itself high environmental loading but still, looking at global values, it is a better choice from the point of view of making the aviation world more eco-friendly.

Chapter 8

User Manual

8.1 How to install

The installation of ALiCIA is a path that begins with downloading the folder ALiCIA. Into it, you should see one sub folder, which is *Databases* and contains two excel files, *Component_production* and *Emissions_processes*, that can be changed and two files, *ShortHaulFrequencies* and *piottoalleotto*, that should not be touched in any case.

After downloading the main folder, my advice is to place it into the desktop, just to ease the tool work.

Moreover, you need to install the following packs: `matplotlib`, `scipy`, `openpyxl`. These are fundamental for the tool, and their installation can proceed into the following way:

- Open the Command Prompt of your computer, in case you are working with Windows, or the terminal, if you are working with Linux or macOS;
- Digit "pip install package" where "package" needs to be substituted by the name of packs enumerated before;
- The system should proceed by itself from now on, you just need to repeat the procedure for every pack and at the end the window should show an output into which it says that the installation has been successful.

It is my advice to run the .exe file from Command Prompt the first time. This way, if any error of easy solution is found, it is possible to solve it by just reading at the error description that will be printed into the window.

8.2 Conceptual analysis assessment

How to call the function and what kind of analysis it makes:

The conceptual analysis assessment can be chosen if at the beginning the word CA is typed. This part of the tool is set upon the statistical analysis made into the thesis and, thereby, the assessment made gives results according with already existing aircraft.

Input necessary to the analysis and how they can be given:

Inputs it takes can be given into two different ways:

- The easiest method is to fill the sheet named “INITIAL DESIGN DATA” into the “INPUT file”, in this way the code will read it and the analysis will be quicker;
- The alternative is to manually insert data from command line, this happens in case there is an error reading the file or the sheet or if data cells have not been filled.

Needed data are the maximum number of passenger of the aircraft, the maximum weight at take off, the maximum range it can fly, the number of aircraft that it is planned to build and finally the acquisition price that each aircraft will have, as can be seen into the table 8.1.

Maximum number of passenger	
Maximum take off weight	Kg
Maximum range	Km
Number of aircraft to build	
Price	Million US 2002 dollars

Table 8.1: Conceptual analysis inputs

There is another input required to the user and it is the confidence level required upon the output values of emission. The value of confidence level will be used by ALiCIA to select the amount of emissions along the probability density function found which includes the confidence level percentage of cases. This input should be given as a number between 0.1 and 0.9.

How the function works:

This ALiCIA function works in the following way: regression curves obtained from statistical analysis have been implemented into the function and through them it is possible to use the input parameters to obtain a mean value of how much will be the emissions. However this type of data alone would be of little interest so the tool create the probability density function associated to each pollutant and there calculate the value of emission that has the confidence level required by the user, knowing that it means that the confidence level percentage of cases should fall into the interval from zero and the output.

Eventual exceptions and notes:

There are only two possible errors that can occur during running this analysis, the first one being the inability of reading the “INPUT file” because of some problem into the name or the directory, this error should never occur but if it happens call for help from someone that has complete access to the code. The second error is more usual and so can be seen as a warning and it occurs if the “INPUT file” is not well filled. In this case, as it has been said before, the tool will asks the user if he wants to exit the process or if he wants to fill values manually from command line.

Limitations:

The only two limitation associated with this function are that:

- Emissions categories are only kg of CO2eq, kg of SO2eq and kg of NOx eq, this fact is due to the limitation of using an EIO-LCA and therefore some emission categories are left apart. This lack is the reason why this analysis can be useful only during conceptual design;

- Price should be filled in 2002 dollars, which means that you need to transform the acquisition price from the value you have into this and also this limitation is associated with the use of EIO-LCA because the last reliable database is dated 2002.

The great power of this instrument is that it can do a quickly estimate of pollutant emissions of major importance which means that it is perfect to make a comparison between different design options, knowing that values in output are not casual and can estimate the final impact to a good approximation.

How the output is given:

The output of this analysis is not printed into any file, differently from what I will show you about others assessment functions, but it is only printed into the command line and it will be in the following form:

```
Insert the confidence level required as a number between 0 and 1: 0.75
The emissions of CO2eq are 4429720.03 kg and the confidence level is 75.08%
The emissions of SO2eq are 11645.49 kg and the confidence level is 75.03%
The emissions of NOxeq are 9639.64 kg and the confidence level is 75.11%
```

The choice of not printing on file these results derives from the facts that these are useful only for a conceptual analysis and can be more a guiding star into the following journey.

8.3 Material production assessment

How to call the function and what kind of analysis it makes:

The material production assessment can be chosen if at the beginning the word M is typed. The scope of this analysis is to flow between the various systems into which the aircraft can be break down and to assess the impact of the production of every one of them.

Input necessary to the analysis and how they can be given:

Now, this function needs to take data from some data-sheets and, thereby, I will begin enumerating them and shortly saying what is their role:

- `Input file`, where the important sheets are the sub-systems ones. Here, there are listed the different sub-systems of each system. Alongside the name of the sub-system there is a cell in which is important to insert its weight otherwise the tool will stop and send out a warning message asking to insert the values from command line. Alongside each possible component or material for a specific sub-system there is a cell that can be filled with the percentage in weight of this component or material, if it is known, and it is usually already filled with a value that comes from statistics. To ease the understanding of which values is fundamental to fill to obtain an analysis and which are optional there is a color pattern, cells in red must be filled while cells in green can be filled if values are known but otherwise are already filled with traditional values;

- `Component_production` file. It is highly recommended not to change its values unless you are sure you understand how it works. The first sheet is the only one that needs to be changed while the others ones are useful only for the software. Into this sheet, the first column usually enumerates the components, under the name of the sub-system whom they belong, and the different parts that can be found into each component, while the second one associates a material for each part. The third column has values that stand for percentage in weight of each part and from the following column on the processes needed for each part production are listed. The only big exception if for `ELECTRICAL GENERATION` sub-system, as will be explained in the following;

- `Emissions_processes` is a file that is useful only to the software and so changing it can lead to problems difficult to solve. It contains data about the emissions of every single process, divided between pollutants as reported into the first line and with the measurement units stated into the second line.

How the function works:

The function is implemented to assess all the sub-systems at once, however if you want to analyze only some of them you can simply fill with zero the weight of sub-systems you don't want to include. The user is called to fill the `Input file` with values coming form its project, keeping in mind that weight values are fundamental while the percentage in weight of each material into a single component can be inserted but if it is not yet known it will be easily estimated from the statistics coming out of ATR family analysis. Moreover, also the break down of weight over different parts into a sub-subsystem or into a component, e.g. the weight of the ribs over the entire wing, can be changed into the `Component_production` varying the value into the third column keeping in mind that within the same component the percentage of weight distribution among the materials has already been stated and therefore these percentages are only related to the weight relative to the component or material they belong. To better show what I am saying here there is an example 8.2 Here the sum of all percentages of aluminium made parts is 1 while the carbon fibre is left apart.

WING		
machined parts	Aluminium	0,1
stamped parts	Aluminium	0,65
cast parts	Aluminium	0,25
carbon fibre parts	Carbon fibre	1

Table 8.2: $Component_production file$

That is all it is needed to be known to work with ALiCIA software for the part of material production assessment. From now on I will explain how calculation are made into detail, using the structure impact calculation as example, in case the user wants to improve it. First of all, the function open the sheet `Structure` into the excel file `Input file`. Here, starting from the first row it reads until it finds that into the first cell there is a string all in caps, which means that components need to be written in caps to be read. When it encounters this line, it reads also the weight and, if not present, it will stop and send a warning message out asking the user to insert the value from command line. After finding the beginning of each component break down, it begins a cycle that ends when it finds a void line and that saves all the values into a matrix where into the first column is reported the name of the possible material, or possible components for other systems, while the second column has its percentage in weight. When the void line is encountered, it opens the file `Component_production` to find how materials are subdivided between each component parts and what are the production processes these parts undergo. For each process, emissions are taken from `Emissions_processes` file and are manipulated and added to find the emissions related to the single component.

Eventual exceptions and notes:

As I previously said, there are some exception.

- The first one is for the `ELECTRICAL GENERATION` sub-system, where instead of materials, into the `Component_production` file, for each component is listed the power density. This parameter is fundamental to obtain a valid analysis since into the "Input file" you are asked to insert the power required from the components, e.g. Electric generator power in kW. That because the design of a electrical generator cannot be attached to its weight as well as it can be linked to to power generated. However, to assess its impact it is important to know its weight and so knowing the power generated, and its power density, it is possible to account for its weight and its innovative technologies all at once. The basic idea is the following: if an electrical generator is technologically advanced it results into a bigger power density so to generate the same power the weight of generator required is littler and littler will be its impact. The same can be said for every component of this sub-system;

- Another thing is related to `ELECTRICAL GENERATION` components and its the fact that there is the possibility to choose between two different electrical generators, the first one more traditional for power densities under 2 kW/kg while the second one is a starter generator common for more electric aircraft whose power densities can vary over 2 kW/kg. The same argument can be made for the case of electric motors;

- The second exception is that for *Electric resistance* into `THERMAL MANAGEMENT SYSTEM` and for *Heating element* into `DE-ICING` where the input required is the power consumption of the element;

- Another thing that you should know is that `SOFTWARE` is included into the material production and its impact accounts for all the hours spent in developing systems software, therefore the input it requires is in hours.

Here there are some special cases that have required hypothesis that comes from *Ecoinvent* database or from [52]:

- Milling aluminium means that only the 80.6% of the initial piece will be transformed into the final product while the remaining 19.4% goes into the scrap and will be melted and reused. This assumption leads to the fact that the impact of production will be multiplied for a factor 1.24 to take into account all the initial piece production and milling, that is calculated for kilogram of material eliminated through the process, will be applied over the a weight that is 0.24 times the final product weight;

- It is considered that steel is produced from a mix of 60% virgin material and 40% recycled one, which is the mix usually present into European market;

- Forging steel has a similar approach to milling aluminium but this time the initial piece as a weight only of 1.24 times the final product one;

- As reported into the disposal paragraph, the disposal of each component is already accounted into its production. The only case where this process is explicit it is for plastic materials, such as carbon fibre panels of the structure, where the treatment process is inserted into the `Component_production` file. In calculations, it is considered that 32.5% of plastic will undergo a recycling process while the rest is incinerated or land filled, and only these last two processes have an environmental impact and are accounted into the process *plastic_treatment*.

Obviously, these values can be changed into the code to account for eventual different hypothesis or technological advances.

How the output is given:

At last, the code calculates the entire impact of each sub-system and writes it on the `OUTPUT.csv`, after writing into a blank line the systems which they belong and the subsystem into the first cell, as can be seen into 8.3. Here only CO2eq. impact is reported but into the `OUTPUT.csv` obviously all impacts are written.

COMPONENT	Global warming [kg CO2 eq]
STRUCTURE	
WING	6,88E+04
FUSELAGE	4,36E+04
TAIL	4,00E+04
LANDING GEAR	2,07E+03

Table 8.3: Material production output

8.4 Immaterial production assessment

How to call the function and what kind of analysis it makes:

The immaterial production assessment can be chosen if at the beginning the word IM is typed. The scope of this analysis is to assess the impact of the immaterial production processes, those that are common to more than one aircraft system.

Input necessary to the analysis and how they can be given:

Inputs are divided between the voices in 8.4.

DEVELOPMENT AND MANUFACTURING	
ENGINEERING	
development	number of hours needed
production	number of hours needed

MANUFACTURING WORK	
development	number of hours needed
production	number of hours needed
TOOLING	
development	total cost in dollars
production	total cost in dollars
QUALITY CONTROL	
development	number of hours needed
production	number of hours needed
PROGRAM MANAGEMENT	
entire program life	number of hours needed
TEST AND EVALUATIONS	
PROTOTYPES PRODUCTION	
production	number of hours needed
tooling	total cost in euros
quality control	number of hours needed
number of prototypes build	
TESTING	
laboratory testing	number of hours needed
simulation	number of hours needed
flight testing	number of hours needed
DATA MANAGEMENT	
SERVER OPERATION	
entire program life	number of hours needed
SITE CONSTRUCTION AND OPERATION	
CONSTRUCTION	
plant build	square meters
shed build	square meters
OPERATION	
plant operation	number of hours needed
INITIAL SPARES	
percentage of initial spares given	

Table 8.4: Immaterial production inputs

As you can see, this table, that needs to be filled in order to get the analysis, requests many data. The majority of them are the number of hours needed to complete that task. For example, into the *manufacturing work*, that states for all these activities like assembling parts together, the number of hours needed means the number of working man-hours sum of all activities taken. However, you must pay attention that hours in some cases have a different meaning, for example into *plant operation* and *flight testing*. That because these activities cannot be considered in terms of working man-hours but instead need a value in calendar time.

If you want to get an output that covers also impact of prototypes built and initial spares it is necessary to fill up also every sheet related to material production because it will use these data to make the assessment.

How the function works:

The functioning of this analysis is quite similar to the material production and fundamentally the code reads the activity into the rows of the `IMMATERIAL PRODUCTION` table and then searches into the file `Component-production` all the processes into which it can be broken down. Linking an impact to each of them and making the sum, the environmental impact of each activity is calculated. Some exceptions into this pattern are present, e.g.the assessment of the number of prototypes build, which impact is the same of the whole material production repeated for the number of times needed in the first case.

Eventual exceptions and notes:

The other exceptions are:

- The *tooling* activity always requires an input in cost in dollars. This can lead to some problems, as explained into chapter of immaterial production inventory, but it is relatively accurate;
- The *construction* requires a value in square foots since if you need to build a new plant you should know how much land you will cementify;
- The *initial spares* are usually given as a percentage of all aircraft components into procurement and thereby this is the method.

The *number of prototypes build* and *initial spares* conditions implies that also tables that refers to material production should be filled, otherwise inputs cannot be given by command line. Moreover, all values are not strictly necessary, and this is underlined by the fact that cells into the table are green, and so, if do not known these values, I advice to set them to zero. This way the analysis will neglect some parts but it won't give a result not attained to reality.

Limitations:

This analysis has some limitations that derive from the fact that many data required as inputs are sometimes not known or have an high degree of uncertainty. My advice is that sometimes it is easier to make this analysis for a fleet so that uncertainties are littler and commonly used life cycle cost assessment tools used into design could extrapolate all the data needed. If this is the case, once you have made the assessment over the entire fleet you can simply divide for the number of aircraft, always remembering to look closely which cost items flow into the voices taken by ALiCIA.

How the output is given:

Once all the calculations are made, the analysis prints the output in the file `OUTPUT.csv` in the same way it does for other calculations.

8.5 Fuel consumption impact

How to call the function and what kind of analysis it makes:

The mission impact assessment can be chosen if at the beginning the word OP is typed. The scope of this analysis is to assess the impact of the fuel consumption during missions, which, as you will see by yourself at the end of each analysis, is the biggest voice of impact across the whole aircraft life. It is important to remember that every assessment also includes the allocation due to the impact of the airport before the take off and after the landing, this way trying to return the best possible picture of a flight and all its correlated emissions.

Input necessary to the analysis and how they can be given:

ALiCIA has been implemented in a way that assure to the user three different methods to assess the impact of the fuel consumption during the operative life of the vehicle. These are not completely different one from each other but offer the possibility of an analysis more or less attached to the state-of-the-art of regional aircraft routes. Having differences means that inputs needed for each methods will also be different. In every case, however, it is fundamental to fill, totally or partially, the sheet `TYPE MISSION` of `INPUT file` with values in 8.5 Which of these inputs will be taken by each method will be explained subsequently, and also if more data are sometimes needed.

Range in km
Kerosene burned in kg
Electricity consumed in kWh
SAF burned in kg
Liquid Hydrogen consumed in kg
Number of flights to evaluate
Maximum range in km

Table 8.5: Mission impact inputs

How the function works:

At the beginning of the mission assessment the tool will ask you which one of the three methods you want to use, also giving a brief explanation of the inputs needed and of differences. Here the three ways are explained more in detail just in case you have any question:

- `First method`: an analysis based upon the statistics of regional flights. The very first method implemented relies upon a statistical analysis made over regional aircraft flights market. Fundamentally, the inputs it takes are the ones contained into the table filled originally but in addiction it also needs, and will ask you to insert this value from command line, the average number of passenger which is expected to flight with the aircraft taken into consideration. This data is important since impacts are here under the form of pollutants emission for person for kilometer traveled. Proceeding by order of the calculations, ALiCIA firstly uses the range of the type mission to search into the database the process that gives the emission values associated with this range. The possible distances among which the database is subdivided are below $800km$, between $800km$ and $1500km$ and over $1500km$, knowing that the first one is the mainly for turboprop aircraft while the latter two are more related to turbofan aircraft. After this, it calculates the medium range between the ones into the statistical analysis knowing that the distribution is a normal logarithmic one. Finally the formula implemented is:

$$\begin{aligned}\text{total impact} &= \text{average number of passengers} \times \text{mean range} \times \\ &\times \text{number of flights} \times \text{passenger per kilometer traveled impact}\end{aligned} \tag{8.1}$$

- `Second method`: a middle ground between a thorough knowledge of the aircraft and a statistical analysis. This second way to assess the impact of the fuel consumption during the operative phase is a middle ground because it need the knowledge by the user of the consumption associated with a type mission, and obviously its range. As an improvement, this method also permits to assess the impact of hybrid electric aircraft since consumption can be given in input in terms of fuel burned and electrical energy charged at the airport.

  Following the calculation made by ALiCIA, firstly the fuel burned and the electricity consumed during the type mission are divided by the distance flown. In this way, it is possible to obtain two values of fuel burned and electricity consumed per kilometer flown. This part is the one not correlated to the statistical analysis while the mean range of all flights that is needed to assess is derived from statistics. At the end, to obtain the total impact of the flights, values previously obtained are used into the following formulas:

$$\begin{aligned}\text{total impact of fuel} &= \text{fuel burned per km} \times \text{fuel burned emissions} \times \\ &\times \text{mean range} \times \text{number of flights}\end{aligned} \tag{8.2}$$

$$\begin{aligned}\text{total impact of electric energy} &= \text{electricity consumed per km} \times \text{electricity emissions} \times \\ &\times \text{mean range} \times \text{number of flights}\end{aligned} \tag{8.3}$$

- `Third method`: complete power to the user. This method gives complete freedom to you by calculating the impact of a mission repeated for a certain number of times. To make this, it needs the consumption of a type mission, both in terms of fuel, kerosene, SAF or liquid hydrogen, and electric energy, the distance flown during the type mission and the number of flights to assess as inputs. This method is very useful and recommended whenever your willing is to assess the impact of a specific route perfectly knowing the aircraft consumption. It means that this method is not very useful in case the willing is to evaluate the impact over the entire life of the aircraft because is extremely improbable for an aircraft to flown the same route over and over. The formula used is:

$$\begin{aligned}\text{total impact} = {} & (\text{fuel burned emissions} \times \text{fuel per km} \times \\ & \times \text{electricity production emissions} \times \text{electricity consumed per km}) \times \\ & \times \text{type range} \times \text{number of flights}\end{aligned} \tag{8.4}$$

How the output is given:

Once all the calculations are made, the analysis prints the output in the file `OUTPUT.csv` in the same way it does for other calculations.

8.6 Maintenance assessment

How to call the function and what kind of analysis it makes:

The maintenance assessment can be chosen if at the beginning the word MAIN is typed. The scope of this analysis is to assess the impact of the maintenance process, which is divided between the the following voices:

ORGANIZATIONAL MAINTENANCE	number of hours needed
INTERMEDIATE MAINTENANCE	number of hours needed
DEPOT MAINTENANCE	number of hours needed
TIRES	replacement rate (in landings)
WHEELS	replacement rate (in landings)
BRAKES	replacement rate (in landings)
BATTERY	replacement rate (in hours of flight)
FUEL CELL SYSTEM	replacement rate (in hours of flight)
HYDRAULIC OIL	replacement rate (in hours of flight)
ENGINES	replacement percentage
APU	replacement percentage
AVIONICS	replacement percentage
FUEL SYSTEM	replacement percentage
HYDRAULIC SYSTEM	replacement percentage
ELECTRIC SYSTEM	replacement percentage
STRUCTURE	replacement percentage

Table 8.6: Maintenance inputs

Input necessary to the analysis and how they can be given:

As said into the paragraph where maintenance life cycle inventory has been explained in details, this phase has been divided into two main voices. The first one is direct work of maintenance, divided by organizational, intermediate and depot. For these impact items, it is important to insert the total man-hours they will take, estimated for the whole life of the aircraft. The second voice is the one constituted by the sum of all component that will be regenerated during the life of the aircraft. For these it is important to know the replacement rate, which means the number of flight hours or landing before the piece should be overhauled or replaced, or the replacement percentage. To explain better this last unit an example is needed. Let's say that during aircraft life engines need to be regenerated more than one time and the sum of all the pieces substituted could have found place into an engine and a half, thereby we could say that it is as if the engine was completely substituted 1.5 times. This 1.5 is the replacement percentage, so the percentage of the systems that will be replaces, whose production is important to assess.

Once this table is filled, it is important to remember that maintenance analysis is based upon information that comes from production and so also the `INPUT file` sheets that contains weights and data for the structure, the power plant and the systems needs to be filled. In this way the code will be able to make the due calculations. If not correctly written into various tables, data will be asked through command line.

How the function works:

Once the tables are filled and the analysis is running, the code will analyze the various voices and sometimes could ask you to insert some more data. In facts, APU weight is not explicitly known during production as it is considered inside the voice "equipped engines and propellers" so here it is asked to the user and then the impact is calculated as the weight for the percentage multiplied by the impact in building a turbofan engine due to similarities. Another case is the weight of hydraulic fluids present on-board, this data is usually contained into the sheet `DISPOSAL` but if not filled, for example if you don't want to make a complete assessment of all phases, ALiCIA will ask you to insert it from command line. Last data needed are the aircraft stop calendar time for both intermediate and depot maintenance. The difference with hours into the table is that they are working man-hours while the stop time is the effective time needed for maintenance. If you know it, it is useful to assess also the use of the facility where maintenance is done, otherwise you can simply let the software use statistical data coming from aviation authorities specifications.

Eventual exceptions and notes:

When you make this analysis you should always keep in mind that maintenance of components and sub-systems has always been interpreted as substitution of the part. However, it is more usual that during maintenance tasks only some parts are completely substituted while the others are repaired and remounted. Obviously, repairing a product is much less impactful than building it from new, so the results you get are conservative. Moreover, into the substitution is included also the disposal of the broken component, while this process is not needed in case of repairing.

Limitations:

Maintenance activities are modeled only accounting for the use of electricity due to the need of using tool to get the work done. Moreover, it is considered that for organizational maintenance every man-hour the operator needs to travel for at least five kilometer while into intermediate maintenance and depot maintenance the use of the facility and its auxilliary energy inputs are accounted and you will be asked to input the amount of hours of aircraft stop for each one, as previously said. In addiction, nothing is said about the travel components need to undergo to reach the maintenance facility.

How the output is given:

Once all the calculations are made, the analysis prints the output in the file `OUTPUT.csv` in the same way it does for other calculations.

8.7 Disposal assessment

How to call the function and what kind of analysis it makes:

The disposal assessment can be chosen if at the beginning the word DIS is typed. When you decide to make an analysis of the disposal phase of the aircraft you should always keep in mind that this means that you are evaluating the impact due to disassembling, dismantling and treating hazardous fluids present on board. That because the disposal of each component and its materials is already implemented into the production phase.

How the function works:

The disposal of an aircraft can be evaluated following two ways:

- The first one require the user to know the number of hours that disassembling and dismantling phases will take. This is not such a common knowledge but sometimes it can be one of the output of a life cycle cost software, because at the end the disassembling is not so different from the assembling;

- The second way requires less knowledge as it is based upon the analysis made by J. Scheelhaase and al. [48] and by X. Zhao and al. [64]. Through these studies, it has been possible to extrapolate a value for the cost of disposal processes. The tool convert this cost into labor hour considering that 90% of the cost is associated with workers labor over the aircraft while the remaining 10% is due to all the program management work that handling and organizing these processes requires. The cost per hour of work of an aircraft mechanic is estimated around 25 dollars while the average cost per hour of program management work is estimated around 60 dollars.

Input necessary to the analysis and how they can be given:

DISASSEMBLING PROCESS	number of hours needed
DISMANTLING PROCESS	number of hours needed
HAZARDOUS FLUIDS	kg of fluids to dispose

Table 8.7: Disposal inputs

Due to the two ways to calculate the impact, data needed are various. In order to use the first method you need to fill the table 8.7 that is into the `DISPOSAL` sheet of the `INPUT file` with values in terms of number of man-hours needed or kg of hazardous fluids, not only hydraulic oil, present on board. The second method is more spartan and only needs the number of engines and kg of hazardous fluids as inputs. All others data are intern to the function.

Eventual exceptions and notes:

Last thing that need to be said is that the weight of hazardous fluids that need to be purged is required for both the ways because the variability of this data between different aircraft models is high, just think how many less kilograms of hydraulic fluid would be required in a more electric aircraft, and treatment of hazardous fluids is so impactful that an approximation is not acceptable.

The first way potential is that it can be more related to the aircraft that you are designing and moreover that data can be changed, taking into account new ways and advances into the treatment process of an aircraft. The second one can be used in an initial moment when not all the due considerations have been already made.

Limitations:

The great limitation about this function is that usually data about dismantling and disassembling are not known in a preliminary design phase. Moreover, these processes are modeled in a very simplified, even if not simplistic, way. To overcome this problem the second method by-passes it but this means make reference to values that comes from an analysis of end-of-life processes of already existing aircraft and so it is difficult to assess improvements into technologies used.

Looking at this difficulties from another point of view, however, it is possible to imagine that increasing attention to environmental issues will lead designer to study their products so that they can be easily disassembled and disposed of, and thus being able to have an end-of-life figure allows comparisons to be made between different architecture proposals while avoiding over-complicating the design in case these choices lead to minimal impact reductions.

How the output is given:

Once all the calculations are made, the analysis prints the output in the file `OUTPUT.csv` in the same way it does for other calculations.

Appendix A

Analysis Results

A.1 ATR42

A.1.1 Material Production

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
WING	6,88E+04	2,94E+02	1,81E+02
FUSELAGE	4,36E+04	2,74E+02	1,37E+02
TAIL	4,00E+04	1,51E+02	8,41E+01
LANDING GEAR	9,88E+03	3,28E+01	2,48E+01
NACELLE AND STRUCTS	2,37E+04	9,80E+01	5,34E+01
EQUIPPED ENGINES AND PROPELLERS	5,44E+04	8,34E+02	1,46E+02
FUEL SYSTEM	6,32E+02	4,49E+00	2,21E+00
HYDRAULIC GENERATION	3,81E+02	4,87E+00	1,39E+00
HYDRAULIC DISTRIBUTION	1,30E+02	4,96E-01	3,23E-01
ENVIRONMENTAL CONTROL SYSTEM	2,30E+03	1,76E+01	7,98E+00
DE ICING	1,48E+03	8,44E+00	4,34E+00
FLIGHT CONTROL SYSTEM	8,56E+02	3,14E+00	2,06E+00
AVIONIC INSTRUMENTS	4,72E+04	2,37E+02	1,57E+02
ELECTRICAL GENERATION	1,67E+04	4,62E+02	8,88E+01

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
ELECTRIC COMMON INSTALLATIONS	5,46E+03	2,29E+01	1,26E+01
THERMO ACOUSTIC INSULATION	4,09E+02	9,76E-01	7,66E-01
FURNISHING	3,42E+03	8,35E+00	5,29E+00
LIGHTING	4,49E+03	2,57E+01	1,53E+01
OPERATIONAL ITEMS	5,67E+03	2,79E+01	1,68E+01
OPERATIONAL EQUIPMENT	2,87E+03	1,72E+01	8,00E+00
SYSTEMS SOFTWARE	1,47E+02	6,85E-01	4,18E-01

A.1.2 Immaterial Production

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
MANUFACTURING WORK	3,07E+04	9,64E+01	6,72E+01
TOOLING	1,63E+04	1,69E+02	5,26E+01
QUALITY CONTROL	2,22E+02	9,46E-01	4,90E-01
PROGRAM MANAGEMENT	3,80E+02	1,56E+00	9,61E-01
PROTOTYPES PRODUCTION	1,90E+03	1,47E+01	5,45E+00
TESTING	4,88E+03	1,63E+01	1,07E+01
SERVER OPERATION	4,07E+01	1,75E-01	1,21E-01
CONSTRUCTION	0,00E+00	0,00E+00	0,00E+00
SITE OPERATION	2,57E+04	2,44E+01	4,55E+01
INITIAL SPARES	4,73E+04	3,66E+02	1,35E+02

A.1.3 Maintenance

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
ORGANIZATIONAL MAINTENANCE	4,49E+03	2,08E+01	4,42E+01
INTERMEDIATE MAINTENANCE	3,11E+04	5,01E+01	5,91E+01
DEPOT MAINTENANCE	3,17E+04	7,25E+01	6,43E+01
TIRES	1,39E+04	5,54E+01	9,47E+01
WHEELS	9,17E+04	2,91E+02	2,35E+02
BRAKES	4,25E+03	2,83E+01	9,44E+00
BATTERY	8,29E+03	2,20E+02	2,59E+01
FUEL CELL SYSTEM	0,00E+00	0,00E+00	0,00E+00
HYDRAULIC OIL	1,09E+04	1,72E+01	2,67E+01
ENGINES	6,53E+04	1,00E+03	1,76E+02
AVIONICS	5,67E+04	2,84E+02	1,88E+02
FUEL SYSTEM	2,53E+02	1,80E+00	8,83E-01
HYDRAULIC SYSTEM	2,04E+02	2,15E+00	6,86E-01
ELECTRIC SYSTEM	4,36E+03	1,83E+01	1,01E+01
STRUCTURE	5,58E+04	2,55E+02	1,44E+02

A.1.4 Fuel consumption

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
FUEL CONSUMPTION	7,54E+07	1,33E+05	1,16E+05

A.1.5 Disposal

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
DISMANTLING AND DISASSEMBLING PROCESSES	9,17E+02	2,88E+00	2,01E+00
HAZARDOUS FLUIDS	3,42E+02	1,73E-02	2,75E-02

A.2 ATR72

A.2.1 Material Production

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
WING	8,25E+04	3,53E+02	2,17E+02
FUSELAGE	5,32E+04	3,34E+02	1,67E+02
TAIL	3,99E+04	1,51E+02	8,39E+01
LANDING GEAR	1,08E+04	3,57E+01	2,69E+01
NACELLE AND STRUCTS	2,37E+04	9,77E+01	5,33E+01
EQUIPPED ENGINES AND PROPELLERS	5,44E+04	8,33E+02	1,46E+02
FUEL SYSTEM	6,67E+02	4,74E+00	2,33E+00
HYDRAULIC GENERATION	3,77E+02	4,82E+00	1,38E+00
HYDRAULIC DISTRIBUTION	1,30E+02	4,96E-01	3,23E-01
ENVIRONMENTAL CONTROL SYSTEM	2,42E+03	1,85E+01	8,40E+00
DE ICING	1,65E+03	9,43E+00	4,85E+00
FLIGHT CONTROL SYSTEM	8,25E+02	3,03E+00	1,99E+00
AVIONIC INSTRUMENTS	4,65E+04	2,33E+02	1,54E+02
ELECTRICAL GENERATION	1,67E+04	4,62E+02	8,88E+01
ELECTRIC COMMON INSTALLATIONS	5,27E+03	2,21E+01	1,22E+01
THERMO ACOUSTIC INSULATION	7,78E+02	1,85E+00	1,45E+00
FURNISHING	4,94E+03	1,21E+01	7,65E+00
LIGHTING	5,24E+03	3,00E+01	1,79E+01
OPERATIONAL ITEMS	7,85E+03	3,86E+01	2,32E+01
OPERATIONAL EQUIPMENT	3,65E+03	2,19E+01	1,02E+01

A.2.2 Immaterial Production

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
ENGINEERING	3,32E+02	1,42E+00	7,34E-01
MANUFACTURING WORK	2,79E+04	8,75E+01	6,10E+01
TOOLING	1,59E+04	1,66E+02	5,15E+01
QUALITY CONTROL	1,75E+02	7,44E-01	3,86E-01
PROGRAM MANAGEMENT	3,00E+02	1,23E+00	7,59E-01
PROTOTYPES PRODUCTION	9,69E+02	6,35E+00	2,65E+00
TESTING	4,40E+03	1,46E+01	9,64E+00
SERVER OPERATION	2,02E+01	8,71E-02	6,00E-02
CONSTRUCTION	0,00E+00	0,00E+00	0,00E+00
OPERATION	3,82E+04	3,64E+01	6,79E+01
INITIAL SPARES	4,84E+04	3,18E+02	1,32E+02

A.2.3 Maintenance

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
ORGANIZATIONAL MAINTENANCE	4,49E+03	2,08E+01	4,42E+01
INTERMEDIATE MAINTENANCE	3,11E+04	5,01E+01	5,91E+01
DEPOT MAINTENANCE	3,17E+04	7,25E+01	6,43E+01
TIRES	1,51E+04	6,03E+01	1,03E+02
WHEELS	9,99E+04	3,17E+02	2,56E+02
BRAKES	4,63E+03	3,08E+01	1,03E+01
BATTERY	8,29E+03	2,20E+02	2,59E+01
FUEL CELL SYSTEM	0,00E+00	0,00E+00	0,00E+00
HYDRAULIC OIL	1,09E+04	1,72E+01	2,67E+01
ENGINES	6,52E+04	9,99E+02	1,75E+02
AVIONICS	5,57E+04	2,79E+02	1,85E+02

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
FUEL SYSTEM	2,67E+02	1,90E+00	9,32E-01
HYDRAULIC SYSTEM	2,03E+02	2,13E+00	6,80E-01
ELECTRIC SYSTEM	4,21E+03	1,77E+01	9,75E+00
STRUCTURE	6,30E+04	2,91E+02	1,64E+02

A.2.4 Fuel consumption

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
FUEL CONSUMPTION	8,60E+07	1,51E+05	1,32E+05

A.3 ATR42Hybr.

A.3.1 Material Production

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
WING	6,14E+04	2,62E+02	1,62E+02
FUSELAGE	4,41E+04	2,76E+02	1,38E+02
TAIL	3,85E+04	1,45E+02	8,10E+01
LANDING GEAR	1,12E+04	3,70E+01	2,80E+01
NACELLE AND STRUCTS	2,36E+04	9,72E+01	5,30E+01
EQUIPPED ENGINES AND PROPELLERS	1,48E+05	9,68E+02	3,30E+02
FUEL SYSTEM	0,00E+00	0,00E+00	0,00E+00
HYDRAULIC GENERATION	0,00E+00	0,00E+00	0,00E+00
HYDRAULIC DISTRIBUTION	0,00E+00	0,00E+00	0,00E+00
ENVIRONMENTAL CONTROL SYSTEM	3,77E+03	2,88E+01	1,31E+01
DE ICING	0,00E+00	0,00E+00	0,00E+00

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
FLIGHT CONTROL SYSTEM	1,34E+03	4,92E+00	3,22E+00
AVIONIC INSTRUMENTS	1,89E+05	9,45E+02	6,27E+02
ELECTRICAL GENERATION	7,00E+04	1,14E+03	2,78E+02
ELECTRIC COMMON INSTALLATIONS	3,68E+04	1,54E+02	8,52E+01
THERMO ACOUSTIC INSULATION	7,80E+02	1,86E+00	1,46E+00
FURNISHING	3,68E+03	9,00E+00	5,70E+00

A.3.2 Maintenance

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
ORGANIZATIONAL MAINTENANCE	4,49E+03	2,08E+01	4,42E+01
INTERMEDIATE MAINTENANCE	3,11E+04	5,01E+01	5,91E+01
DEPOT MAINTENANCE	3,17E+04	7,25E+01	6,43E+01
TIRES	1,57E+04	6,27E+01	1,07E+02
WHEELS	1,04E+05	3,29E+02	2,66E+02
BRAKES	4,80E+03	3,20E+01	1,07E+01
BATTERY	1,46E+06	1,32E+04	4,50E+03
FUEL CELL SYSTEM	0,00E+00	0,00E+00	0,00E+00
HYDRAULIC OIL	0,00E+00	0,00E+00	0,00E+00
ENGINES	1,77E+05	1,16E+03	3,96E+02
AVIONICS	2,26E+05	1,13E+03	7,52E+02
FUEL SYSTEM	0,00E+00	0,00E+00	0,00E+00
HYDRAULIC SYSTEM	0,00E+00	0,00E+00	0,00E+00
ELECTRIC SYSTEM	4,42E+04	1,85E+02	1,02E+02
STRUCTURE	5,36E+04	2,45E+02	1,39E+02

A.3.3 Fuel consumption

	Global Warming [CO2eq.]	Terrestrial Acidification [SO2eq.]	Ozone formation [NOxeq.]
FUEL CONSUMPTION	5,77E+07	9,77E+04	8,72E+04

A.4 HETP

A.4.1 Material Production

	Global Warming [CO2eq.]	Terrestrial Acidification [SO2eq.]	Ozone formation [NOxeq.]
WING	2,44E+05	9,20E+02	5,13E+02
FUSELAGE	6,53E+04	4,10E+02	2,05E+02
TAIL	6,31E+04	2,38E+02	1,33E+02
LANDING GEAR	2,25E+04	7,45E+01	5,63E+01
NACELLE AND STRUCTS	6,01E+04	2,48E+02	1,35E+02
EQUIPPED ENGINES AND PROPELLERS	4,70E+04	6,38E+02	1,25E+02
FUEL SYSTEM	1,29E+03	9,16E+00	4,50E+00
ENVIRONMENTAL CONTROL SYSTEM	4,29E+03	3,27E+01	1,49E+01
THERMAL MANAGEMENT SYSTEM	4,81E+04	2,09E+02	1,47E+02
DE ICING	9,20E+02	6,84E+00	3,31E+00
FLIGHT CONTROL SYSTEM	9,55E+02	3,51E+00	2,30E+00
AVIONIC INSTRUMENTS	5,68E+04	2,85E+02	1,89E+02
ELECTRICAL GENERATION	5,41E+05	1,56E+04	4,59E+03
ELECTRIC COMMON INSTALLATIONS	1,04E+04	4,36E+01	2,41E+01
THERMO ACOUSTIC INSULATION	7,92E+02	1,89E+00	1,48E+00
FURNISHING	5,34E+03	1,31E+01	8,27E+00

	Global Warming [CO2eq.]	Terrestrial Acidification [SO2eq.]	Ozone formation [NOxeq.]
LIGHTING	5,55E+03	3,18E+01	1,89E+01
OPERATIONAL ITEMS	1,13E+04	5,57E+01	3,35E+01
OPERATIONAL EQUIPMENT	5,09E+03	3,05E+01	1,42E+01

A.4.2 Fuel consumption

	Global Warming [CO2eq.]	Terrestrial Acidification [SO2eq.]	Ozone formation [NOxeq.]
FUEL CONSUMPTION	5,02E+07	8,93E+04	7,73E+04

A.5 Commuter

A.5.1 Material Production

	Global Warming [CO2eq.]	Terrestrial Acidification [SO2eq.]	Ozone formation [NOxeq.]
WING	2,07E+04	8,85E+01	5,45E+01
FUSELAGE	9,09E+03	5,70E+01	2,85E+01
TAIL	9,90E+03	3,74E+01	2,08E+01
LANDING GEAR	2,71E+03	8,99E+00	6,79E+00
NACELLE AND STRUCTS	5,94E+03	2,45E+01	1,34E+01
EQUIPPED ENGINES AND PROPELLERS	1,92E+04	2,95E+02	5,16E+01
FUEL SYSTEM	2,15E+02	1,53E+00	7,51E-01
ENVIRONMENTAL CONTROL SYSTEM	6,49E+02	4,95E+00	2,25E+00
DE ICING	1,53E+02	1,14E+00	5,52E-01
FLIGHT CONTROL SYSTEM	3,30E+00	1,30E+00	2,30E+00
AVIONIC INSTRUMENTS	1,27E+04	6,35E+01	4,21E+01

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
ELECTRICAL GENERATION	5,87E+02	8,16E+00	1,77E+00
ELECTRIC COMMON INSTALLATIONS	1,01E+03	4,22E+00	2,33E+00
THERMO ACOUSTIC INSULATION	1,61E+02	3,84E-01	3,01E-01
FURNISHING	1,11E+03	2,71E+00	1,71E+00
LIGHTING	1,16E+03	6,66E+00	3,96E+00
OPERATIONAL ITEMS	1,42E+03	6,99E+00	4,20E+00
OPERATIONAL EQUIPMENT	7,06E+02	4,37E+00	1,92E+00

A.5.2 Fuel consumption

	Global Warming [CO2eq.]	**Terrestrial Acidification [SO2eq.]**	**Ozone formation [NOxeq.]**
FUEL CONSUMPTION	5,62E+07	9,89E+04	8,65E+04

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