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Life Cycle Assessment of the Airbus A330-200 Aircraft

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Abstract

This thesis addresses the environmental problems of the aviation sector, consisting in a environmental impact assessment of the Airbus A330-200 aircraft. In order to do so, a Life Cycle Assessment (LCA) of the aircraft was performed, which takes into account the environmental impacts of the aircraft from a cradle-to-grave perspective, meaning the entire aircraft life cycle is analysed. In order to do so, the Simapro software was used to model the manufacturing, operation, and end-of-life phases of the A330-200 aircraft. Thus, through the Life Cycle Assessment of the aircraft, guidelines and conclusions for improving the environmental performance of the aircraft are provided.

Being so, this thesis was the result of a collaboration with a Portuguese company that specialises in life cycle assessments, named '3 Drivers - Engenharia, Inovação e Ambiente', under the guidance of Professor Paulo Ribeiro. In addition, this work was carried out with the assistance of the airliner 'TAP Portugal', who provided A330-200 aircraft manuals in which indispensable data was contained, as well as valuable expertise opinions in many visits to TAP, which were carried out throughout the development of this work.

The results obtained with the Simapro software indicate that the operation phase of aircraft account for most of the environmental impacts, while the manufacturing of the aircraft is responsible for a much smaller contribution. The end-of-life scenario results in a small positive contribution for all environmental impacts considered, according to the Airbus 'Process for Advanced Management of End of Life of Aircraft' project.

Keywords: Airbus A330-200 aircraft, Life Cycle Assessment, Climate Change, Aviation Environmental Impact.

Resumo

A presente tese aborda os problemas ambientais do sector da aviação, consistindo numa avaliação do impacto ambiental da aeronave Airbus A330-200. De modo a fazer tal avaliação, uma Análise de Ciclo de Vida (LCA) foi levada a cabo, tendo em consideração os impactos ambientais da aeronave segundo uma perspectiva 'craddle-to-grave', o que significa que todo o ciclo de vida da aeronave é contabilizado. O software Simapro foi utilisado para modelar as fases de produção, operação e final de vida da aeronave A330-200. Deste modo, através da Análise de Ciclo de Vida realizada, linhas orientadoras de futuro trabalho e outras conclusões são apresentadas, de modo a melhorar o desempenho ambiental da aeronave.

Para além disso, esta tese é o resultado de uma colaboração com uma empresa Portuguesa especialisada em conduzir análises de ciclo de vida, de nome '3 Drivers - Engenharia, Inovação e Ambiente', sob a orientação do Professor Doutor Paulo Ribeiro. Para além disso, este trabalho foi conduzido com o auxílio da companhia aérea 'TAP Portugal', que disponibilizou vários manuais da aeronave A330-200 com dados indispensáveis, assim como valiosas peritagens prestadas durante várias visitas à TAP que tiveram lugar durante a realização deste trabalho.

Os resultados obtidos com o software Simapro indicam que a fase de operação da aeronave é responsável pela grande maioria dos impactos ambientais, enquanto que o processo de fabrico tem uma contribuição muito reduzida. Os resultados do fim de vida da aeronave resultaram numa pequena contribuição positiva para todas as categorias de impacto ambiental consideradas, o qual foi modelado segundo o projecto da Airbus 'Process for Advanced Management of End of Life of Aircraft'.

Palavras Chave: Aeronave Airbus A330-200, Análise de Ciclo de Vida, Alterações Climáticas, Impacto Ambiental da Aviação.

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List of Acronyms

AIC Aviation-Induced Cloudiness

ASK Available Seat Kilometres

ATM Air Traffic Management

CFRP Carbon Reinforced Plastic

GFRP Glass Fiber Reinforced Plastic

EPA United States Environmental Protection Agency

EU European Union

EU ETS European Union Emission Trading Scheme

EUROCONTROL European Organisation for the Safety of Air Navigation

FESG Forecasting and Economic analysis Support Group

GCI Global Commons Institute

GDP Gross Domestic Product

GE General Electric

GHG Greenhouse Gases

IATA International Air Transport Association

ICAO International Civil Aviation Organization

IEA International Energy Agency

IPCC Intergovernmental Panel on Climate Change

ISO International Organization for Standardization

IST Instituto Superior Técnico

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LOSU Level Of Scientific Understanding

MEW Manufacturer Empty Weight

MLG Main Landing Gear

NLG Nose Landing Gear

PAMELA Process for Advanced Management of End-of-Life Aircraft

PDF Probability Distribution Functions

PSK Passenger Kilometre

REPA Resource and Environmental Profile Analysis

RF Radiative Forcing

RPK Revenue Passenger Kilometres

SARS Severe Acute Respiratory Syndrome

SETAC Society of Environmental Toxicology and Chemistry

SRES Special Report on Emissions Scenarios

SRM Structure Repair Manual

UNEP United Nations Environment Programme

USG United State Gallon

UV Ultraviolet

WBM Weight and Balance Manual

WTC World Trade Center

List of Symbols

$\triangle T_s$ Global mean surface temperature

λ Climate sensitivity parameter

RF Radiative forcing

Chapter 1

Introduction

Specially since the 1960s the issue of environmental awareness has become increasingly important, leading to the creation of numerous regulations and laws, and leading to an increase of academical and scientific knowledge concerning this worldwide concern. Being so, many environmental categories have been studied and have gained a great popularity along scientific, political and general communities alike. These popular environmental categories include ozone depletion and climate change, being that latter has gained a high level of scientific understanding, while others categories still need further study and research. Lately, it has been recognized that the transportation sector is responsible for a high contribution to the total anthropogenic activities, and the aviation sector has also been regarded from a environmental perspective.

Thus, despite the fact that the aviation sector contribution to the environmental impact of the total anthropogenic activities is relatively low on the present time, it has been predicted that such contribution is bound to increase in the near future, has it has been since the beginning of commercial aviation. It then becomes imperative to have systematic and methodical ways to holistically assess and improve the environmental performance of aircrafts. Being so, an increasing environmental awareness has been embraced by airliners worldwide.

The Life Cycle Assessment (LCA) is a well-known tool for performing the evaluation of a product environmental impacts throughout its life cycle, from a cradle-to-grave approach. Being so, many softwares have been developed to assist and facilitate life cycle assessments, through the utilisation of extensive databases that contain reliable and validated data regarding several processes. One of the most popular LCA softwares has been used in this thesis, Simapro, in its version 7.2, and the Ecoinvent database has been used to model the aircraft life cycle, namely its manufacturing phase, operational life cycle, and its end-of-life scenario.

This thesis was carried out in a Portuguese company named '3 Drivers - Engenharia, Inovação e Ambiente', under the supervision of the Engineer Paulo Ribeiro. Furthermore, the manufacturing phase of the aircraft was carried out with the assistance of the Portuguese airliner 'TAP Portugal', that during several visits provided indispensable data and assistance throughout the evolution of this thesis thanks to Engineers João Carrolo and João Martins. Thus, access to several A330-200 aircraft manuals was provided, in order to detailly specify the weight and material constitution of each aircraft component.

Moreover, the operational data regarding the A330-200 was almost entirely provided by an airliner, on a confidential basis. Regarding the end-of-life scenario of the aircraft, the Airbus 'Process for Advanced Management of End of Life of Aircraft' (PAMELA) project that initiated in 2002 was used to model this life cycle phase. In order to do so, besides the data made available by Airbus, a personal communication with Airbus Engineer François Museux was established, in order to acquire further data that would allow a more accurate modelling.

Being so, this thesis had the main objective of evaluating the environmental load of the aircraft regarding several environmental categories, with a focus on climate change, as well as providing efficient and reasoned mitigation strategies regarding the reduction of the environmental load of aircrafts.

1.1 Research Problem

As it has been stated before, in the aviation sector there has been an urge to improve the environmental performance of aircrafts, due to the regulations and requirements that will soon be fully established. Thus, it is increasingly important to improve manufacturing and end-of-life processes, while reducing the inherent emissions occurring during the aircraft flights. In order accomplish such improvement, the assessment of the environmental impact of the aircraft through a systematic and methodical analysis must be performed, which provides the necessary knowledge and insight to address the environmental problems concerning aviation.

Therefore, this thesis can be said to be divided into the following main objectives:

1. Evaluate the aircraft A330-200 impact on the environment throughout its life cycle, providing valuable insights on the relative contribution of each life cycle phase to environmental harmful processes, namely the contribution of: each aircraft structural component and the different materials used; the fuel burn and operational procedures; recycling, landfill and other end-of-life processes;
2. Provide an assessment of the aircraft environmental impact, not only on climate change, but in other environmental impact categories as well;
3. Develop a aircraft life cycle model and framework that can easily adapted to other aircrafts and operations, as well as being a improvement of the air transportation process in the LCA databases;
4. Provide guidelines and orientations that have the potential of improving the aircraft environmental performance, either in processes regarding the manufacturing process, operational life cycle, and end-of-life scenario.

Being so, this thesis ends with the conclusions that indicate what should be altered in the aircraft life cycle in order to efficiently improve the aircraft environmental load.

1.2 Thesis Outline

This thesis is divided into six chapters, outlined as follows:

Chapter 1 comprises a brief introduction to this thesis.

Chapter 2 addresses the environmental problems regarding aviation, including predictions for aviation growth and its consequential environmental load.

Chapter 3 describes the life cycle assessment theoretical framework, namely its concept, methodology and computerization.

Chapter 4 discusses the modelling of the aircraft life cycle that has been done in this work, including the data collection process.

Chapter 5 presents the results obtained using the Simapro software, and its interpretations.

Chapter 6 summarises the results and conclusions. Moreover, includes recommendations for improving the aviation environmental performance.

Chapter 2

Aviation and the Environment

It is widely recognised that important environmental impacts are inherent to the aviation sector. Moreover, the aviation impact on the environment contributes to climate change, which has been a subject of great research, and a good knowledge level on this environmental impact category has been acquired. Thus, even though the climate change is not the only category to which aviation contributes, it is regarded as the most discussed, with several work being available in literature. Being so, the present chapter addresses the impacts of aviation on climate change, although the work developed for this thesis accounts for many other environmental categories besides climate change (see *Chapter* 4 and *Chapter* 5)

Aviation emissions alter the composition of the atmosphere, and thus it contributes to climate change, ozone depletion and other undesirable environmental impacts. Specifically, aviation changes the concentration of greenhouse gases (GHG) in the atmosphere, leading to climate change. According to global and EU inventories in 2004 [9], international aviation was responsible for approximately 3% of carbon dioxide (CO_2) emissions, being that from 1990 to 2004, CO_2 emissions from aviation increased 85% (bigger growth than maritime emissions and the domestic transportation sector) [9].

In 1999, in a response to a request by the International Civil Aviation Organization (ICAO), the Intergovernmental Panel on Climate Change (IPCC) published a landmark report, 'Aviation and the Global Atmosphere' [10], which consisted on the assessment of aviation's impacts on climate change and ozone (O_3) depletion. As a mean to assess environmental loadings, this report used the climate metric 'Radiative Forcing' (RF). Radiative Forcing has been used as a measure of the perturbation of the Earth atmosphere energy balance since 1750 (by convention in IPCC usage), resulting from changes in trace gases and particles in the atmosphere and other effects such as albedo. Being a measure of the importance of a potential climate change mechanism, it is expressed in watts per square meter $W.m^{-2}$. Positive values imply a net warming, whereas negative values imply a cooling effect. Being so, the IPCC report from 1999 largely contributed to a better understanding of aviation impacts on the atmosphere, estimating that non-CO_2 RF effects were responsible for 63% of the total radiative effect from aviation in 1992 (excluding cirrus clouds).

Accordingly, apart from CO_2 emissions, aircraft also contribute to the radiative forcing of climate by emitting nitrous oxides (NO_x : $NO\,and\,NO_2$), sulfur oxides (SO_x), water vapour and soot. Other greenhouse gas effects from aviation emissions have proven to be relevant, despite being less well understood, such as the formation of condensation trails (contrails) and cirrus clouds [10].

Furthermore, in assessing the potential anthropogenic activities, aviation emerges as a unique sector, since the majority of its emissions take place not at the surface of Earth, but at aircraft cruise altitudes of 8-12 km. At these altitudes, the emissions have a greater effect on atmospheric composition changes, causing chemical and aerosol effects relevant to climate forcing [2].

In 1999 it was concluded in [10] that aviation represented a small but increasingly relevant forcing of climate, that is difficult to be precisely estimated, mainly due to non-CO_2 effects. Nevertheless, on this report the IPCC estimated that aviation represented 3,5% of the total anthropogenic RF in 1992 (excluding AIC), being that mid-range emission scenarios projected this value would increase to 5% by 2050.

In 2005 the RF effects of aviation were re-evaluated in [11], concerning the year 2000. The obtained result was 47,8 $mW.m^{-2}$(excluding Aviation Induced Cloudiness - AIC), a quite similar value to the 48,5 $mW.m^{-2}$ present in the IPCC report for the year 1992. Despite airplane traffic growth, this similarity is explained through an improvement of the calculation of the RF, using more realistic assumptions and models. For AIC, the calculated mean estimate was 30 $mW.m^{-2}$, with an uncertainty range from 10 to 80 $mW.m^{-2}$, being that the upper limit of this range is twice the once assumed in the IPCC report from 1999. In 2009, the RF for the year 2005 was calculated, and the values of 55 $mW.m^{-2}$ (excluding cirrus cloud effect) and 78 $mW.m^{-2}$ (including cirrus cloud effect) were obtained in [2], respectively corresponding to 3,5% and 4,9% of the total anthropogenic RF in the year 2005. The discussion regarding the impacts of aviation on the environment will be addressed in the *Section* 2.1 of the present work, with further detail.

Civil aviation has been a strongly expanding sector that has steadily been growing since the end of 1960s, when air travel became more widespread and economically accessible. Hence, aviation passenger transport volume, in terms of Revenue Passenger Kilometers (RPK)[1], has grown since 1960 at nearly 9% per year, which is 2,4 times the average growth rate of Gross Domestic Product (GDP) [10]. As the aviation industry became more mature, the growth rate of passenger traffic decreased to 5,2%, despite the occurrence of world-changing events that harmed the aviation sector, such as the 1970s oil crises, the first Gulf War, the World Trade Center attack and outbreaks of Severe Acute Respiratory Syndrome (SARS) (see *Figure* 2.1[2]).

Furthermore, the number of aircrafts is expected to continue to grow, being that aircraft manufacturers estimate an evolution from around 20500 aircrafts in 2006 to 40500 aircrafts in 2026 [14]. The prospects for the evolution of aviation climate forcing and predictions for the aviation sector growth is addressed in the *Section* 2.3.

In 1997, the Kyoto Protocol was established, targeting GHG emissions from domestic aviation, but it didn't include aviation emission from international flights. However, in 2008 the European Parliament made the decision to include the aviation sector in the European Union Emission Trading Scheme (EU ETS) [3], even though aviation emissions will only be effectively included in the EU ETS in 2012. Consequently, aviation emissions inclusion in the EU ETS is broadly regarded as a subject of a great deal of importance, being that it will be the first international policy measure with compulsory goals and targets, with the aim of reducing CO_2 emissions from aviation. EU ETS and other mitigation strategies (discussed in *Section* 2.4) have the potential to induce behavioural changes in the aviation sector, despite being dependent on a proper implementation, and so reduce the environmental load of the aviation sector.

The European Union (EU) has set the goal of stabilizing CO_2 emissions below 450

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[1] Revenue passenger-km is a measure of the passenger traffic in commercial aviation: one revenue-paying passenger, travelling along one kilometer distance

[2] The top chart (Aviation Fuel Use and RPK) was obtained according to Sausen and Schumann [12] and extended with data from the IPCC report [10] and from the IEA 2007 report[13]. World events that influenced the aviation status through recent time are also represented through arrows proceeded by the event name, namely: the 1970s oil crisis, the first Gulf War in the early 1990s, the Asian financial crisis in the late 1990s, the World Trade Center (WTC) attack in 2001 and the global health crisis due to the Severe Acute Respiratory Syndrome (SARS). In the inward right hand axis represents the Revenue Passenger Kilometers (RPK), referring to the growth of air passenger traffic from 1970 to 2007 (source: ICAO traffic statistics from http://www.airlines.org/economics/traffic/World+Airline+Traffic.htm, 2007). In the outward right hand axis the annual change in RPK is represented (RPK per year).

[3] EU ETS (European Union Emission Trading Scheme) is the largest multi-national emission trading scheme in the world, standing as a major pillar of the European Union climate policy.

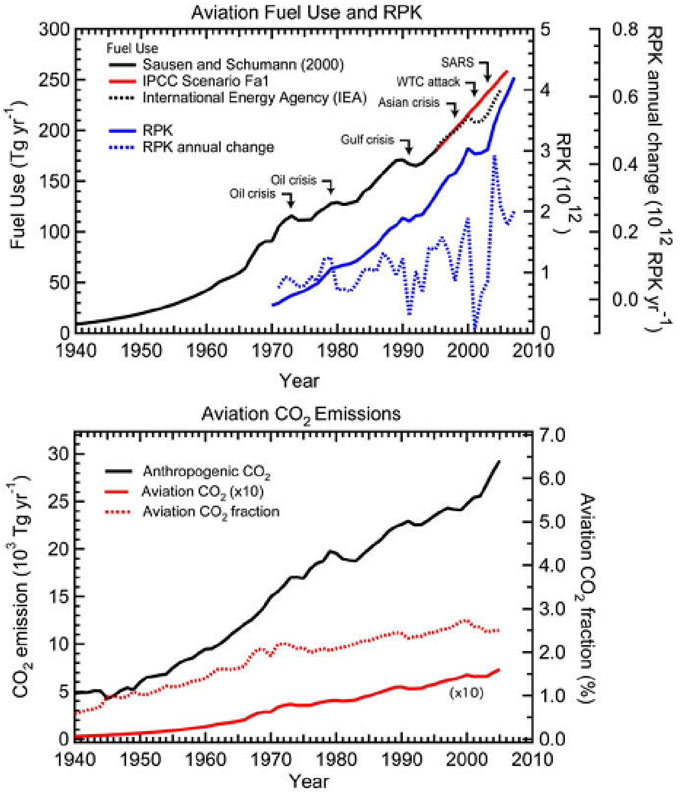

Figure 2.1: (Top) Aviation fuel usage since 1940 to 2010, expressed in Teragrams per year ($Tg\ yr^{-1}$). (Bottom) Evolution of CO_2 emissions for all anthropogenic activities and for the aviation sector (scaled by ×10).

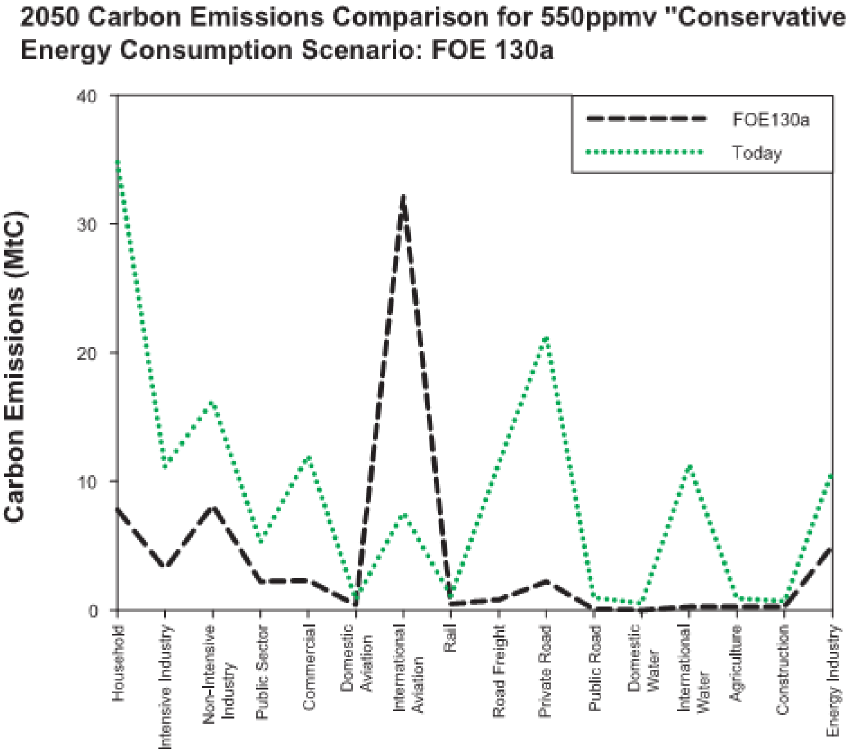

Figure 2.2: Comparison of Carbon Emissions in the UK for 2050, according to the Energy Consumption Scenario FOE 130a (source: [1])

or 550 parts per million by volume (*ppmv*), in 2050 [15], thanks to the global framework 'Contraction and Convergence', conceived by the Global Commons Institute (GCI) [16]. It has been argued that for that year, aviation contribution to CO_2 emissions will be 39% and 79% (for 450 and 550 *ppmv*, respectively), which would place aviation emissions at the top of the CO_2 emissions covered by EU ETS [1]. As a consequence, aviation growth and its inherent emissions would stand as a major threat in the overall effort of the EU in GHG reductions, which extent to several other sectors (see *Figure* 2.2[4]) .

Subsequently it is clear that the aviation sector will become a major problem in the near future regarding environmental problems. Moreover, the limitations and regulations imposed by governmental institutions will strongly affect the future of this sector, as well

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[4] The FOE 130a scenario assumes a conservative annual economic growth of 1,6 per annum and a primary energy consumption of 130 million tonnes of oil equivalent (Mtoe), lower than the present time primary energy consumption of 170Mtoe.

as aircraft's manufacturers policies and success.

Being so, it is vital that the environmental aspects of aircrafts are taken into account, and that more studies are made in order to successfully overcome the problem of aviation impacts on the environment. Life Cycle Assessment (LCA) naturally emerges as a very useful tool in assessing an aircraft environmental impact, for it stands as the environmental assessing technique of a product par excellence (LCA will be addressed further in *Chapter* 3).

2.1 Impacts of Aviation on Radiative Forcing and Ultraviolet Radiation

By convention, the climate impact induced by current and future prospects of aviation is quantified by the metric 'radiative forcing of climate'. This consensus is sustained by many climate experiments that suggested a approximately linear relationship between a change in global mean radiative forcing and a change in global mean surface temperature ($\triangle T_s$), when the system has reached a new equilibrium, i. e.:

$$\triangle T_s \simeq \lambda \times RF \tag{2.1}$$

where λ is the 'climate sensitivity parameter', measured in $K(W.m^{-2})^{-1}$, a value proven to be specific, yet stable, for different forcing agents.

Aircraft emit gases and particles directly into the upper troposphere and lower stratosphere, having an impact on the composition of the atmosphere. Consequently, aircraft emissions alter the RF of the Earth's climate system, which potentially leads to climate change impacts and ultimately result in damages affecting human health and ecosystems (among others). Aircraft emissions and its impacts on climate change can be seen on *Figure* 2.3, Here it can be seen that radiative forcing potentially leads to climate change, which is reflected through changes in the nature. In turn, climate changes have an impact on human activities, human health and ecosystems, which can be seen on).

Being so, aircraft emissions have an impact on the atmosphere that contribute to climate change, namely: the concentration of GHG is altered, namely carbon dioxide, ozone and methane; formation of condensation trails (contrails); potentially increases cirrus cloudiness.

According to the current state of knowledge, in terms of radiative forcing, subsonic

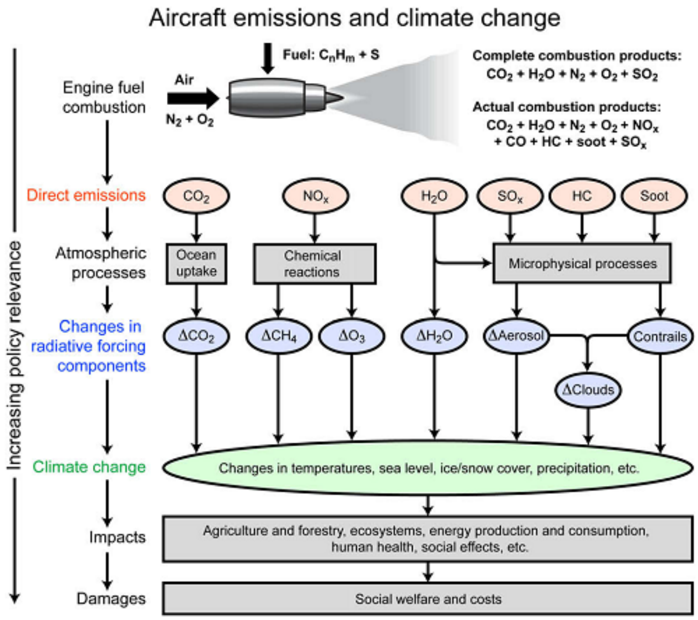

Figure 2.3: Main emissions from aircraft operations and the consequent atmospheric processes that lead to changes in radiative forcing (source: [2]).

aviation[5] affect climate due to the following processes [2], [6], [11]:

- emissions of CO_2, that result in a positive RF (warming);
- emissions of NO_x, resulting in the formation of tropospheric O_3 through atmospheric chemistry (positive RF). Moreover, there is a long-term reduction of methane (positive RF), also via atmospheric chemistry, which is accompanied by a parallel long-term small decrease in O_3 (negative RF, cooling effect);
- emissions of H_2O (positive RF);
- formation of persistent linear contrails that, depending on the weather conditions, may be formed in the wake of an aircraft (positive effect);

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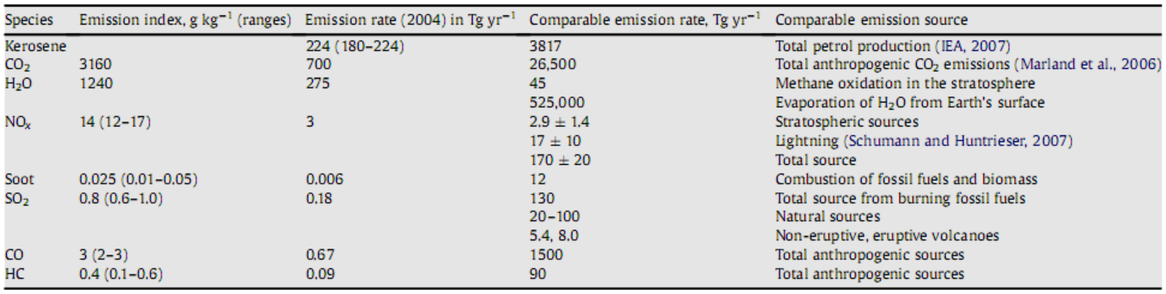
[5] supersonic aviation impacts differ from subsonic conditions, but will not be discussed throughout the present study, due to its non relevance to the analysis hereby endorsed. However, it can briefly be stated that H_2O emission play a much more important role, standing by far as the dominant RF term for supersonic aircraft. (for further information, refer to: [6] and [10])

- emissions of sulphate particles caused by the existence of sulphur in the fuel (negative RF);
- emission of soot particles (negative RF);
- aviation-induce cloudiness (AIC; potentially a positive RF).

The majority of the emitted species (gases and soot particles) present in the aircraft exhaust plume are formed due to the combustion of fuel with ambient air, which occurs in the engine's combustion chamber. The most common fuel used in aviation is kerosene, and although it exists in several types, the Jet A-1 is the most popular type of kerosene. Due to the importance of fuel combustion process, all aviation fuels have rigorous specifications and regulations, that cover their physical properties, chemical combustion and performance [10]. Aviation kerosene combustion mainly produces CO_2 and H_2O, which directly affect the concentration of GHG, but apart from these gases many other species are formed, such as NO, NO_2, SO_2, CO, hydrocarbons (HCs), and soot particles. Being so, in *Table* 2.1 some of the aircraft emitted species can be seen, along with the respective quantification and various comparisons from different sectors and activities.



Species	Emission index, g kg^{-1} (ranges)	Emission rate (2004) in Tg yr^{-1}	Comparable emission rate, Tg yr^{-1}	Comparable emission source
Kerosene		224 (180–224)	3817	Total petrol production (IEA, 2007)
CO_2	3160	700	26,500	Total anthropogenic CO_2 emissions (Marland et al., 2006)
H_2O	1240	275	45	Methane oxidation in the stratosphere
			525,000	Evaporation of H_2O from Earth's surface
NO_x	14 (12–17)	3	2.9 ± 1.4	Stratospheric sources
			17 ± 10	Lightning (Schumann and Huntrieser, 2007)
			170 ± 20	Total source
Soot	0.025 (0.01–0.05)	0.006	12	Combustion of fossil fuels and biomass
SO_2	0.8 (0.6–1.0)	0.18	130	Total source from burning fossil fuels
			20–100	Natural sources
			5.4, 8.0	Non-eruptive, eruptive volcanoes
CO	3 (2–3)	0.67	1500	Total anthropogenic sources
HC	0.4 (0.1–0.6)	0.09	90	Total anthropogenic sources

Table 2.1: Fuel consumption and emitted species, mean emission indices (mass of emissions per unit mass of burned fuel, for the fleet of aircraft in 2000), total emission rates due to aviation and for comparison emission rates from other sources. Fuel consumption is based on data from the International Energy Agency (2007). (source: [6])

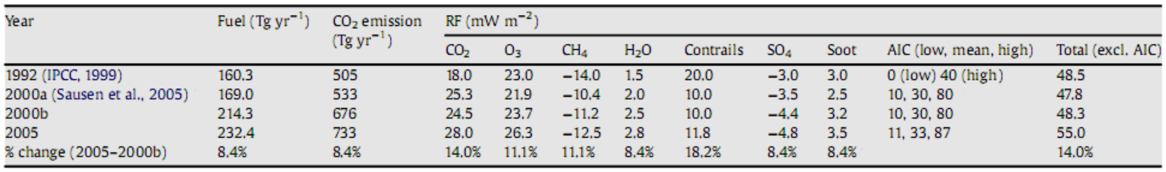
Commercial aviation is characterized by flights taking place at altitudes around 8 to 12 Km, emitting a multitude of species having a direct impact on atmospheric composition, or via chemical reactions. For that reason, the understanding of the pathways of the aircraft emitted species is crucial to rightfully determine the spacial distribution of the compounds and, hence, control the chemical fate of the species formed during the flights. Thus, similarly to CH_4, in the case of CO_2 it is known that it has a long atmospheric residence time ($\simeq$ 100 years) and so it becomes well mixed in the atmosphere, and therefore the spacial distribution of its emissions are not relevant. On the other hand, other gases (for instance NO_x, SO_x, water vapour) and particles have shorter atmospheric residence time and remain concentrated near aircraft pathways, mainly in the northern mid-latitudes [10]. It becomes clear that aircraft emissions may lead to regional forcings near flight routes, due to the its inherent emissions.

2.2 Past and Recent Emissions in Aviation

When aviation related emissions are discussed, it is unavoidable to address the aviation traffic volume, for there is a direct relationship between the two, despite the fact that, due to improved aircraft efficiency, an aviation traffic growth is not necessarily quantitatively equal to its inherent emission growth. Moreover, by convention, aviation traffic volume is reported in Revenue Passenger Kilometres (RPK), whereas air traffic capacity is usually expressed as Available Seat Kilometres (ASK).

Numerous global-scale events throughout recent history affected aviation growth and popularity, such as the 1970s oil crisis, the Gulf War in 1991 and the World Trade Center attack in 2001. Although, and despite the impact of these events, aviation traffic growth resumed shortly afterwards, and from 2001 to 2007 aviation traffic experienced a remarkable increase in RPK of 38%, despite strong year to year variations and intense regional differences (see $Figure$ 2.1 and [14]). It is also relevant to note that, regarding military aviation, this sector was responsible for 18% of fuel usage in the early 1990s, and 11% in 2002, although military fleets and movements are much more difficult to precisely estimate [6]. However, despite all the important declines, so far there has always been a correspondent strong recovery in aviation traffic volume, standing as a proof of the resilience of the industry and the public interest in air travelling.

In the calculation of CO_2 aviation emissions, this value is usually underestimated, due to several reasons such as the non-inclusion of military aviation data, non-inclusion of general aviation (small aircrafts flying under visual flight rules) and incomplete or erroneous inventories data. Therefore, it is important that the calculation of CO_2 aviation emissions refers to the total kerosene fuel sales, which reflects the total impact of all aviation emissions. The calculated RF for aviation in 2005 is given in $Table$ 2.2, which comprises results from the years 1992, 2000 and 2005, referring to aviation fuel consumption, CO_2 aviation emissions,



Year	Fuel (Tg yr^{-1})	CO_2 emission (Tg yr^{-1})	RF (mW m^{-2})								
			CO_2	O_3	CH_4	H_2O	Contrails	SO_4	Soot	AIC (low, mean, high)	Total (excl. AIC)
1992 (IPCC, 1999)	160.3	505	18.0	23.0	−14.0	1.5	20.0	−3.0	3.0	0 (low) 40 (high)	48.5
2000a (Sausen et al., 2005)	169.0	533	25.3	21.9	−10.4	2.0	10.0	−3.5	2.5	10, 30, 80	47.8
2000b	214.3	676	24.5	23.7	−11.2	2.5	10.0	−4.4	3.2	10, 30, 80	48.3
2005	232.4	733	28.0	26.3	−12.5	2.8	11.8	−4.8	3.5	11, 33, 87	55.0
% change (2005–2000b)	8.4%	8.4%	14.0%	11.1%	11.1%	8.4%	18.2%	8.4%	8.4%		14.0%

Table 2.2: Historical and recent aviation fuel usage, CO_2 annual emissions, and radiative forcings. (taken from $Ref.$ [2])

and the correspondent RF. Being so, in 2005 the total RF for aviation is estimated to be 55 $mW.m$ (22 to 87 $mW.m$, 90% likelihood range), excluding AIC, corresponding to a 14% increase in comparison to the year 2000, exceeding the IPCC 1999 report prediction [6]. Considering estimates that include aviation-induced cirrus, the updated RF value for 2005 is 78 $mW.m^{-2}$ (38 to 139 $mW.m^{-2}$, 90% likelihood range), representing 4,9% of the total anthropogenic forcing for the same year. Moreover, for the year 2005, when comparing the values of the aviation forcing to the total anthropogenic radiative forcing, the obtained values are 3,5% (excluding AIC) and 4,9% of the total radiative forcing, with reference to the values obtained in [17].

In the calculation of aviation climacteric impacts there are several limitations due to the current knowledge regarding the effects of certain emission species, and RF terms, apart from CO_2, are difficult to estimate. In spite of this, it is important to know which uncertainties exist, and what is the level of understanding associated to each uncertainty, in order to correctly evaluate the limitations of the RF estimates, and to allow a comprehensive assessment of the contribution of aviation to climate change. Thus, uncertainties are regarded from two different perspectives: a more subjective approach, Level Of Scientific Understanding (LOSU), as it is carried out in IPCC analysis [17]; quantifying the uncertainties using Probability Distribution Functions (PDFs), standing as a more objective approach than LOSU.

The magnitude, LOSU and spacial scale of the updated aviation radiative forcing for 2005 is shown in $Figure$ 2.4 with 90% likelihood range, along with values taken from the IPCC AR4 report from 2007 [17]. Moreover, in this figure the bars represent best estimates and IPCC AR4 values are indicated by the white lines in the same bars (numerical values are given on the right for updated values and the IPCC AR4 values, the latter in parentheses). Error bars represent 90% likelihood range for each estimate. The median values and uncertainties range for the total NO_x RF and the total aviation RF (excluding and including AIC) are calculated using a Monte Carlo simulation. The total NO_x RF comprises the contribution of O_3 and CH_4 terms. The geographic spatial scale of the radiative forcing from each component and the Level Of Scientific Understanding (LOSU) are also shown on the right. The LOSU scale adopted here is the same has in the IPCC AR4 report and it can be seen that the total aviation radiative forcing is assigned to a LOSU of 'low', basing mostly on the uncertainties concerning non-CO_2 effects (which are responsible for at least half of the total aviation RF).

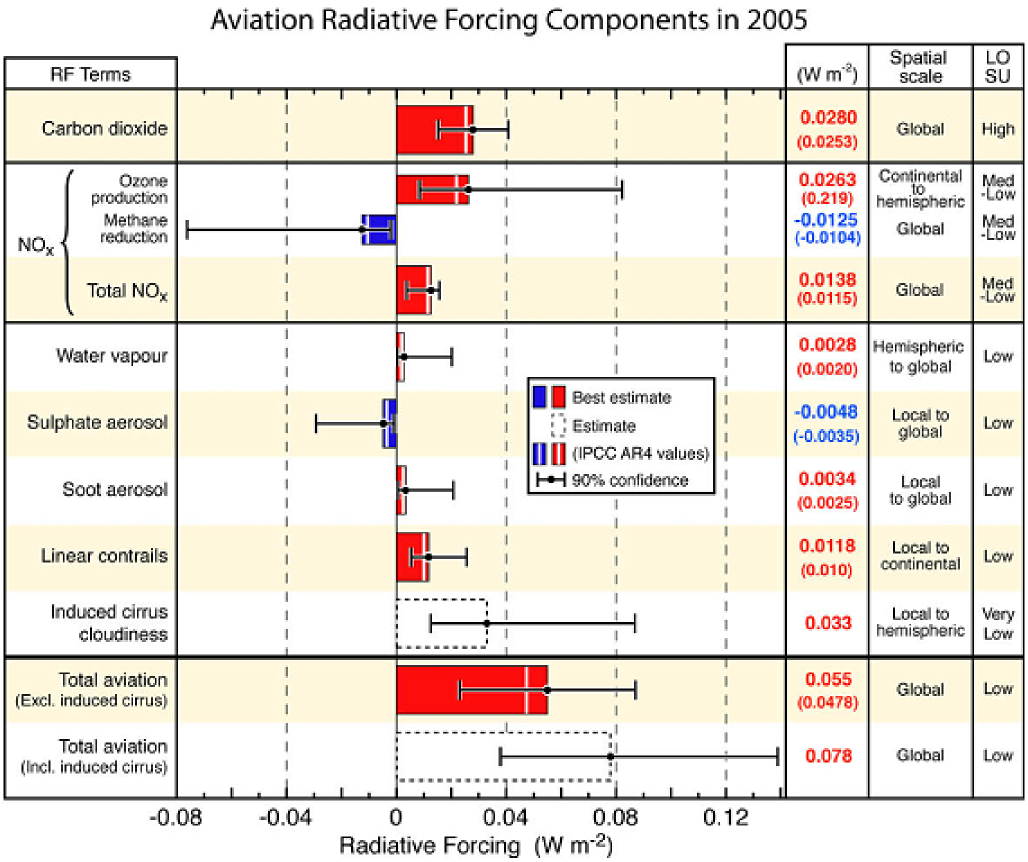


Figure 2.4: Global aviation radiative forcing, evaluated from preindustrial times until the year 2005.

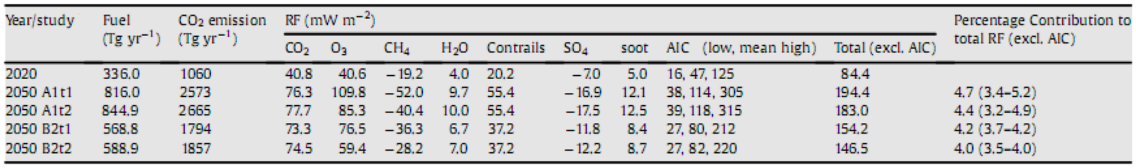
2.3 Aviation Climate Forcing: Prospects and Future Growth

Radiative forcing regarding the year 2005 was addressed above, and it can be concluded that aviation RF is moderate, representing 3,5% of the total radiative forcing (excluding AIC). However, due to the expected growth of the aviation sector, the contribution of aviation to the total RF is expected to dangerously increase, unless mitigation strategies are successfully put in practice and so reducing aircraft emissions. Aviation growth has been predicted by ICAO and the aviation industry [14, 1], coming to the conclusion that on a annual basis, the sector should grow at a rate of 4,5 to 6% (in RPK), over the next 20 years, doubling the number of passengers every 15 years. Since the IPCC report from 1999, which firstly predicted aviation RF evolution for the year 2050, a multitude of future projection have been made assuming different traffic and technology scenarios.

So far, the most comprehensive and updated radiative forcing projection has been made in 2009 [6], using a sophisticated global aviation inventory model, FAST [18], based on RPK and Gross Domestic Product (GDP) projections to 2050 [19]. This report included GDP scenarios given in IPCC Special Report on Emission Scenarios (SRES) - A1 and B2 GDP scenarios (detailly described in [20]) -, as well as two NO_x technology variants - '$t1$' and '$t2$' (detailly described in [10]). Being so, '*technology* 1' assumes business-as-usual improvements in airframe and engine technology, while '*technology* 2' focus on NO_x control through a modest expense of fuel flow improvements.

The obtained results are given in *Table* 2.3 and shown on *Figure* 2.5 representing an increase of aviation RF by factors of 4 and 3 for scenarios A1 and B2, comparing the results from 2000 and 2050. Moreover, basing on SRES, the contribution of aviation for the total RF in 2005 represents 4 to 4,7%, which would be even more if AIC contribution was included (exclusion due to a LOSU of 'very low' in 2005).

It is reasonable to conclude that despite the predictable technological advance in aviation, in 2020 and 2050 there will be an increase in the aviation radiative forcing, due to the expectable growth of this sector. Such result has been predicted in 1999 IPCC report [10], and it is related to the fact that technological improvements in aviation tend to be put in use at a slow pace, which is a consequence of the aircraft's long utilization lifetime (around 24 years [21]).



Year/study	Fuel (Tg yr^{-1})	CO_2 emission (Tg yr^{-1})	RF (mW m^{-2})									Percentage Contribution to total RF (excl. AIC)
			CO_2	O_3	CH_4	H_2O	Contrails	SO_4	soot	AIC (low, mean high)	Total (excl. AIC)	
2020	336.0	1060	40.8	40.6	−19.2	4.0	20.2	−7.0	5.0	16, 47, 125	84.4	
2050 A1t1	816.0	2573	76.3	109.8	−52.0	9.7	55.4	−16.9	12.1	38, 114, 305	194.4	4.7 (3.4–5.2)
2050 A1t2	844.9	2665	77.7	85.3	−40.4	10.0	55.4	−17.5	12.5	39, 118, 315	183.0	4.4 (3.2–4.9)
2050 B2t1	568.8	1794	73.3	76.5	−36.3	6.7	37.2	−11.8	8.4	27, 80, 212	154.2	4.2 (3.7–4.2)
2050 B2t2	588.9	1857	74.5	59.4	−28.2	7.0	37.2	−12.2	8.7	27, 82, 220	146.5	4.0 (3.5–4.0)

Table 2.3: Aviation fuel usage, CO_2 emissions and radiative forcings for 2020 and 2050.

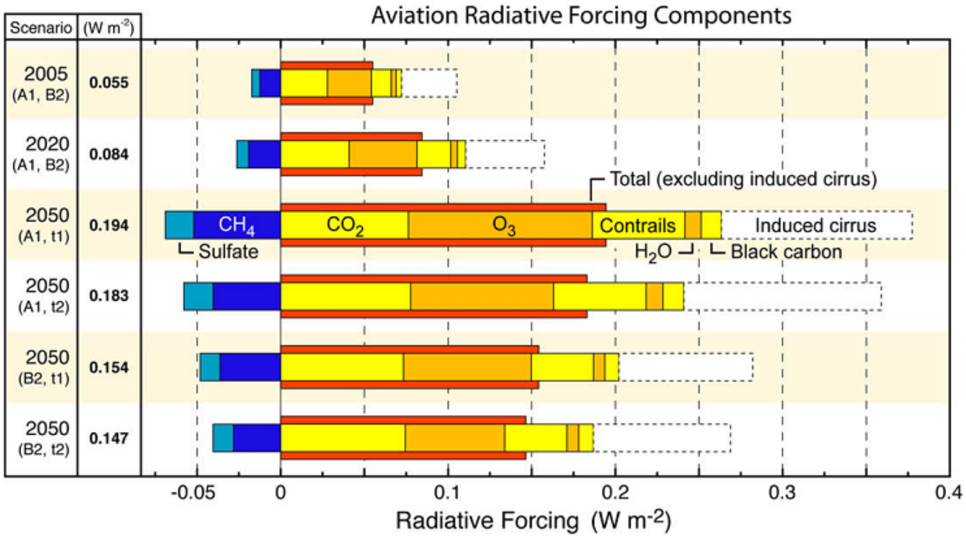


Figure 2.5: Aviation RF components for 2005, 2020 and 2050 scenarios, as listed in *Table* 2.3. The total aviation radiative forcing is shown in red bars, and the correspondent quantitative values are shown in term of Radiative Forcing, in the second column on the left (excluding AIC).

2.4 Mitigation Measures

Mitigation of aviation impacts on climate change can be addressed in a plural number of options, namely changes in aircraft and engine technology, fuel, operational practices, and regulatory and economic measures. Being so, technological improvements have the problem of requiring long research time, as well as taking too long to be broadly available to airlines. However, operational procedures have the potential of reducing aircraft emissions in the short-term, and thus reduce the climate impacts of aviation.

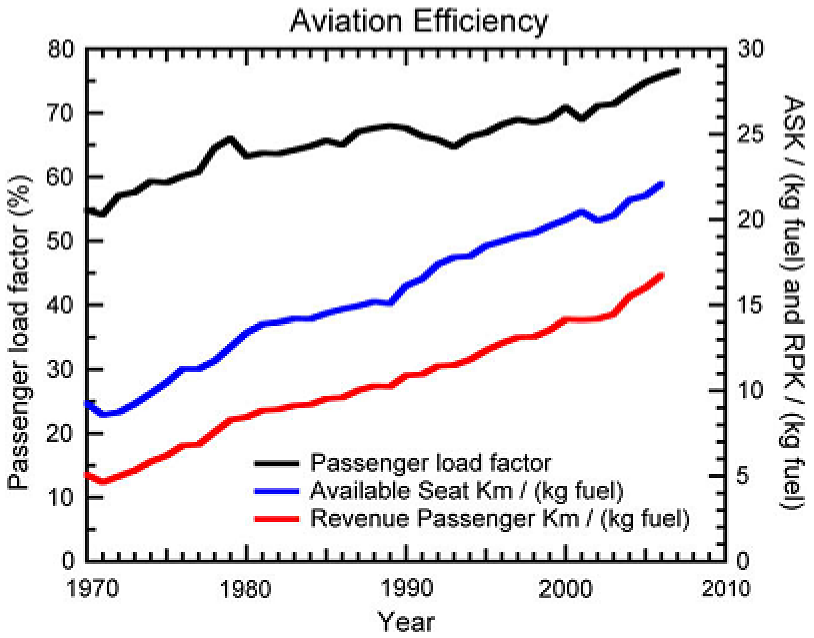


Figure 2.6: Aviation efficiency, in terms of: passenger load factor (in %; left hand axis) and RPK and ASK per unit fuel burn (right hand axis). (source: ICAO)

Aviation efficiency, in general, depends on the load factor, system efficiency of the operations (delays, routing, etc.), improved technology, rate of fleet renewal and average size of aircraft [2]. This way, in *Figure* 2.6 it can clearly be seen that aviation efficiency has been improving regularly over the years, despite the increase in emission rates (see *Table* 2.2). Thus, the passenger load factor has increased from 68% in 1970 to 76%, in 2006, while ASK and RPK per unit of fuel burn have also been increasing since 1970 to the present date. However, it should be noted that the passenger load factor has reached its historical maximum value, and further improvements are unlikely to take place [14].

Mitigation measures through technological improvements could potentially slow the rate of the aviation radiative forcing increase, but like in many other sectors, market-based and regulatory measures seem to be more desirable.

2.4.1 Mitigation Technologies and Strategies

Aircraft and Engine Technology

Technology advances have been responsible for most of emission reductions per passenger.km, usually involving aerodynamic changes, weight reductions, greater fuel-efficient engines and increased operational efficiency.

Fuel efficiency of aircrafts have been improved by more than 60% over the past 40 years in terms of CO_2 emissions per passenger km [10], mostly based on technology changes (e.g., turbojet-to-first-generation turbofan engines and first-to-second-generation turbofans). Moreover, improved airframe aerodynamics and material changes (reducing aircraft's weight) have also contributed to increased efficiency gains, being that there are several aircrafts soon to be available in the market (e.g., Airbus 350, Airbus 350, Boeing 787) in which lightweight materials (namely Carbon Fiber Reinforced Plastics, CFRP) compose more than half of the aircraft's weight [22]. For further improvements, it has been stated by the IPCC AR4 WGIII [7] that more unconventional designs will be needed, such as blended-wing body and unducted-profan engine aircraft.

Reducing the impact of aircrafts on climate through improved fuel efficiency is a complex issue. Namely, tradeoffs between noise and emissions performance must be carefully accounted for, and well as ensuring compliance with safety, performance and reliability requirements, all of which impose constraints to the improvements being pursued. One of these tradeoffs is clearly evident in the case of using a higher bypass ratio to reduce fuel consumption and aircraft noise, which would imply a greater engine weight and diameter, increasing NO_x emissions due to higher temperature and pressure at the combustor inlet. Moreover, tradeoffs are inherent to the atmospheric physics and chemistry since, for instance, flying at stratospheric heights would reduce contrail and cirrus formation, while the residence time of the emitted species would increase.

Fuel Options

The improvement of fuel used in aviation has long been an important area of technological research and development, due to its direct relation with airlines operation costs and environmental loads. Being so, the use of alternative fuels to kerosene have been studied and considered, since it may offer advantages in the long term.

Liquid hydrogen fuel have the advantage of eliminating CO_2 emissions from the aircraft, however not only it would increase those of water vapour (leading to contrails formation) and it would require larger airframe storage capacity (increasing weight and drag to conventional aircrafts). Moreover, the used of hydrogen fuel would require a carbon-neutral production process, in order to offer substantial advantages to kerosene, in terms of climate impact. Thus, this option is consensually said to be at least a decade or more away, and its use in aviation is dependent on a future general move to a hydrogen-based fuel economy.

Regarding biofuels, it is considered as a unviable option although it may offer interesting advantages. However, biofuels are not regarded as being capable of fulfilling the demanding performance and safety standards required in aviation. In addition to this, there are problems in the economic and ecological viability (mainly land use concerns) of producing the sufficient quantity of biofuel, being more likely to find its usefulness and practical uptake on other transport sectors [7].

Operational Options

On the contrary to the case of technological improvements, Air Traffic Management (ATM) and other operational changes have the potential of inducing reductions on aircraft emissions in a shorter period of time. Thus, a improved ATM system stands as a prominent measure in the mitigation of aviation's environmental impacts, through a fuel reduction based on Reduced Vertical Separation Minimum (RVSM) and reduced delays and holding time on arrival. Being so, in 2002 the European Organisation for the Safety of Air Navigation (EUROCONTROL) published a study in which was estimated that the introduction of RVSM in Europe would lead to a 1,6% to 2,3% fuel burn and CO_2 emissions reduction, relatively to the prior conditions [23]. Nevertheless, it is important to mention that the ATM system improvement is a one-off saving, meaning that these changes could be established only once, with no more potential for reducing aviation environmental effects even further.

There is also potential for reducing non-CO_2 emissions through operational measures, by changing cruise altitudes. This conclusion was reached in recent studies [24], that indicate the effects of contrails and O_3 can be reduced by a minor reduction of cruise altitudes, thus avoiding ice-supersaturated regions. Nevertheless, there are also relevant tradeoff issues involved, namely a fuel consumption penalty, upon lowering flight altitudes, although such penalty is not easily quantified. Moreover, a reduction of flight speed can also contribute to a fuel usage decrease, but only if the engines and airframes were design with such purpose. Once more, flying at lower speeds has the disadvantage of increased noise and possibly less passenger comfort. However, the necessary technology for implementing this option is already available and unducted-propfans could be further developed, since they are more fuel efficient than turbofan engines at low speed.

2.4.2 Mitigation Potential Study

In 2007 the IPCC AR4 Work Group III issued a report [7] in which, among other things, the mitigation potential until 2030. In this report, using ICAO Forecasting and Economic analysis Support Group (FESG) fleet forecast, five different scenarios were analyzed, namely:

1. assumed no technology change from 2002 to 2030. This case shows only the effects of traffic growth on emissions;
2. as Case 1, but assumes all new aircraft deliveries after 2005 would be 'best available technology at a 2005' performance standard, and with specific new aircraft (A380, A350, B787) delivered from 2008;
3. as Case 1, but with assumed annual fleet fuel efficiency improvements of 1.3% per year to 2010, assumed then to decline to 1.0% per year to 2020 and 0.5% per year thereafter. This is the reference case;
4. as Case 3, plus the assumption that regulatory pressures will result in a further 0.5% fuel efficiency improvement per annum from 2005, assuming technologies such as winglets, fuselage skin treatments (riblets) and further weight reductions and engine developments will be introduced by airlines;
5. as Case 4, but instead assuming a 1.0% fuel efficiency improvement per annum from 2005, again influencing the introduction of additional technologies.

The results obtained can be consulted in $Table$ 2.4 [6]. Thus, it can be concluded the quantity of CO_2 emissions by 2030 is sensitive to mitigation measures, despite the fact that an increase of CO_2 emissions by 2030, in comparison to 2002, appears to be unavoidable (increase factor between 1.98 and 3.29).

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[6] Mt stands for Megatonne: $1Mt = 10^6 ton$

Technology scenario	2002 CO_2 (Mt)	2030 CO_2 (Mt)	Deviation from Case 3	Ratio $\frac{2002\,values}{2030\,values}$
Case 1	489.29	1609.74	29% increase	3.29
Case 2	489.29	1395.06	11.9% increase	2.85
Case 3	489.29	1247.02	0%	2.55
Case 4	489.29	1100.15	11.8% decrease	2.25
Case 5	489.29	969.96	22.2% decrease	1.98

Table 2.4: Summaries of CO_2 mitigation potential analysis in aviation (adapted from [7])

Chapter 3

Life Cycle Assessment: Theoretical Framework

The evaluation of environmental impact of a product or service can be performed in several ways, being that the life cycle assessment has stand out as the environmental assessment tool par excellence, taking into account the whole life cycle, through a holistic perspective. Being so, the life cycle assessment in described in this chapter. Being so, *Section* 3.1 consists on a historical contextualization of the environmental issues, namely the evolution of the ecology science. Afterwards, the concept inherent to the LCA approach is given in *Section* 3.2, followed by the description of its methodology (*Section* 3.3). Finally, the present chapter ends with a brief description of the software used in this thesis, which is given in *Section* 3.4.

3.1 Historical Contextualization

Throughout history man as always taken resources from nature, firstly as a mean for surviving and subsiding.

In the middle of the 19th century, the emergence of thermodynamics served as inspiration to individuals to regard economics in a different perspective: economic processes were considered in terms of flows of energy and matter (biophysical terms). Thus, under the first law of thermodynamics, the interactions between economy and environment could be characterized through flows, on a open-loop system. Similarly, under the second law of thermodynamics, the inexistence of materials wastes in the form of a complete recycling process is not feasible. Through this perspective it became noticeable that while handling economy, the environment can be harmed, and that reciprocally, an environmental impact can alter the state of the economy (ex. shortage of environmental goods), i. e., economy and environment depend on each other.

However, this perspective did not have an immediate breakthrough. There have been many discussions on why this new perspective failed to be established, being that the division of labour between disciplines is frequently emphasized, besides the fact that other problems were, at the time, considered more relevant by both the academic community and the society in general.

Therefore, only when new social conditions occurred, these new ideas concerning the industry and economy could be rooted within the academic community and broader social groups. These circumstances finally occurred during the 1960s, with the general acceptance of transdisciplinarity and other favourable social circumstances. Thus, the general public became aware of a new concept of pollution and environment, partially through a landmark book by Rachel Carson, named "Silent Spring ", in the year of 1962 [25]. As a result, by the end of the 1960s many Western politicians took the first steps towards regulation through the establishment of expertise councils and branches of bureaucracy, mainly due to social movements based on an increasing public interest in the issues of pollution and environment.

During the 1960s and the beginning of the 1970s, two concerns also played a fundamental part in ecology history: the astonishing increase in world population, highlighted by Paul Ehrlich's polemic book "The Population Bomb" [26], and the question of food sufficiency and other resources.

Even though the question of natural resources had been given attention in the wake of the Second World War (for example, the establishment of Resources for the Future in the 1950s), it was not until the release of "Limits to Growth" in 1972 [27] that popular interest was definitely gained. This best seller book basically describes the results of a computational humankind evolution model, that identifies the consequences of the population growth and economic and industrial activities, to the environment. The contents of this book, marked by some frightening results, were the starting point for a strong interest on these issues by the scientific community and general public alike. Thus, the challenges regarding population growth, environment and natural resources were now commonly acknowledge.

In 1972 the United Nations held a conference with the subject "Human Environment", in Stockholm. Despite not being the first conference of this kind, it became quite important because it gathered a large number of countries (119 countries) discussing the environment for the first time in history. Finally, with the oil crisis in the 1970s, the discussion regarding energy in relation to the existing resources became widely popular.

The birth of Industrial Ecology (IE) took place in the year of 1989, upon the release of an article on Scientific American named "Strategies for Manufacturing", written by Robert Frosh and Nicholas Gallapoulos [28]. In this seminal article Frosh and Gallapoulos proposed a restructured industry, in which industry processes were modelled after natural ecosystems, with materials (including wastes) flowing through a multitude of interconnected processes. In this article, the following can be found: "... the traditional model of industrial activity ... should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process ... serve as raw material for another process".

"Strategies for Manufacturing" also mentions two terms that became important then, and still maintain their importance at the present time: 'Dematerialization' and 'Life Cycle'. The first can be defined as the use of plastics, composites and high-strength alloys in order to reduce the mass of products, which has been a trend in many industries, such as aviation. The second term to be introduced by Frosh and Gallapoulos, 'Life Cycle', is used on the article when the origin, active period and final destination of the materials are studied together to identify opportunities for resource savings. Overall, the publication of this article conveniently came at a time when, in the USA, the discussion concerning long-term sustainability of our planet was increasing.

3.2 Life Cycle Assessment: Conceptualization

Enthused by the increasing environmental awareness, different industries have taken interest in assessing the environmental impact of their activities. Thus, there is a common interest in making products and processes less harmful to the environment ("greener" products and processes). In order to improve the environmental performance of such products and processes, companies have been looking for ways to address this problem in a holistic, systematic, alongside financial and technical manner. One of the tools that emerged as a possible answer to this problem is LCA. Life cycle assessment considers cradle-to-grave implications of actions, basing on the premise that products and processes have life cycles. Being so, during each phase of the life cycle (extracting and processing raw materials, manufacturing, transportation, distribution, use/reuse, recycling and waste management) products and processes interact with the environment.

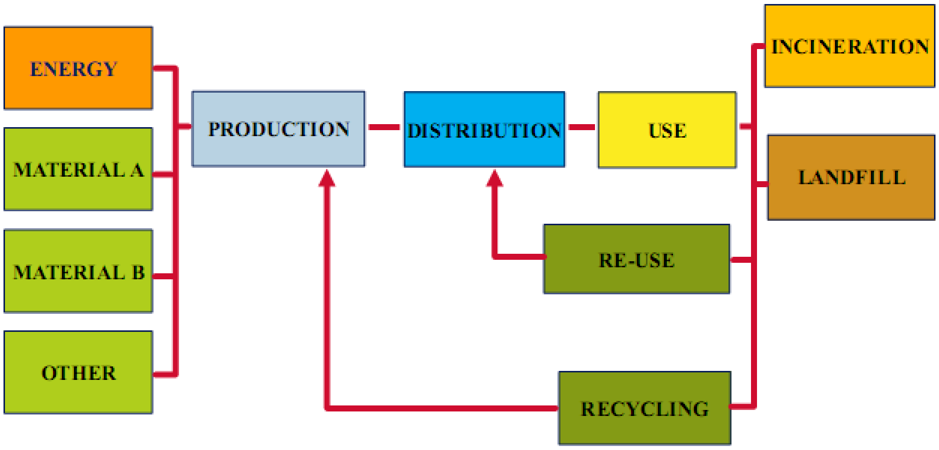


Figure 3.1: Representation of the different life cycle stages

Life Cycle Assessment basically consists of an environmental management tool that quantifies the environmental impact of a product over the whole life cycle of a product, activity or process. Being characterized by a "cradle-to-grave" approach, the environmental assessment begins with the extraction of the raw materials in use, which at the end of the life cycle are either returned to the nature or reintegrated in an industrial process. Through the evaluation of a product's life cycle in all stages, LCA gives a comprehensive view of the environmental performance of a product, providing a more realistic global picture of the product's true impacts on nature.

3.2.1 Brief History of Life Cycle Assessment

In the wake of World War 2, new kinds of energy technologies tested the energy balance question. Nuclear, wind, geothermal and other renewable sources were at the time an enthusiastic and often polemic novelty. Therefore, energy analysis grew increasingly complex, systemic and sophisticated through successive empirical developments. Firstly, the energy analysis technique consisted on the assessment of a single unit of energy, taking solely into account the immediate inputs in the production system. Unavoidably, the analysis extended as more complex technologies were examined. A landmark example of energy's analysis evolution happened with the arising of the following question: given a certain nuclear energy generation process, is the energy consumption higher than the energy produced? In a quest to find the answer, researchers were led to look beyond the energy's production facilities, and started to take into account raw materials extractions (namely uranium), 'yellow cake' production, long-term waste management, transportation inherent to the processes (of personnel, materials and equipment), and associated research, development, marketing and management services. Hence, this was the forerunner of what became known as Life Cycle Assessment.

Moreover, at the end of 1960s, the first Resource Environmental Profile Analysis (REPA) were undertaken in the United States of America. Notably, in 1969 The Coca-Cola Company commissioned an internal study led by a group of researchers (who lately became Franklin Associates) that laid the foundation for modern LCA. The study consisted in the comparison of different beverages containers regarding their distinct environmental performance, by quantifying the raw materials, fuels used, and environmental burdens for the manufacturing process of each type of container. Similar comparative life cycle inventory analysis were taken during the beginning of 1970's in Europe and USA, by other companies.

The previously mentioned REPAs had a correspondent name in Europe, Ecobalance, and between 1970 and 1975 approximately 15 REPAs were performed, mainly due to the oil shortages in the early 1970s and to the public demand on accurate information provided by the industries. During this time, protocols and standard research technology for conducting these studies were developed, and the inherent assumptions and techniques were reviewed by the United States Environmental Protection Agency (EPA) and industry representatives. These conditions led to the evolution of the environmental impact analysis and its methodologies.

Throughout the period between 1975 and 1980 the interest on these kind of studies was diminished, mainly due to the fading influence of the oil crisis and the rising importance of hazardous and households waste management. Nevertheless, life cycle analysis were still conducted, but at slower pace (around two per year) and mostly concerning the issue of energy requirements. During this period, the European Commission established an Environment Directorate, which played an important role on standardization of pollution regulations.

During the 1980s, the importance of LCA as a tool for analyzing environmental problems was re-established, due to the rising importance of the solid waste issue. By then, multi-criteria systematic inquiry had spread to include a wider range of areas besides energy, such as automobiles, housing and appliances. Motivated by a growing interest on the environment and in all areas affecting resources, LCA's methodology was expanded and polished. Finally, in the year of 1990 during a workshop promoted by the Society of Environmental Toxicology and Chemistry (SETAC) in Vermont, USA, the term 'life cycle analysis' was proposed and agreed on.

From this point, LCA suffered a rapid development, growing into a body of systematic, inclusive and analytical approaches to environmental impact assessment. Driven by inappropriate use of LCAs by product manufacturers trying to promote and marketing their products, SETAC initiated the development and extension of LCAs by publishing various 'best-practice' guides and by giving directions on LCA simplification and methods. Furthermore, applications to both public policy and particular sectors were studied, as well as applications regarding more embedded management modes within organizations. Ultimately, and reinforced by the pressure from environmental organizations, this conditions led to the standardization of LCA's methodology in the International Organization for Standardization (ISO) 14000 series (1997 – 2002). This action done by the worldwide recognized organization ISO stands as a proof of the dynamics and relevance of Industrial Ecology and its existing tools, such as LCA.

In the year of 2002, the United Nations Environment Programme (UNEP) and SETAC created the UNEP/SETAC Life Cycle Initiative to assist the development and comprehension of LCA. This initiative seeks to put life cycle thinking into practice, and comprises three programs:

- Life Cycle Management (LCM) – creates awareness and enhances decision-makers skills by generating information materials, creating forums for sharing best practice, and carrying out training of individuals around the globe;
- Life Cycle Inventory (LCI) – improves the accessibility to transparent and reliable life cycle data by hosting and aid expert groups whose work results in web-based information systems;
- Life Cycle Impact Assessment (LCIA) – improves the quality and global reach of life cycle indicators by assisting and encouraging the exchange of views and best-practices among experts whose work provides respectable recommendations.

During the last decade, the growing interest on this area is proved by the constant investigation effort. As a consequence, international journals regarding this subject have emerged, such as 'The International Journal of Life Cycle Assessment'. LCA comprises a myriad of areas of knowledge, and it has given significant contributions in the fields of engineering, management, economy and ecology, serving as a link between them. For these reasons, LCA is widely regarded as a fundamental tool in the world of industrial ecology.

3.3 Methodology of the Life Cycle Assessment

On the following subsections the methodology of the LCA will be addressed, in a generic approach. Thus, the main steps of a LCA will be briefly described, namely: Goal Definition & Scope, Life Cycle Inventory, Life Cycle Impact Assessment and Life Cycle Interpretation (see *Figure* 3.2).

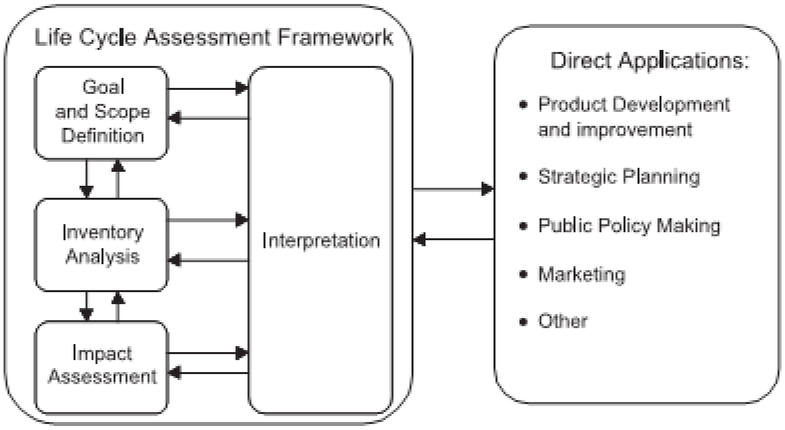


Figure 3.2: Phases and applications of the Life Cycle Assessment (based on ISO 14041)

3.3.1 Goal Definition and Scope

Goal definition and scoping is the phase of a LCA where it is clearly described the purpose and method of including life cycle environmental impacts into the decision-making process. The main goal of any LCA is, in general, to foment the assessment of the environmental impact of a process, product or service. Thus, LCA can help to choose the best system with the least possible effect on human and environmental health, providing a precious help in the development and improvement of that same system. While defining the goal of the LCA, the following questions are supposed to be addressed: reasons for conducting the LCA; the purpose of the study; the product's function; to whom the results are destined.

The scope of the LCA should contain the appropriate limits of the study. Setting these limits, includes the definition of the entire production and final destination of the materials and services involved in the product life cycle under analysis. One should take into account that decisions can be made in order to simplify the system processes for practical purposes, and rough estimates can be made to specific systems in order to verify if they can be neglected from the overall assessment. Finally, after performing all necessary analysis, the definition of the system boundaries should comprise every step that affects the overall interpretation and results of the LCA, taking in consideration the questions that led to the study in the first place.

According to ISO 14041, the scope definition of a product's LCA must include the description of the following steps:

1. Product function or service;
2. Temporal and spacial boundaries in which the product evolves during its life cycle;
3. Necessary data for the system's characterization;
4. Hypothesis under consideration;
5. Study's limitations;
6. Type of evaluation to be used;
7. Quality of the intended results;
8. Type of critical revision and validation to perform;
9. Type and structure of the final report;

The goal definition and scope of a LCA will determine the time, effort and resources needed for the entire study, serving as a guide through all the processes. Thus, a proper approach on this initial phase ensures that the final results are obtained accordingly to one's requirements, and having an impact throughout the conduction of the study on every subsequent phases.

The definition of the scope requires the specification of the functions carried out by the product under analysis, which implies the definition of a functional unit.

The functional unit emerges from the necessity of quantifying the performance of the product. This way, by serving as a measure of the product's function, the functional unit represents a reference through the construction of the Life Cycle Inventory, meaning that the input and output data are determined in light of the functional unit. The functional unit should describe the product's function regarding a single utilization, be measurable, and should take into account the efficiency and life-span of the product in question. When comparing different products with LCA, the basis of the comparison should be the same, meaning that the products must have similar functions (the same functional unit must be used) and each system should be defined so that an equal amount of the product is delivered to the consumer.

3.3.2 Life Cycle Inventory

The Life Cycle Inventory (LCI) constitutes the core of the LCA, and it is usually the most time-consuming phase of the whole study. In the LCI phase, data is collected as a process of quantifying inputs and outputs of the system under analysis, being that the data may regard energy, raw materials and other physical inputs; products, co-products and wastes; releases to air, water and soil; and other environmental aspects. Thus, all relevant data is collected and organized, being that the accuracy and detail of the collected data is reflected throughout the LCA study.

The LCI provides a mean to evaluate comparative environmental impacts or potential improvements, and it can be used in many ways: support an organization in the comparison of products or processes and considering environmental aspects during the selection of used materials; decision and policy-making, by assisting governments to regulate environmental emissions and resource use.

During the execution of the LCI, it is often necessarily to go through its different stages more than once. The framework of the inventory analysis, along with the assessment of both data and results, was provided in EPA's document "Life-Cycle Assessment: Inventory Guidelines and Principles" and "Guidelines for Assessing the Quality of Life Cycle Inventory Analysis". Accordingly, a LCI is composed of the following steps:

1. Development of a flow diagram representing the system under study;
2. Collection of the data;
3. Data processing;

4. Assessment and analysis of the obtained results.

A brief description of each LCI step is given next.

Flow Diagram

The flow diagram consists of a tool in which inputs and outputs of a system are mapped, providing a useful description of the system. Such description is achieved through a simple and clear representation of the unit processes that constitute the system, as well as the relationship between them.

The system boundary of the flow diagram is defined during the goal and scope definition phase, and it establishes what should be included in the LCA.

The flow diagram of a LCA study represents, therefore, a schematic representation of the most relevant processes that constitutes the system. As can be seen on insert figure, these diagrams are composed by a sequence of blocks (representing unit processes), connected by arrows (representing mass or energy flows).

As the complexity of a flow diagram increases, so does the accuracy and the utility of the results. However, it is impossible to make a complete LCA, and so it becomes necessary to choose the unit processes to be modelled, which emissions to the environment will be considered, which energetic consumptions will be evaluated, and its detail. Thus, the more complex the flow diagram, the greater time and resources must be spent.

Given the difficulty to properly rank each unit process, it becomes even more clearer that LCI is characterized by a iterative nature.

Data Collection

After making the flow diagram of the system under analysis, the process of gathering data for the LCA begins. The data collection process involves a combination of research, direct contact with experts, among other means of obtaining information, being that it is likely that a large amount of data is gathered in the end. During this research, it may be noticed that some processes must be decomposed in elementary subprocesses, while others need to be grouped due to the lack of information that characterize them.

This step, basically consisting of finding and filling the flow diagram with numerical data, may not be a simple one. It might occur that some data is not obtainable, or that the data is hardly converted to the adopted functional unit. Thus, once more the iterative nature of the life cycle inventory comes to evidence, being that the system boundaries, the data quality goals, and the functional unit may have to be redefined based on data availability. One very important decision to be made on this phase is the following: which raw materials requirements should be included in the LCI? While many options can be reasonable depending on the case in specific, there are four options that deserve some special attention:

- Incorporate all requirements, despite how minor they may seem, under the premises that nothing should be excluded a priori. In spite of having the advantage of absence of assumptions regarding the definition of the system boundary, this approach may turn out to be too complex, and impossible to perform;
- Within the defined scope of the study, exclude inputs that fall under a threshold defined by the analyst. Being easier and cheaper to implement than the first option, it is nevertheless possible to exclude a certain element with a significant environmental impact;
- Within the defined scope of the study, exclude inputs that under a sensibility analysis are shown to be negligible. The best feature regarding this option is the fact that instead of having a arbitrary approach such the use of a threshold, in this case there is a systematic approach. However, this option is only feasible under a large number of constraints, namely the existence of a large database and a perfect clarity regarding the sensitivity analysis;
- Within the defined scope of the study, exclude certain kinds or classes of inputs, that are negligible to the study (such as capital equipment, for instance). Thus, many complex systems can be simplified, although a preliminary analysis should be performed in order to make sure no significant class is left out.

The data collection is then a phase that can take a great amount of time and effort, being indispensable that the analyzer endures a pragmatic attitude, while constantly verifying the consistency of the data acquired. On top of this, it is also important to systematize all the information gathered, so that it can easily be consulted and the data origin be promptly identified.

In the first instance, data collection aims to quantify mass flows and it should begin with the quantification of the various raw material flows, regarding each unit process. This stage should be performed with specific data concerning the study, or publish data regarding analogous processes. According to ISO 14041, it should be taken into account the combined contribution of mass, energy and environmental relevant substances. It is also important to notice that as outputs of the product life cycle inventory analysis, the environmental releases are usually divided into three categories: atmospheric emissions, waterborne waste and solid waste.

Data Processing

After collecting the information concerning the elementary processes of the LCA study, the quantity and quality of the data obtained should be confronted to the initial expectations and requirements, being that, if necessary, the scope and limits of the study should be corrected. Upon this stage, there should be a full flow diagram of the system, as well as an inventory table. Such inventory table must contain the list of the substances that stand as environmental relevant, with concern to the chosen functional unit. Thus, in processing the data obtained, it should be handled in a way that enables the calculation of the contribution of each impact along the product's life cycle, which should be done with the assistance of a computer software. The computerization of LCA, which comprises the LCI stage, will be addressed in more detail later in *Section* 3.4.

Results Analysis

In the Results Analysis phase of the life cycle inventory, a consideration of study goal and scope is carried out, by revising the quality of the data obtained in the previous stages of the LCI. Thus, a validation process should be described, which can be performed by the author of the LCA practitioner or by an external expertise that revises the data obtained.

Being so, only after such revision is undertaken, the LCA can move on to the subsequent phase, life cycle impact assessment, with the necessary assurance that the study will not be compromised by erroneous data not acceptable according to the requirements established in the goal and scope definition.

3.3.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) consists in the assessment of the results obtained in the LCI (quantified inputs and outputs) to understand their environmental significance, taking into account resource depletion, human health and environmental impacts. Thus, the purpose of the LCIA is to connect a product or process to the correspondent consequences in terms of potential environmental impacts, through a systematic procedure (see *Figure* 3.3).

To conduct an LCIA in a formal way, three steps are mandatory, according to a standard for conducting an impact assessment named ISO 14042, "Life Cycle Impact Assessment (ISO 1998)". Additional steps can be taken if so is desirable, and methods for these additional steps have been defined. The three basic steps required by the ISO standard for performing an LCIA are the following:

1. Selection and Definition of Impact Categories: Identification of the environmental impact categories (e.g., global warming, acidification) for a given LCA, which will depend on that LCA's goal and scope. Moreover, the chosen impact categories will determine the types of data to be collected during the LCI. The method of the assessment to be performed is also chosen on this step.

2. Classification: In this step, results from the LCI (e.g., quantity of SO_2 emitted per functional unit) are assigned to the environmental impact category to which they contribute. Let it be noted that a certain LCI result can be associated to multiple environmental categories (e.g., SO_2 emissions simultaneously contribute to the environmental impact categories of acidification and human health).

3. Characterization: Consists in the calculation of the magnitude of the environmental impacts for each environmental impact category, and so the contributions to each impact category are quantified. Thus, through science-based conversion factors, the LCI results are converted and combined into representative indicators to human and ecological health. These conversion factors are called characterization factors, and indicate how much a substance contributes to an impact category in comparison to a reference substance, providing a chance to compare different LCI results within each impact category. The following equation illustrates how an impact indicator can be obtained:

   $$Impact\, Indicator = Inventory\, Data \times Characterization\, Factor \tag{3.1}$$

   For a certain impact category there are many different models that can be used to obtain a characterization factor, being that for some impact categories such as global warming and ozone depletion, there is a consensus regarding the best choice for the characterization factor. Moreover, the importance of the characterization factors on impacts characterization is enormous, and a great share of LCIA research is aimed at developing and refining more robust characterization factors.

In the case of acidification, for instance, all the contributing substances to this impact category (e.g., sulfur dioxides, mono-nitrogen oxides) are summed based on their characterization factors, generating an indicator of the generic potential impact of acidification.

The basic LCIA methodology consists in the three steps described above, and even though some judgments are sometimes required, their nature is objective. Moreover, it is possible to go further on the LCIA phase, and there are optional steps that can be taken. Some of these optional LCIA steps are briefly described, as follows:

- Normalization: In this step, an indicator value (from the LCIA) is divided by a reference number (from outside the LCIA), providing a new perspective to the results (*Equation* 3.2).

  $$Normalized\, Indicator = \frac{Impact\, Indicator}{Reference\, Value} \tag{3.2}$$

  Thus, normalization allows the results of the LCIA to be analyzed in relation to outside concerns, and the normalized results can increase the comparability between the data from different impact categories. Furthermore, there are many methods of choosing a reference value, namely the total emission or resource use for a given area or region, or the total emission or resource use for a given area or region on a *per capita* basis. Once again, the goal and scope of the study may influence the selection of the most suitable reference value.

- Weighting: Given the possibility that, from the LCA user perspective, some category indicators may be more important than others, the weighting step assigns weights to each impact category, based on their relative importance. Such feature is accomplished by multiplying each indicator by the respective weighting factor (*Equation* 3.3), providing a way to reflect the study goals and stakeholder values.

  $$Weighted\, Indicator = Indicator \times Weighting\, Factor \tag{3.3}$$

  Given the fact that the weighting step doesn't have a scientific nature, it is important to clearly explain and document this methodology.

- Aggregation: This step is taken with the purpose of reducing the number of environmental indicators that fundament the interpretation and assessment of environmental impacts. Thus, it is possible to aggregate the results from the characterization step, in order to produce a single index. Such aggregation can be very useful when using LCA to compare multiple alternatives, or when using the LCA to provide an eco-label to a product, being that the LCA will serve to decide whether or not a product is worthy of such label.

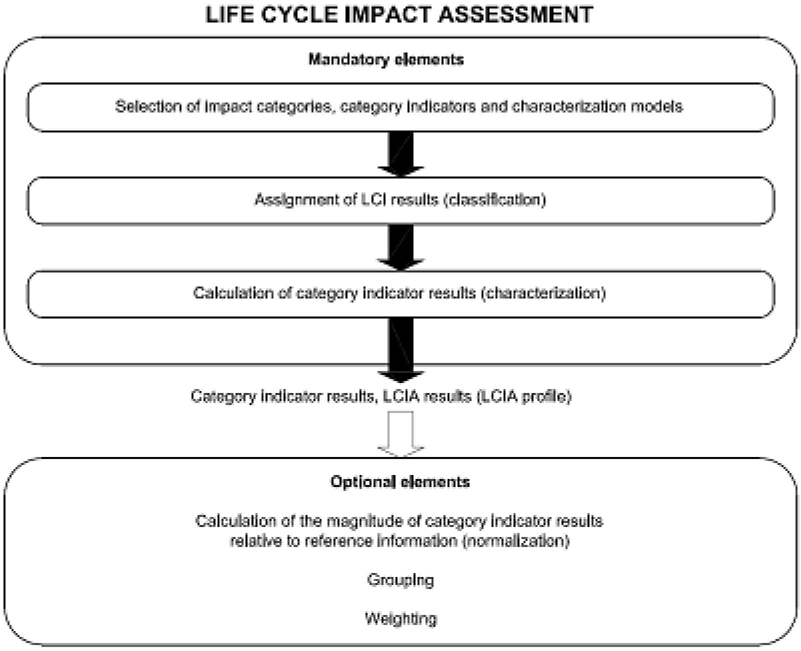


Figure 3.3: Life Cycle Impact Assessment steps, according to ISO 14042

Being so, the translation between the inventory results into their consequences, which oftenly are more significant, is the main objective of the LCIA. Thus, for a certain process, the amount of SO_2 emitted, whose significance can hardly be understood by a layman, is converted to the information that the process has a higher potential for increasing acidification. Given so, the LCIA can reduce the quantity of LCI results to a much smaller amount of environmental impact categories. For instance, LCIA can aggregate emissions of CO_2, methane and other greenhouses gases into one single impact category (climate change).

Environmental Impact Assessment Methods

The LCIA aims for establishing a relation between the product system and its potential environmental impacts. In order to do so, environmental mechanisms characterize the process through which the LCI results (environmental interventions) are transformed into environmental impact categories. Such process is accomplished with the use of indicators, namely midpoint or endpoint indicators. The first relates more directly to environmental interventions and translate the LCI results into impact categories (e. g., radiation, acidification), thus reducing the complexity of the models and results, as well minimizing assumptions and subjectivity in assessing the environmental impact of a process. On the other hand, endpoint indicators translate the damage of the environmental impacts on resource depletion, ecological and human health (e. g. skin cancer, deforestation), thus being more easy for a layman to understand, however increasing the subjectivity and uncertainty of the assessment.

A multitude of environmental impact assessment methods have been developed, either with midpoint or endpoint indicators, being that the choice of method depends on the work being developed (namely, depending on the goal and scope of the LCA). The choice of environmental impact assessment methods is given in *Section* 5.1.

3.4 Computerization of the Life Cycle Analysis

Performing a life cycle analysis requires a large amount of data which characterizes the product in its manufacturing, service and end-of-life periods. It then becomes clear that a wide access to databases is imperative to properly model the system under study, being that such databases should contain reliable and transparent information which are handled through various calculations. Moreover, environmental processes are often very complex, and therefore software tools were developed. Such softwares help structuring the modelled scenarios, displaying the process chains and presenting and analyzing the obtained results. So, a LCA software should be able to organize data and minimize the necessary effort to perform an inventory analysis or a impact assessment; provide documentation that validates the study; be compatible to other softwares, given the possibility of interaction between the LCA software and other softwares used by the LCA practitioner.

In the life cycle inventory phase, the software can provide a prominent assistance. This assistance is usually provided through the use of spreadsheets, as a input data type, calculation system and results obtaining support. Thus, in order to fully describe a system process, the user only needs to specify the type and quantity of the materials in use, being that all material and energy input and output become immediately connected and specified. Moreover, in order to overcome problems regarding process data availability, it is possible to use external databases in the software, that have the advantage of being documented and reliable.

The present thesis has been done with the auxiliary of the LCA software Simapro, in its 7.2 version (from now on, simply referred as Simapro), which was developed by the Dutch company 'Pré Consultants' [29]. This software is the most widely used in life cycle assessment, and it has been used in many studies at Instituto Superior Técnico (IST) as well as being addressed in books by IST professors (e.g. [30]). Moreover, these softwares can be very expensive (Simapro 7.2 Developer Single User costs 9600 €) and I.S.T. bought the right to own a restricted number of licenses, to which the author of this work had access.

Being so, Simapro is a professional tool for assessing the environmental impacts through a product life cycle. The information is available in a organized way, through models regarding several phases of the life cycle, and with processes that can be taken from the software database. These processes in the databases are present in the Inventory section of Simapro, and are organized in the following way: material, energy, transport, processing, use, waste scenario, waste treatment. Thus, with this software a product life cycle can be modelled according to regulations in ISO 14040 [31]. Moreover, in Simapro the life cycle is structured through three different, but interconnected, parts:

1. Assembly: a set of processes referring to the manufacturing, distribution and utilization of the product. One assembly can contain multiple sub-assemblies;
2. Disposal Scenario: describes how a product is processed during its end-of-life phase, namely characterizing end-of-life processes such as disassembly, recycling and reuse;
3. Life Cycle: integrates the product's manufacturing phase (described in Assembly) and its end-of-life processing (described in Disposal Scenario).

In addition to this, four environmental assessment methods are used in this work, which will be explained further in *Section* 5.1 of the present work.

Chapter 4

Modelling the Life Cycle of the Aircraft Airbus A330

After the main principles and methodology of the life cycle assessment have been briefly described throughout the previous chapter, hereby the modelling of the aircraft A330-200 life cycle will be addressed. Being so, in *Section* 4.1 the goal and scope of the life cycle assessment is addressed, and the life cycle inventory is described in *Section* 4.2.

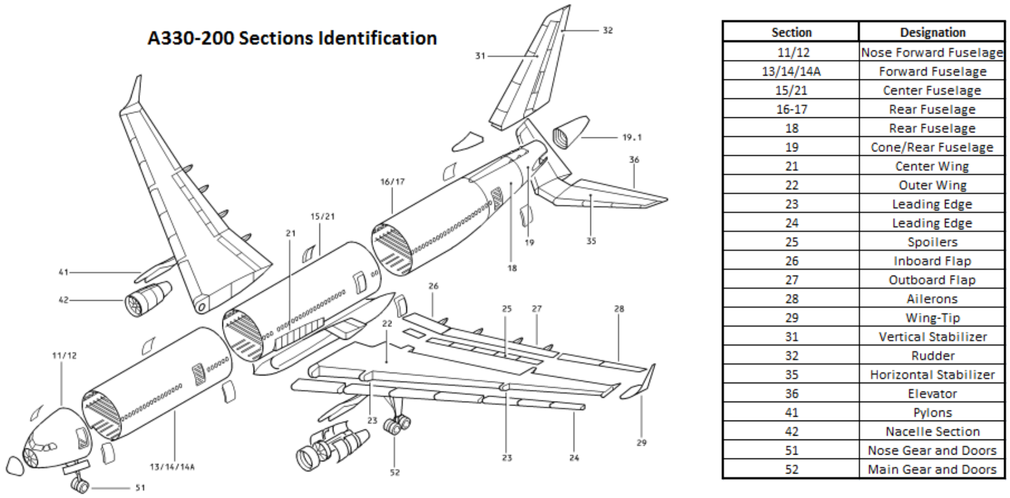
The Airbus A330 is a commercial passenger aircraft meant for medium-to-long range, with a large capacity and with two engines, and it is manufactured by Airbus. Launched in 1995, the Airbus A330-200 is similar to the A340-200, and a shortened version of the A330-300. Thus, it uses the fuselage of the A340-200, and the wings and engines of the A330-300. The A330 has been a commercial success for Airbus, being that for the A330-200 and until October 2010, there have been 576 orders, 395 deliveries, and 391 aircrafts are still in operation.

Moreover, the Airbus 330-200 can be operated with three different engines: the General Electric (GE) CF6-80E1, the Rolls-Royce Trent 700 and finally the Pratt & Whitney PW4000. In this work, the selected engines were the General Electric model CF6-80E1, due to the fact that this are the engines in the A330-200 aircrafts owned by TAP (from which the data refer to).

The main data for the A330-200 is given in *Table* 4.1. Moreover, the identification of the aircraft components and sections (major structure layout) is shown in *Figure* 4.1.

A330-200 Main Characteristics	
Maximum Range	13430 km
MTOW (in Kg)	230000
Manufacturer's Empty Weight - MEW (in Kg)	108206
Operating Empty Weight (in Kg)	124359
Typical Single Class Layout	303 Seats
Maximum Speed	Mach 0,86
Engines (×2)	General Electric CF6-80E1

Table 4.1: Main Characteristics of Airbus A330-200



Section	Designation
11/12	Nose Forward Fuselage
13/14/14A	Forward Fuselage
15/21	Center Fuselage
16-17	Rear Fuselage
18	Rear Fuselage
19	Cone/Rear Fuselage
21	Center Wing
22	Outer Wing
23	Leading Edge
24	Leading Edge
25	Spoilers
26	Inboard Flap
27	Outboard Flap
28	Ailerons
29	Wing-Tip
31	Vertical Stabilizer
32	Rudder
35	Horizontal Stabilizer
36	Elevator
41	Pylons
42	Nacelle Section
51	Nose Gear and Doors
52	Main Gear and Doors

Figure 4.1: Identification of the Airbus A330-200 main components. (adapted from [3])

4.1 Goal and Scope

The present study has been done with a partnership between two companies, 'TAP Portugal' (TAP) and '3Drivers - Engenharia, Inovação e Ambiente', with the final objective of elaborating a Master Thesis in Aerospace Engineering. A detailed explanation and description of each goal and scope phase is described next, following the methodology suggested in [30],[31] and [32].

4.1.1 Goal Definition

The goal definition must comprise the objectives of the study, providing an understanding of the system under analysis. Thus, according to the methodology suggested in [30], there are descriptions that should be made, namely: the reasons that led to the study; the study's object (i. e. the product); the function performed by the product; to whom do the results are meant. These questions will be addressed next.

Environmental awareness has been a matter of increasing importance in the last years, and throughout many industrial sectors, environmental issues have been carefully regarded. With further regulation and penalties regarding the environmental performance of products and services, it becomes imperative to fully acknowledge the environmental profile of systems. The aviation sector in particular poses as a major pillar on the sustainability world, having the largest growth rate in the transportation sector and an increasing contribution on the global radiative forcing (see *Section* 2.2 and *Section* 2.3). Thus, it is of great importance to systematically and scientifically assess the environmental load of the different aircrafts in use, through a holistic perspective. LCA emerges as the environmental tool par excellence, providing the assessment of the product during its whole life cycle, and allowing a valuable insight to the contribution of each process and life phase of the aircraft. Moreover, the European airline company Airbus has issued a report in which the life cycle assessment methodology is discussed [33]. The present study aims for the environmental impact evaluation of the Airbus A330-200 aircraft, as well as providing the identification of potential improvements in the different processes of the aircraft life cycle. Moreover, it is possible to compare this aircraft with any other, which is a common practice in LCA, and this study can easily be extended if there is the intention of detailing and improving the analysis hereby made.

As for the object of the study, it is the Airbus A330-200 aircraft, a large-capacity commercial passenger aircraft, meant for medium-to-long range distances. More technical details regarding this aircraft have previously been shown, in the introduction of this chapter. The function of this product is the air transportation of passengers, being that the functional unit for this study will be described in *Section* 4.1.3. Finally, the results are of interest to the companies 3 Drivers and TAP, as well as having the academical purpose of being a master thesis for Universidade Técnica de Lisboa - Instituto Superior Técnico.

4.1.2 Scope Definition

According to ISO 14041 and the description previously made in *Section* 3.3.1, the scope definition should comprise a clear description of many important aspects of the study.

System Boundaries

In this study the whole life cycle of the aircraft has been considered, namely the manufacturing of the different aircraft components, the operational life of the aircraft, and the final destination phase (re-use, recycling, landfill, etc). The life cycle of the aircraft was considered to be 24 years [21], after which the final life cycle stage followed. Let it be noted that a aircraft can be operated more than 24 years, but in terms of value, it is assumed that it reaches its end-of-life in 24 years. For the manufacturing phase of the aircraft, the transportation was considered, according to the data from Airbus reports available for the general public in the internet [34, 35].

Data Sources

The data used in this study had its origin in multiple sources. Hence, throughout the aircraft life cycle, and with the indispensable assistance by TAP and Airbus, the data sources used were:

- Structure Repair Manual (SRM) [3]: the majority of the material data came from this manual, provided by TAP;
- Weight and Balance Manual (WBM) [36]: the majority of the weight data were retrieved from this manual;
- Aircraft Recovery Manual (ARM) [37]: for additional weight data of the A330-200 aircraft;
- Maintenance Facility Planning (MFP) [38]: Aircraft manual that provided additional weight and material constitution data;
- Material Breakdown of the A330-200, provided by Airbus engineer François Museux [39];
- Expertise opinions, on both material and weight data, provided by Eng. João Carrolo and by Eng. João Martins, from TAP;

- Weight and Material identification for the GE CF6-E1 engine in "Manufacturing Technology for Aerospace Structural Materials" [40];
- Airbus PAMELA Results [41, 42]: Provided data for modelling the aircraft's end of life;
- Expertise opinions on the PAMELA Results for the A330-200 aircraft, provided by Airbus engineer François Museux;
- Validated databases (Ecoinvent system and unit processes, European Life Cycle Database v2.0) in Simapro software regarding the several processes modelled [43];

Study Limitations

In principle, a life cycle assessment should quantify all material and energy fluxes, from its origin until its devolution to nature. However, there are time, resources, and data limitations that make such details impossible to take into account, in practice. Therefore, when performing a LCA, one should make reasonable decisions and choose what unitary processes will be modelled, what emissions will be considered, and what energy consumptions will be take into account and the respective detail level. In this manner, the system boundaries will greatly depend on the data availability, being that any omission should be clearly referenced and justified. Accordingly, the aircraft was considered only in its structural form, being that catering allowances, galley structures, cabin interiors and passenger seats were not included in the study. The reasons behind this decision were based on the intention of enabling this work to be suitable and useful for any airliners that own this aircraft, or for airliners that want to adapt this work to another similar aircraft. Also, data availability turned out to be a problem, especially in terms of the materials that compose the excluded parts mentioned above: in WBM the weight of these components can be found, but the respective materials are not in the SRM manual, nor in any other A330 manual. Not all distances travelled by the aircraft components to the final assembly line have been accounted for, but given its small overall impact, and the fact that it is difficult data to precisely determine, the information retrieved from [35, 34] was considered sufficient.

In relation to the operational data, a linear relation between the fuel consumption and the emissions to air was assumed, this way enabling the modelling of the fuel burn through an adaption from the Ecoinvent database.

Type of Assessment Performed

A life cycle assessment software was used, *Simapro* 7.2, through the following environmental impact assessment methods: ReCiPe Midpoint, ReCiPe Endpoint, Cumulative Energy Demand and Ecological Footprint.

Data Quality Requirements

It is intended that the data used in this study ensures a proper LCA study, providing also the possibility for further data improvement, as well as providing a suitable framework for aircraft LCA, so that more aircrafts can be subjected to this type of study in the future. Thus, this should be useful to decision-makers, providing a scientific base for the environmental profile of the aircraft under analysis.

Validation and Critical Review

The data used was mainly taken from aircraft manuals, and it was further subjected to a critical review by the TAP engineer João Carrolo. Further validation with comparisons with data provided by Airbus through personal communication [39]. Moreover, comparisons between the obtained results and those in the TAP Sustainability Report [44], and with the transportation processes in the Ecoinvent Database [45]. For further description of results analysis and validation, refer to *Section* 4.2.4, and *Section* 5.3, being that the latter consists on a uncertainty analysis.

Type and Structure of the Final Report

This study has the typical structure of an LCA study, framed and adapted to be a master thesis, with all the requirements such work must obey.

4.1.3 Functional Unit

When performing an LCA, the choice of the functional unit is of the most extreme importance, influencing the outcome of the study. For the passenger transportation sector, the functional unit usually adopted is: *passenger.km* [30]. This means that the product will be analysed referring to the transportation of one passenger, through a travelled distance of $1\,km$. The Ecoinvent database also used the functional unit *passenger.km* in its processes that regard the transportation of passesngers [45]. Being that in order for two products or services to be compared in the LCA approach the functional must be the same, the choice of functional unit was clear from the start. This way, the comparison between the A330-200 aircraft life cycle and any other transportation process in the Ecoinvent database could be performed.

Being so, this was the functional unit adopted in this work.

4.2 Life Cycle Inventory

The life cycle inventory is the LCA stage in which, considering the predefined goal, scope and functional unit, the necessary data is collected, processed and analysed. Oftenly the LCA ends at this phase, for it can already offer useful insights and information. Thus, it constitutes the most time and effort demanding phase of the LCA, being that in the end a flow diagram of the system is obtained, as well as the inventory table with all the inputs and outputs that the whole system contains.

4.2.1 Flow Diagram

A very simplified flow diagram of the Airbus A330-200 aircraft life cycle is shown on *Figure* 4.2, with the objective of merely illustrating the different life cycle phases.

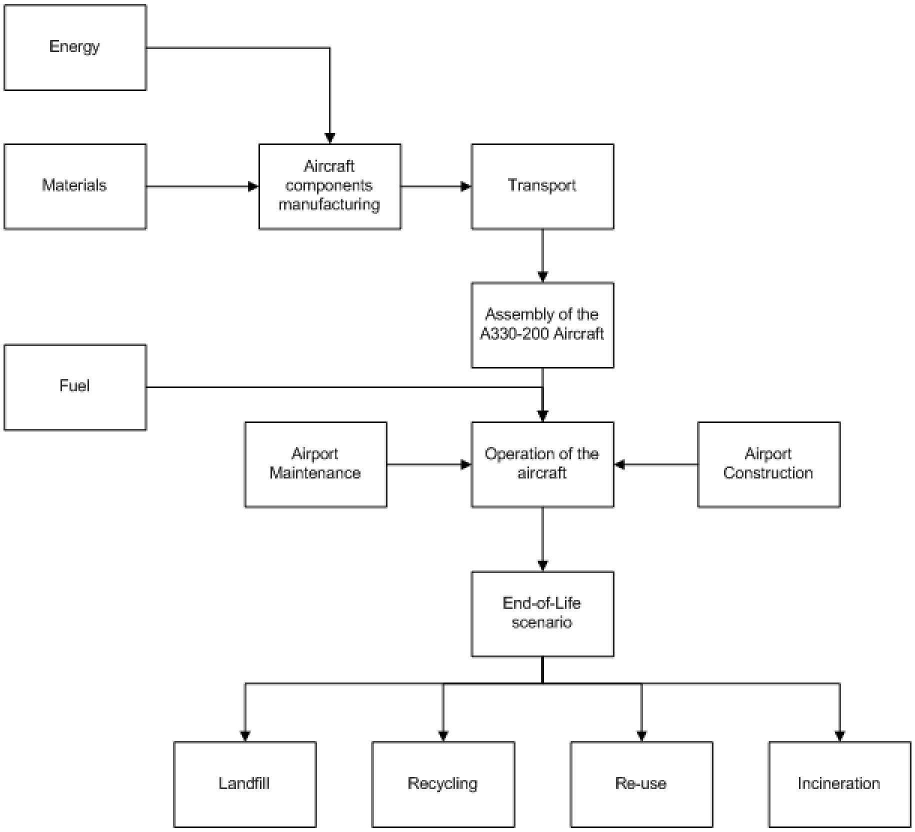


Figure 4.2: Flow diagram of the A330-200 life cycle

4.2.2 Data Collection

Performing the life cycle assessment of an aircraft, the data collection was the hardest and most effort demanding part of this work. Not only the complexity of the aircraft posed as a major problem, but the data availability was also a big problem, mainly due to the confidentiality regarding almost every aspect of the aircraft. Nevertheless, thanks to the assistance of TAP engineers João Carrolo and João Martins, the most important data managed to be collected through the information in several A330-200 manuals (see *Data Sources* in *Section* 3.3.1 for further information). Being so, and concerning the material data of the aircraft, all information can be consulted in *Appendix B*. Here, the information regarding material composition and structural weights is given in detail.

In order to perform the LCA of the A330, regarding the manufacturing process, the materials and corresponding weight for each aircraft component were needed. Moreover, the transportation of each component to the final assembly line (in Toulouse, France) was also taken into account. Being so, the software Simapro would then calculate the environmental impacts of all processes and produce an organized and extensive inventory table. Moreover, after the manufacturing phase then came the active life cycle of the aircraft, which corresponds to the use of the product through its expected lifetime of 24 years.

The operation (active) life stage of the aircraft was supposed to be fully obtained with data provided by an airliner with A330-200 using the GE CF6-E1 engine on its fleet. A contact was established and the airliner provided confidential data regarding all the A330-200 aircrafts composing its fleet, for the year of 2009. This data consisted, among other things, of the number of flights, passengers transported, and travelled distances for each aircraft in each month of 2009. To calculate the fuel consumption of one passenger travelling one kilometer (according to the functional unit chosen), the fuel consumption of the aircraft was also needed. This data was supposed to be provided by the same airliner, but unfortunately this data was not provided in time of considering it in this work, and further research had to be carried out in order to find out this value (once again the iterative nature of the LCA is visible). Being so, the fuel consumption of the aircraft was retrieved from the aviation maganize 'Aircraft Commerce' [46], using some additional technical data from a British Petroleum report [47]. The calculation of the fuel consumption regarding the functional unit is described in $Operation Life Cycle$ of *Section* 4.2.2.

Finally, the aircraft end of life had to be modelled. In order to do so, firstly a research was conducted aiming to find out what was the disposal scenario of the A330-200 aircraft, which resulted in the acknowledgment of the Airbus PAMELA (Process for Advanced Management of End-of-Life Aircraft). This project stands a example of the life cycle holistic perspective adopted by Airbus, and has the objective of creating new best practices to disassemble and recycle aircrafts in its end-of-life phase.

The explanation of the data collection process in each of the aircraft life cycle phase follows next.

Ecoinvent Database

The Simapro software is capable of performing helpful calculations and it displays results in a quick and organized way. However, the LCA software greatest richness comes from the databases it uses, which are indispensable for its utilisation. Among these is the Ecoinvent database, which contains a large amount of data (more than 4000 LCI datasets) regarding many areas (e.g., energy supply, waste management, transport, construction and mechanical engineering). This database was developed in a joint effort of various Swiss institutions, and basing on validated industrial data, it has become the most widespread and acknowledged life cycle inventory database worldwide [48].

Given the wide range of processes that compose the Ecoinvent database, and its reliability, this database was used to model the life cycle of the A330-200 aircraft with the Simapro software.

Structural and Components Weights

The final material and weight distribution of the A330-200 can be found in *Appendix B*, where a clear description of the aircraft components in terms of weight and materials is given. Moreover, it should be taken into account that either in the Simapro model, and in the data that is shown throughout the present work, the aircraft structural component 'Engine' comprises not only the engine itself, but other components as well, namely: pylons; inlet, fan and core cowl; thrust reverser; and the primary nozzle.

Given the impossibility of finding specific weight data regarding aircrafts components on the internet or public literature, technical A330-200 manuals had to be consulted. These were all provided by TAP Structural and Maintenance Engineer João Carrolo. Being so, the manuals in which weight information was included were the Weight and Balance Manual [36] and the Aircraft Recovery Manual [37]. Fortunately, these manuals are not very extensive (1366 pages all together) and information was retrieved. Moreover, these two manuals despite having very detailed information regarding some components (cabin emergency rope, fire extinguishers, etc.) it lacks weight information regarding some heavy structural components. Therefore, the information that was lacking have been provided by personal communication with TAP engineers João Carrolo and João Martins.

After gathering all the necessary weight data, the generic weight distribution can be found in $Table$ 4.2, and it is shown in $Figure$ 4.3. In the Weight and Balance Manual, the Aircraft Weighting Report performed by Airbus resulted in a measurement of 108206 Kg, for the Manufacturer Empty Weight (MEW)[1] of the A330-200. The final value obtained here is 106218 Kg, which accounts for more than 98% of the MEW calculated by Airbus,

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[1] Manufacturer Empty Weight - "The weight of structure, power plant, systems, furnishings and other items of equipment that are an integral part of the aircraft configuration, including the fluids contained in closed systems. The weights of all operator's items are excluded" (source: [36])

standing as a reasonably approximate value. This difference between the aircraft weight values can be explained by the fact that aircraft elements such as electronics, navigation instruments and closed system fluids (e.g. hydraulic fluids) were not considered in this study. However, these elements to not constitute a significant amount of weight, and being very difficult to characterize in terms of material composition, were chosen not to be taken into account.

Structural Part	Weight (in Kg)
Wings	43722
Main Landing Gears	12296
Nose Landing Gear	1213
Fuselage	27495
Vertical Stabilizer	1192
Horizontal Stabilizer	1877
Engines	18424
TOTAL	106218

Table 4.2: Generic Weight Composition of the aircraft Airbus A330-200, by aircraft parts.

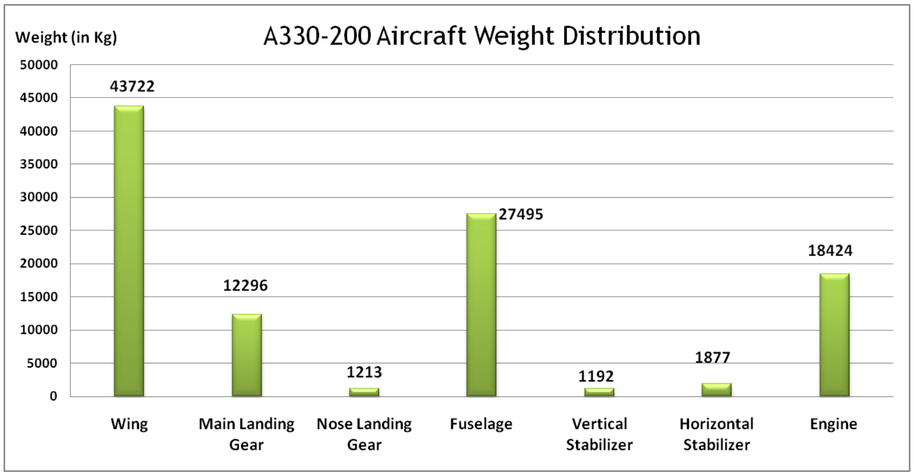


Figure 4.3: Generic Weight Distribution in A330-200

Materials in Aircraft Components

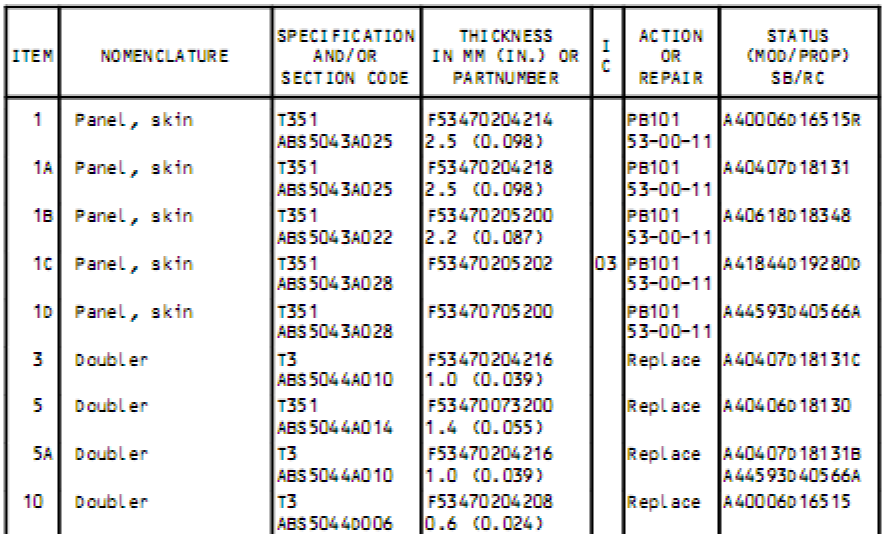
After gathering the information regarding the weight of the various components in the aircraft, the discrimination of the materials that compose each component was needed.

This turned out to be a hard task, given the complexity of such a product as an aircraft, and given the issue of data availability. However, the author of this work had privileged access to different manuals of the aircraft, and the Structure Repair Manual managed to provide detailed and valid data concerning the materials that compose the aircraft. The information needed was dispersed through this manual, which is made out of more than 1400 files in the *.pdf* format, resulting in total of more than 600 MB. The SRM comprises the following main sections:

- Chapter SRI (Structural Repair Inspection)
- Chapter 51 - Standard Practices and Structures
- Chapter 52 - Doors
- Chapter 53 - Fuselage
- Chapter 54 - Nacelles / Pylons
- Chapter 55 - Stabilizers
- Chapter 56 - Windows
- Chapter 57 - Wings

Being so, for instance, the materials of the skin plates on the rear fuselage are given in the file 53-41-11-001, and a small part of this information is in *Table* 4.3. In this manual, a detailed figure referring to each item (first column) is given, and after the nomenclature (second column), the material specification is given in a code (third column). Afterwards, giving that the code itself does not provide the material type, a cross reference with another file (51-31-00-001 for metallic materials and 51-33-00-001 for nonmetallic materials, such as composites) would provide the information regarding the material used. Being so, after performing this operation for the entire aircraft, a matching between the codes and the materials was made, and the final result is the information regarding the materials composing the aircraft. This was, by far, the most time and effort demanding part of this work, but in the end it provided accurate and official data regarding most of the materials in the A330-200 aircraft.

Nevertheless, in SRM not all parts of the aircraft were described and further information regarding materials was needed. To complete these data, through personal communication



ITEM	NOMENCLATURE	SPECIFICATION AND/OR SECTION CODE	THICKNESS IN MM (IN.) OR PARTNUMBER	I C	ACTION OR REPAIR	STATUS (MOD/PROP) SB/RC
1	Panel, skin	T351 ABS5043A025	F53470204214 2.5 (0.098)		PB101 53-00-11	A40006D16515R
1A	Panel, skin	T351 ABS5043A025	F53470204218 2.5 (0.098)		PB101 53-00-11	A40407D18131
1B	Panel, skin	T351 ABS5043A022	F53470205200 2.2 (0.087)		PB101 53-00-11	A40618D18348
1C	Panel, skin	T351 ABS5043A028	F53470205202	03	PB101 53-00-11	A41844D19280D
1D	Panel, skin	T351 ABS5043A028	F53470705200		PB101 53-00-11	A44593D40566A
3	Doubler	T3 ABS5044A010	F53470204216 1.0 (0.039)		Replace	A40407D18131C
5	Doubler	T351 ABS5044A014	F53470073200 1.4 (0.055)		Replace	A40406D18130
5A	Doubler	T3 ABS5044A010	F53470204216 1.0 (0.039)		Replace	A40407D18131B A44593D40566A
10	Doubler	T3 ABS5044D006	F53470204208 0.6 (0.024)		Replace	A40006D16515

Table 4.3: SRM section referring to skin plates on the rear fuselage (taken from [3])

with TAP Structural and Maintenance Engineer João Carrolo [49], the missing data was acquired. This expertise opinion included conversations between the author of this thesis, Engineer João Carrolo, and the mechanics personnel working in the TAP hangars, being that the information obtained would later be revised by Engineer João Martins [50], also from TAP.

However, one of the most important material in the aircraft, carbon fiber reinforced plastic, was not in the software database, even though that was not the case for glass fiber reinforced plastic. Thus, additional research was needed in order to create a process that modelled the production of one Kg of CFRP. Being so, from $Ref.$ [51] the material constitution of CFRP was retrieved, and from $Ref.$ [52] the energy input data was obtained. Additionally, CFRP was considered be produced in Japan, since it is the most important supplier of CFRP worldwide [53].

In addition to this, the SRM only comprises materials regarding the aircraft structure, and being that the A330-200 can be operated with three different engines, the material identification and characterization of the GE CF6-E1 is not contained in any of the obtained aircraft manuals. Being so, the material identification and respective weight contribution was retrieved from “Manufacturing Technologies for Aerospace Structural Materials” [40], in which a detailed description of the GE CF6 engine is provided. Furthermore, it is stated that the superalloy ’Inconel 718’ is the predominant alloy (34% of the engine weight) that

Inputs for 1 Kg CFRP production	Quantity
Nitrogen, liquid, at plant/RER U	6,33 Kg
Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S	0,93 Kg
Epoxy resin, liquid, at plant/RER U	0,398 Kg
Heat, natural gas, at industrial furnace >100kW/RER s	105,3 MJ
Electricity, production mix JP/JP U	135,85 kWh

Table 4.4: Carbon Fiber Reinforced Plastic process definition, as in Simapro.

Engine material composition, as modelled in Simapro	Weight (in Kg)
Iron-nickel-chromium alloy, at plant/RER U	864
Aluminium alloy, $AlMg3$, at plant/RER U	465
CFRP	216
Titanium zinc plate, without pre-weathering, at plant/DE U	1310
Nickel, 99,5%, at plant/GLO U	1472
Chromium, at regional storage/RER U	447
Molybdenite, at plant/GLO U	76
Cast iron, at plant/RER U	456
Tantalum, powder, capacitor-grade, at regional storage/GLO	94
TOTAL	5400

Table 4.5: General Electric CF6-E1 material composition, as inserted in Simapro.

composes the engine. In the same book, a description of the each alloy in the engine is provided, which allowed a detailed material and weight description of the engine, which was then modelled in the Simapro software. In addition to this, despite the material composition of the engine is not in SRM, its weight (5400 kg each) can be found in the Maintenance Facility Planning [38], which also was provided by TAP. Thus, the engine material and weight data can be found in *Table* 4.5.

Finally, all the information regarding the material composition of the A330-200 aircraft is given in *Appendix B*. Furthermore, a general picture of the material distribution (commonly referred to as 'material breakdown') referring to the A330-200 total weight is shown on *Figure* 4.4[2], in reference to the aircraft weight of 106218 kg calculated in this work. It can be seen that aluminium is the most used material (58% of the total weight), followed by steel (19%) and the composites represent around 11% of the aircraft total weight. Being so,

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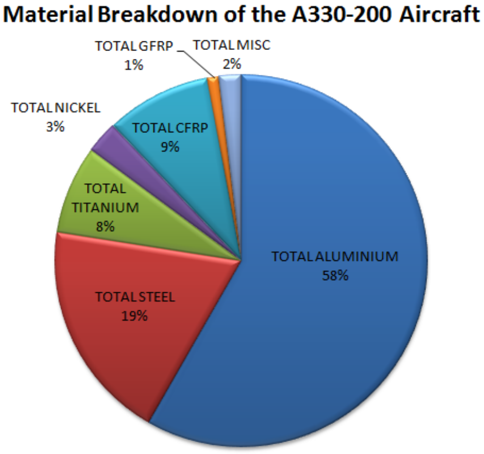
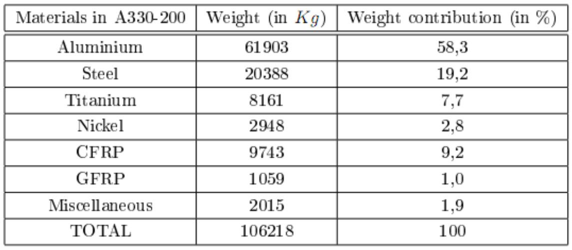
[2] The A330-200 Material Breakdown refers to the fuselage, wings, stabilizers and also takes into account two engines and the main and nose landing gears.





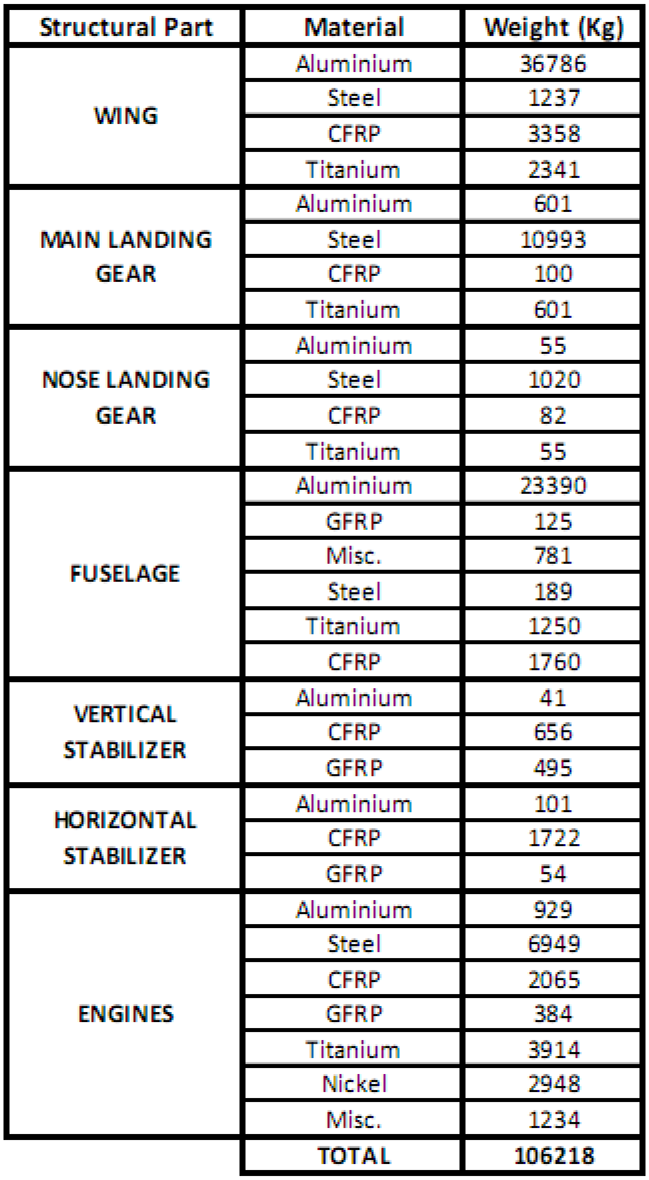
Materials in A330-200	Weight (in Kg)	Weight contribution (in %)
Aluminium	61903	58,3
Steel	20388	19,2
Titanium	8161	7,7
Nickel	2948	2,8
CFRP	9743	9,2
GFRP	1059	1,0
Miscellaneous	2015	1,9
TOTAL	106218	100

Figure 4.4: Generic Material Breakdown of the aircraft A330-200, including Main and Nose Landing Gears and Engines.

carbon fiber reinforced plastic stands, by far, as the largest composite in use, a trend that seems to extend to the most recent Airbus aircrafts as well [22]. On *Table* 4.6 the weight of each material in the aircraft main structural components is also shown. Furthermore, for a more detail description of the weight of the materials distribution on the A330-200 aircraft, see *Appendix B*.

Transportation of Components to the Final Assembly Line

Despite not being of the most relevance for the final results obtained in this work, the transportation of the aircrafts components to the final assembly line in Toulouse, France, was also taken into account, for they also represent an environmental load. The information regarding the manufacturing location of each aircraft component is in [35, 34], and the data obtained is shown in *Table* 4.7.



Structural Part	Material	Weight (Kg)
WING	Aluminium	36786
	Steel	1237
	CFRP	3358
	Titanium	2341
MAIN LANDING GEAR	Aluminium	601
	Steel	10993
	CFRP	100
	Titanium	601
NOSE LANDING GEAR	Aluminium	55
	Steel	1020
	CFRP	82
	Titanium	55
FUSELAGE	Aluminium	23390
	GFRP	125
	Misc.	781
	Steel	189
	Titanium	1250
	CFRP	1760
VERTICAL STABILIZER	Aluminium	41
	CFRP	656
	GFRP	495
HORIZONTAL STABILIZER	Aluminium	101
	CFRP	1722
	GFRP	54
ENGINES	Aluminium	929
	Steel	6949
	CFRP	2065
	GFRP	384
	Titanium	3914
	Nickel	2948
	Misc.	1234
	TOTAL	**106218**

Table 4.6: A330-200 material weight distribution for each structural part of the aircraft

Origin	Destination	Direct Distance (in Km)	Components
Broughton (UK)	Filton (UK)	1257	Wings, outer wing box
Filton (UK)	Toulouse (France)	928	Wing assembly
Nantes (France)	Toulouse (France)	464	Keel beam, wing centre box, ailerons
Saint-Nazaire (France)	Toulouse (France)	591	Assembly of central and forward fuselage sections
Getafe (Spain)	Toulouse (France)	562	After fuselage
Illescas (Spain)	Toulouse (France)	583	Rudder, horizontal tail box
Puerto Real (Spain)	Toulouse (France)	1017	Cabin doors, leading edges, elevators
Stade (Germany)	Toulouse (France)	1257	Vertical Tail

Table 4.7: Transportation of A330-200 components, from the manufacturing location to the final assembly line

Operation Life Cycle

The data concerning the active life cycle of the aircraft was requested to a airliner, whose identity, for confidentiality reasons, cannot be revealed. Moreover, the data obtained is also confidential, and therefore only the final result used in this work will be presented. However, an explanation of how the final values were obtained can be given, and such explanation follows next. Being that the functional unit is *passenger.km* (PSK), two main quantities were needed to model the aircraft's active life cycle:

1. the total number of passengers transported and total number of kilometres travelled by the aircraft throughout its life cycle;
2. fuel consumption of a passenger travelling a distance of one kilometer;

Moreover, the airliner provided the following data, regarding to the year of 2009, for the each A330-200 that compose the airliner's fleet:

- An average of the air distance travelled, for each month;
- Number of flights made, for each month;
- Total number of passengers transported, for each month;

Unfortunately, by the time this thesis has been written, the data that refers to the fuel consumption of the A330-200 is still not available. In order to address this problem, further research had to be made, in order to find out the A330-200 fuel consumption (in $kg/hour$), using the GE CF6-E1 engines. Reliable data was found in a article of a well known aircraft magazine, named “Aircraft Commerce”[46]. This article referred that for an average A330-200 flight of 695 minutes travelling over 5500 nautical miles (nm), the fuel burn is 21300 United State Gallons (USG), which is equivalent to an average fuel consumption of 5596,5 $kg/hour$, as in *Equation* 4.1. This fuel consumption calculation used a Jet A1 fuel density value of 0,804 kg/dm^3, according to the British Petroleum (BP) 'Handbook of Products' [47].

$$fuel\,consumption\,(kg/hour) = \frac{21300 \times 3,78541178 \times 0,804}{5500 \times 1,852} = 5596,5\,(kg/hour) \quad (4.1)$$

Knowing the fuel consumption of the A330-200 aircraft, and the average passenger number per flight, the fuel consumption per passenger was easily calculate by simply dividing the two quantities, as in *Equantion* 4.2. Being so, a fuel consumption per passenger value of 0.034383 Kg/PSK was obtained:

$$fuel\,consumption_{per\,passenger}\,(kg/PSK) = \frac{fuel\,consumption}{average\,number\,of\,passengers} \quad (4.2)$$

Being so, in order to calculate the total number of *passengers.kilometres* over the aircraft life time, the (average) number of passengers for 2009 was multiplied by the (average) travelled distance, times the estimated aircraft lifetime squared, as in *Equation* 4.3[3].

$$passengers_{2009} \times Distance\,travelled_{2009} \times lifetime^2 = (passengers \times kilometres)_{lifetime} \quad (4.3)$$

The inverse of this value gives us the aircraft manufacturing scaled to the functional unit of one PSK. In addition, the operational life cycle of the aircraft in the Simapro software was modelled, according to the data that was obtained. The Ecoinvent database has a broad number of processes regarding the transportation sector, namely aviation. What has been done in this work to model the A330-200 fuel consumption and air emissions was, firstly a simple copy of the Ecoinvent process 'Operation, aircraft, passenger, intercontinental/RER

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[3] In Equation 4.3, subscripts indicate the time period considered

U', and afterwards changing the fuel consumption, calculated with *Equation* 4.2. Finally, to take into account the construction of the airport and its maintenance, the Ecoinvent processes '*Airport/RER/I U*' and '*Operation*, *maintenance*, *airport/RER U*' were used, respectively, to model each one.

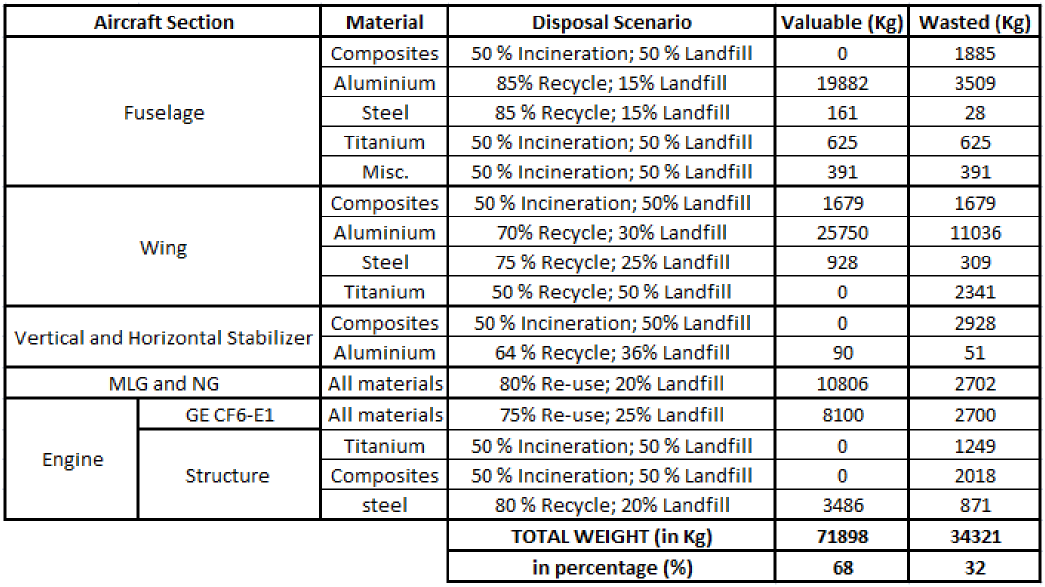
On *Section* 5.3 an uncertainty analysis is performed, taking into account the operational data used.

End-of-Life Scenario of the A330-200 Aircraft

The end-of-life scenario information was considered in consonance with the results of the PAMELA project of Airbus. Due to the inefficient and environmental harmful current status of aircraft end-of-life scenarios (storage in deserts, abandonment at airports, wild destruction of non ferrous salvaged materials) [42], Airbus endorsed a commitment towards a responsible environmental management throughout the life cycle of the aircraft, namely, its final stage. Thus, integrating a full life cycle approach, the PAMELA project aims to [41]:

- Protect the environment: setting up reference and best practices to manage aircraft retiring from service for the benefit of a more eco-efficient aerospace industry;
- Maintain high standards of safety: control and qualification of second-hand parts in terms of safety and tracking as well as working in safe conditions for the personnel;
- Gather technological expertise: the experimental project established and implements efficient dismantling and recovery practises through the combined expertise of the project participants;
- Integrate the latest economic trends: the increasing number of end-of-life aircraft generates a new market for re-used parts, valorisation and recovery of aircraft materials;
- Generate financial gains: the benefits of recycling activities can generate gains in the short-medium term.

In addition to the information present in the Airbus PAMELA reports, a personal communication with Airbus engineer François Museux [39], who provided a further detailed end-of-life scenario results for the PAMELA project. It was revealed that, despite the technological availability for recycling most of the materials that compose the aircraft, given



Aircraft Section		Material	Disposal Scenario	Valuable (Kg)	Wasted (Kg)
Fuselage		Composites	50 % Incineration; 50 % Landfill	0	1885
		Aluminium	85% Recycle; 15% Landfill	19882	3509
		Steel	85 % Recycle; 15% Landfill	161	28
		Titanium	50 % Incineration; 50 % Landfill	625	625
		Misc.	50 % Incineration; 50 % Landfill	391	391
Wing		Composites	50 % Incineration; 50% Landfill	1679	1679
		Aluminium	70% Recycle; 30% Landfill	25750	11036
		Steel	75 % Recycle; 25% Landfill	928	309
		Titanium	50 % Recycle; 50 % Landfill	0	2341
Vertical and Horizontal Stabilizer		Composites	50 % Incineration; 50% Landfill	0	2928
		Aluminium	64 % Recycle; 36% Landfill	90	51
MLG and NG		All materials	80% Re-use; 20% Landfill	10806	2702
Engine	GE CF6-E1	All materials	75% Re-use; 25% Landfill	8100	2700
	Structure	Titanium	50 % Incineration; 50 % Landfill	0	1249
		Composites	50 % Incineration; 50 % Landfill	0	2018
		steel	80 % Recycle; 20% Landfill	3486	871
			TOTAL WEIGHT (in Kg)	**71898**	**34321**
			in percentage (%)	**68**	**32**

Table 4.8: End-of-life scenario for the A330-200 aircraft, according to the PAMELA project by Airbus.

its complexity, it was difficult to properly separate all materials to the correspondent material type (metallic, composites, elastomers, fluids/gas, miscellaneous) which meet their final destination on the appropriate specialised recovery channel. Being so the life cycle scenario for the aircraft was obtained, and the results are shown in *Table* 4.8. Here, it can be seen that with the PAMELA project a valorisation of 68% of the total aircraft weight is obtained, even though new research is being developed by Airbus in order to improve this scenario, being that the major challenge reside in recycling composites and recycling parts in which materials are difficultly separated correctly.

4.2.3 Data Processing

Following the data collection phase, comes the phase in which the data obtained is processed. In the data processing stage, the data collected is handled in such a way that enables the calculation of the contribution of the different impacts that take place during the product life cycle. This data processing was performed with the assistance of the Simapro software, which having the quantification of each life cycle process, groups all the quantities (per substances) associated with every process of the aircraft lifetime. For instance, in the data processing phase, all the emissions of CO_2 that have been identify throughout the aircraft life cycle are summed in order to obtain the final quantity of CO_2 emitted.

Using the Simapro, all life cycle phases have been modelled, given that all the necessary data had been collected. In order for the life cycle model to be understood, a brief practical explanation of how Simapro works will be given next (for better understanding of how Simapro works, refer to [29]). In $Figure$ 4.5 the 'LCA Explorer can be found on the left, being divided into 'Wizards', 'Goal and Scope', 'Inventory', 'Impact Assessment', 'Interpretation', and 'General data'. Modelling a system with simapro requires the definition of the processes that characterize the system under study, and the processes defined in Simapro fit in the the following categories: materials, energy, transport, processing, use, waste scenario and waste treatment. Thus, each process can contain information regarding: outputs to technosphere; inputs from nature (resources) and technosphere (materials/fuels and electricity/heat); emissions to air, to water and to soil; final waste flows; social and economic issues; and outputs to technosphere in the form of waste and emissions to treatment. Moreover, each process can either be a 'unit process' or a 'system process', although they produce almost the same inventory results. However, a unit process encloses all the unit processes that are involved in the process under analysis, generating very transparent and long networks (allowing to see different unit processes contribution), while a system process includes all the inputs and outputs inherent to the process, but represents them more simply (through a black box), which results in simpler but less transparent networks. In the present work, for initial estimates system processes were used, and unit processes were later used, so that the contribution of each unit process could be visualised and analysed.

Thus, all the processes are combined and linked together to form the life cycle of a product, which can be shown in Simapro in the form of a network. Such networks can contain thousands of processes, and usually a 'cut-off'[4] must be used in order to properly analyse the network, and a 'show top processes only' button also exists with the same objective (reducing network's size).

The 'Product Stages' is where, in the Simapro software, the product manufacturing, active and end-of-life phases are described. Such characterization is made through the definition of assemblies and subassemblies that contain material/assemblies and processes data. (transportation, energy, etc.). Moreover, in the 'Life cycle' (product stage) the main assembly is specified, with additional processes and the correspondent generic disposal

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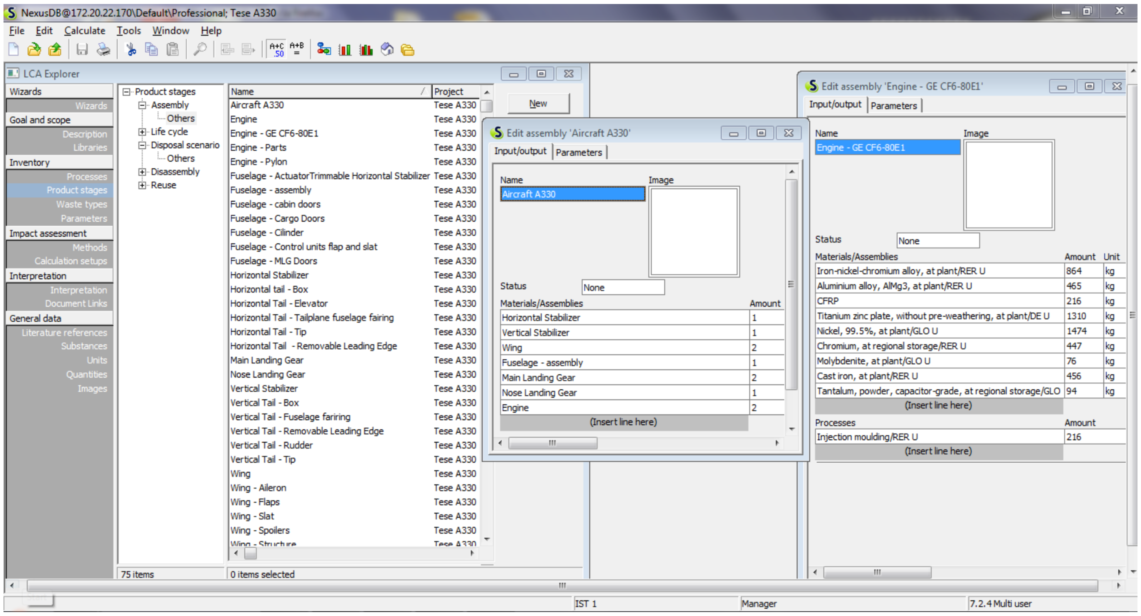
[4] In Simapro, a cutt-off is a button in which the user can set a percentage bellow which any process with a smaller contribution (percentage value) to the final impact won't be shown in the network.

scenario for the main assembly.

Finally, on *Figure* 4.5 the Simapro environment is shown, and three windows can be seen. The first is the 'LCA Explorer' in which the life cycle is modelled and the assemblies can be seen. The 'Aircraft A330' assembly is shown, which all the subassemblies it is composed of. Moreover, the subassembly 'Engine - GE CF6-80E1' is also shown, where the materials that compose it are shown (the units are given in *kg*). Being so, a inventory table is generated, which accounts for all the inputs and outputs needed to process a unitary functional unit. Thus, in the current study, the inventory table will concern the processes involving the transportation of one passenger through one kilometer, using the aircraft A330-200. Being so, the life cycle inventory of the aircraft can be seen in *Appendix* A.



Name	Project
Aircraft A330	Tese A330
Engine	Tese A330
Engine - GE CF6-80E1	Tese A330
Engine - Parts	Tese A330
Engine - Pylon	Tese A330
Fuselage - ActuatorTrimmable Horizontal Stabilizer	Tese A330
Fuselage - assembly	Tese A330
Fuselage - cabin doors	Tese A330
Fuselage - Cargo Doors	Tese A330
Fuselage - Cilinder	Tese A330
Fuselage - Control units flap and slat	Tese A330
Fuselage - MLG Doors	Tese A330
Horizontal Stabilizer	Tese A330
Horizontal tail - Box	Tese A330
Horizontal Tail - Elevator	Tese A330
Horizontal Tail - Tailplane fuselage fairing	Tese A330
Horizontal Tail - Tip	Tese A330
Horizontal Tail - Removable Leading Edge	Tese A330
Main Landing Gear	Tese A330
Nose Landing Gear	Tese A330
Vertical Stabilizer	Tese A330
Vertical Tail - Box	Tese A330
Vertical Tail - Fuselage fariring	Tese A330
Vertical Tail - Removable Leading Edge	Tese A330
Vertical Tail - Rudder	Tese A330
Vertical Tail - Tip	Tese A330
Wing	Tese A330
Wing - Aileron	Tese A330
Wing - Flaps	Tese A330
Wing - Slat	Tese A330
Wing - Spoilers	Tese A330
Wing - Structure	Tese A330

Edit assembly 'Aircraft A330'

Input/output | Parameters

Name: Aircraft A330

Status: None

Materials/Assemblies	Amount
Horizontal Stabilizer	1
Vertical Stabilizer	1
Wing	2
Fuselage - assembly	1
Main Landing Gear	2
Nose Landing Gear	1
Engine	2
(Insert line here)	

Edit assembly 'Engine - GE CF6-80E1'

Input/output | Parameters

Name: Engine - GE CF6-80E1

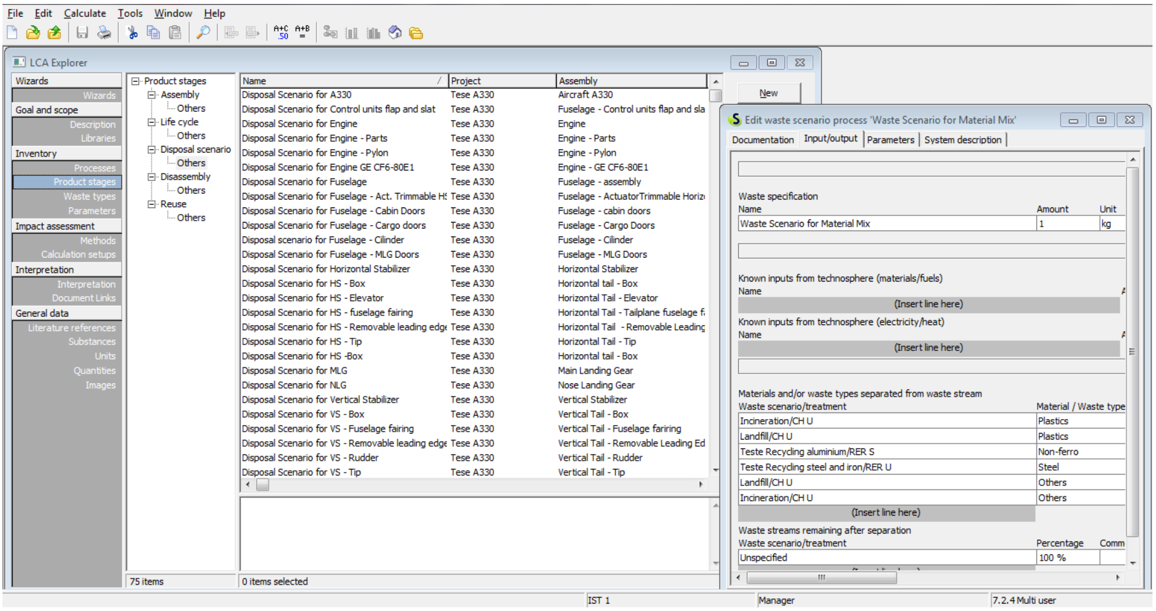
Status: None

Materials/Assemblies	Amount	Unit
Iron-nickel-chromium alloy, at plant/RER U	864	kg
Aluminium alloy, AlMg3, at plant/RER U	465	kg
CFRP	216	kg
Titanium zinc plate, without pre-weathering, at plant/DE U	1310	kg
Nickel, 99.5%, at plant/GLO U	1474	kg
Chromium, at regional storage/RER U	447	kg
Molybdenite, at plant/GLO U	76	kg
Cast iron, at plant/RER U	456	kg
Tantalum, powder, capacitor-grade, at regional storage/GLO	94	kg
(Insert line here)		

Processes	Amount
Injection moulding/RER U	216
(Insert line here)	

Figure 4.5: Modelling the manufacturing phase of the A330-200 life cycle, using the Simapro software

This disposal scenario has been modelled for every aircraft components in Simapro, which enables a detailed description of the assemblies and components. To do so, disposal scenarios in Simapro firstly refer to the disassembly of the aircraft, and then for each disassembled component, a disposal scenario is described. The latter can comprise a waste scenario, another disassembly process, or a reuse. The waste scenario includes waste scenarios treatment, such as landfill and recycling, to each material/waste type as well as inputs from technosphere (materials/fuels and electricity/heat). A general picture of the Simapro environment in modelling the life cycle scenario is shown on *Figure* 4.6.



Name	Project	Assembly
Disposal Scenario for A330	Tese A330	Aircraft A330
Disposal Scenario for Control units flap and slat	Tese A330	Fuselage - Control units flap and sla
Disposal Scenario for Engine	Tese A330	Engine
Disposal Scenario for Engine - Parts	Tese A330	Engine - Parts
Disposal Scenario for Engine - Pylon	Tese A330	Engine - Pylon
Disposal Scenario for Engine GE CF6-80E1	Tese A330	Engine - GE CF6-80E1
Disposal Scenario for Fuselage	Tese A330	Fuselage - assembly
Disposal Scenario for Fuselage - Act. Trimmable H:	Tese A330	Fuselage - ActuatorTrimmable Horiz
Disposal Scenario for Fuselage - Cabin Doors	Tese A330	Fuselage - cabin doors
Disposal Scenario for Fuselage - Cargo doors	Tese A330	Fuselage - Cargo Doors
Disposal scenario for Fuselage - Cilinder	Tese A330	Fuselage - Cilinder
Disposal Scenario for Fuselage - MLG Doors	Tese A330	Fuselage - MLG Doors
Disposal Scenario for Horizontal Stabilizer	Tese A330	Horizontal Stabilizer
Disposal Scenario for HS - Box	Tese A330	Horizontal tail - Box
Disposal Scenario for HS - Elevator	Tese A330	Horizontal Tail - Elevator
Disposal Scenario for HS - fuselage fairing	Tese A330	Horizontal Tail - Tailplane fuselage f
Disposal Scenario for HS - Removable leading edg	Tese A330	Horizontal Tail - Removable Leading
Disposal Scenario for HS - Tip	Tese A330	Horizontal Tail - Tip
Disposal Scenario for HS -Box	Tese A330	Horizontal tail - Box
Disposal Scenario for MLG	Tese A330	Main Landing Gear
Disposal Scenario for NLG	Tese A330	Nose Landing Gear
Disposal Scenario for Vertical Stabilizer	Tese A330	Vertical Stabilizer
Disposal Scenario for VS - Box	Tese A330	Vertical Tail - Box
Disposal Scenario for VS - Fuselage fairing	Tese A330	Vertical Tail - Fuselage fariring
Disposal Scenario for VS - Removable leading edg	Tese A330	Vertical Tail - Removable Leading Ed
Disposal Scenario for VS - Rudder	Tese A330	Vertical Tail - Rudder
Disposal Scenario for VS - Tip	Tese A330	Vertical Tail - Tip

Edit waste scenario process 'Waste Scenario for Material Mix'

Waste specification

Name	Amount	Unit
Waste Scenario for Material Mix	1	kg

Known inputs from technosphere (materials/fuels)

Name

(Insert line here)

Known inputs from technosphere (electricity/heat)

Name

(Insert line here)

Materials and/or waste types separated from waste stream

Waste scenario/treatment	Material / Waste type
Incineration/CH U	Plastics
Landfill/CH U	Plastics
Teste Recycling aluminium/RER S	Non-ferro
Teste Recycling steel and iron/RER U	Steel
Landfill/CH U	Others
Incineration/CH U	Others
(Insert line here)	

Waste streams remaining after separation

Waste scenario/treatment	Percentage	Comm
Unspecified	100 %	

.

Figure 4.6: Modelling the End-of-Life Scenario for the A330-200 aircraft using the Simapro software.

4.2.4 Results Analysis

The results analysis consists basically on critically revise and validate the data that has been obtained, considering the goal and scope of the life cycle assessment of the product under study.

Although the majority of the material and weight data had its origins mostly on fully validated Airbus manuals, a validation procedure was undertook, in order to ensure the final data obtained was indeed correct. Being so, the final data obtained was revised by TAP engineers João Carrolo [49] and João Martins [50]. Moreover, a contact was established with Airbus Engineer François Museux [39]. This communication provided the official Airbus material breakdown for the A330-200, excluding landing gears and engines. In *Table* 4.9 the comparison between the official material breakdown from Airbus and the material breakdown obtained in this work (subtracting landing gears and engines contribution), is shown. This way, for the 'Obtained Breakdown' data, nickel weight was included under

		Aluminium	Steel	Composite	Titanium	Miscellaneous
Airbus Breakdown	in %	72	7	12	6	3
	Weight (in Kg)	59287	5873	10068	5034	2517
Obtained Breakdown	in %	72	7	12	6	3
	Weight (in Kg)	60318	5783	10189	4840	2769

Table 4.9: Comparison of the Airbus Material Breakdown with the obtained results.

the category 'Miscellaneous', and the material category 'Composites' is the sum of CFRP with GFRP. Thus, for comparison between the material breakdown of Airbus and the one obtained in this work, the material categories were matched, and a comparison was made feasible. It can be seen that in terms of weight percentage (aircraft weight without landing gears and engines), the two scenarios are the same in percentage, despite some differences in absolute weight values. These small differences in absolute weight values are not relevant comparing to the total aircraft weight, and are most likely due to the non-consideration of small aircraft components, mathematical rounding errors, and slightly erroneous estimations.

Being so, and taking into account the scope of this study, the favourable expertise opinions by TAP and Airbus engineers and the great similarity between the aircraft weight (see *Figure* 4.3) and material breakdown (*Figure* 4.4) obtained for this study and the values provided by Airbus, the data for material and weight composition of the A330-200 is then validated.

Chapter 5

Life Cycle Assessment Results for the A330-200 Aircraft

In *Chapter* 5 of this work, the results of the life cycle modelling described in *Chapter* 4 are shown and analysed. The results, standing as a part of the life cycle impact assessment phase of the LCA, were obtained with the Simapro software. In order to do so, environmental impact assessment methods had to be chosen. Firstly the ReCiPe Midpoint method was used, in order to give a general picture of the LCA results. Afterwards, three additional environmental assessment methods present in the Simapro software were used, namely ReCiPe Endpoint, Cumulative Energy Demand and Ecological Footprint, being that the description of these environmental impact assessment methods is given in *Section* 5.1. Thus, these additional choices were made after having the global picture provided by the ReCiPe midpoint method, and were chosen due to being especially suitable and useful in present case of this work.

Being so, the results obtained are shown, analysed and interpreted in *Section* 5.2. Finally, on *Section* 5.3 a uncertainty analysis is performed, comparing the results that have been obtained with optimist and pessimist perspectives, providing a final uncertainty range.

5.1 Environmental Impact Assessment Methods

Being that the Simapro software comprises different environmental impact assessment methods, after getting a first idea of each aircraft life cycle phase to the total environmental load, four methods were chosen (once more, the iterative nature of the LCA plays its part). Thus, the following methods were chosen:

1. ReCiPe Midpoint method, versions 1.04, specifically the ReCiPe Endpoint from the Hierarchist (H) perspective (see *Table* 5.1), with the Europe ReCiPe H/H normalisation/weighting set;
2. ReCiPe Endpoint method, version 1.04, specifically the ReCiPe Endpoint (H) perspective, with the Europe ReCiPe H/H normalisation/weighting set;
3. Cumulative Energy Demand, version 1.07;
4. Ecological footprint, version 1.01.

Next, a more detailed description of each method used is given.

Perspective of basishouding	Time perspective	Manageability	Required level of evidence
H (Hierarchist)	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
I (Individualist)	Short time	Technology can avoid many problems	Only proven effects
E (Egalitarian)	Very long term	Problems can lead to catastrophy	All possible effects

Table 5.1: Different perspectives in environmental assessment methods. (taken from [8])

ReCiPe

The ReCiPe LCIA method was recently created (in 2008) standing as an improvement and follow up of the Eco-indicator 99 and the CML 2002 environmental impact assessment methods. Thus, it has the objective of transforming the inventory results into a limited number of indicator scores, that serve as a quantification of the relative severity on an environmental impact category. ReCiPe enables to choose between using midpoint indicators or endpoint indicators. Being so, there are eighteen midpoints, relatively robust, but harder to interpret, and on the other hand there are three end points available (damage to human health, to ecosystems and to resource availability) more easily understood but more uncertain and subjective.

On *Figure* 5.1 the general structure of the ReCiPe method can be found, being that further information regarding this method can be found in [4]. In addition, the characterisation factors can be found in *Table* 5.2, which was adapted from [4]. For information regarding the characterisation factors, a spreadsheet is available on the ReCiPe website [www.lcia-recipe.net/].

This was used as the main environmental impact assessment method, due its wide utilisation among LCA practitioners and the fact that it is a recent and improved method.

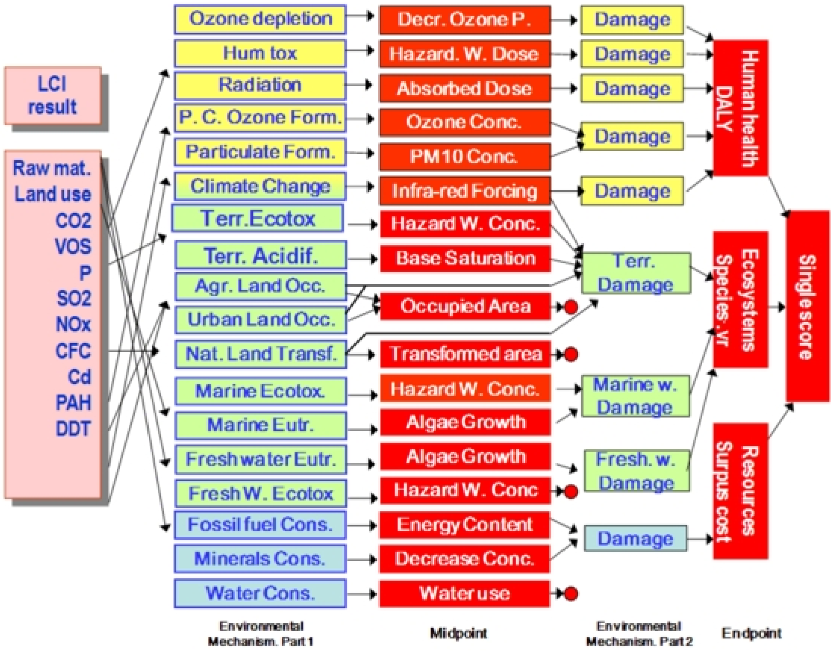
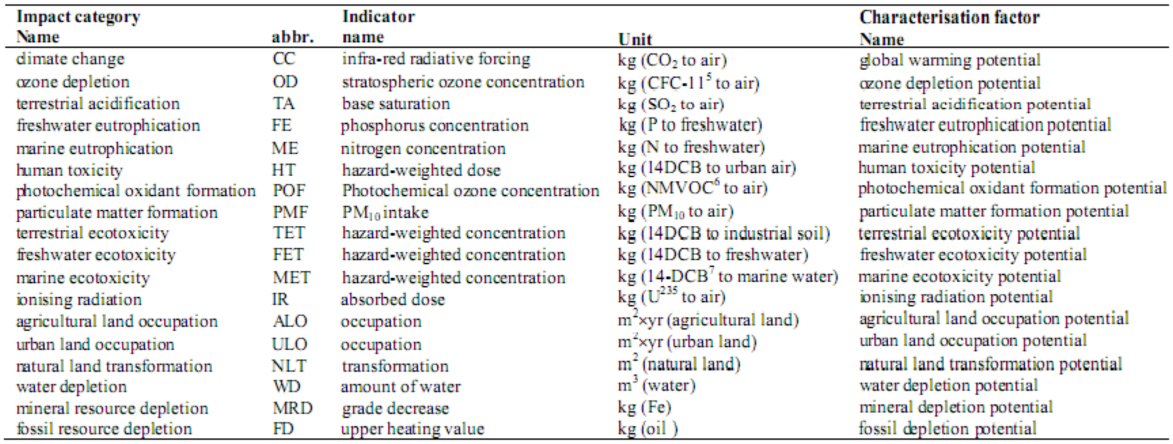


Figure 5.1: Structure and methodology of the ReCiPe environmental assessment method (source: [4])



Impact category Name	abbr.	Indicator name	Unit	Characterisation factor Name
climate change	CC	infra-red radiative forcing	kg (CO_2 to air)	global warming potential
ozone depletion	OD	stratospheric ozone concentration	kg (CFC-11[5] to air)	ozone depletion potential
terrestrial acidification	TA	base saturation	kg (SO_2 to air)	terrestrial acidification potential
freshwater eutrophication	FE	phosphorus concentration	kg (P to freshwater)	freshwater eutrophication potential
marine eutrophication	ME	nitrogen concentration	kg (N to freshwater)	marine eutrophication potential
human toxicity	HT	hazard-weighted dose	kg (14DCB to urban air)	human toxicity potential
photochemical oxidant formation	POF	Photochemical ozone concentration	kg (NMVOC[6] to air)	photochemical oxidant formation potential
particulate matter formation	PMF	PM_{10} intake	kg (PM_{10} to air)	particulate matter formation potential
terrestrial ecotoxicity	TET	hazard-weighted concentration	kg (14DCB to industrial soil)	terrestrial ecotoxicity potential
freshwater ecotoxicity	FET	hazard-weighted concentration	kg (14DCB to freshwater)	freshwater ecotoxicity potential
marine ecotoxicity	MET	hazard-weighted concentration	kg (14-DCB[7] to marine water)	marine ecotoxicity potential
ionising radiation	IR	absorbed dose	kg (U^{235} to air)	ionising radiation potential
agricultural land occupation	ALO	occupation	m^2xyr (agricultural land)	agricultural land occupation potential
urban land occupation	ULO	occupation	m^2xyr (urban land)	urban land occupation potential
natural land transformation	NLT	transformation	m^2 (natural land)	natural land transformation potential
water depletion	WD	amount of water	m^3 (water)	water depletion potential
mineral resource depletion	MRD	grade decrease	kg (Fe)	mineral depletion potential
fossil resource depletion	FD	upper heating value	kg (oil)	fossil depletion potential

Table 5.2: Overview of the midpoint categories and characterisation factors

Cumulative Energy Demand

The Cumulative Energy Demand (CED) is based on the method developed by the Research Institute for Energy in Munich, Germany, about ten years ago. Basically, cumulative energy demand is the total quantity of primary energy needed to produce, use, and dispose a product, including the transportation process. Being so, it reflects the total energy demand of the product throughout its life cycle, enabling the identification of the most energy-consuming phases.

This method was made available in the Simapro software based the method published by Ecoinvent v2.0 and expanded by PRé Consultants (the Simapro developers) for the energy resources available on the Simapro v.7 database. Furthermore, the characterization LCIA step is included, while the weighting step is used to show results by type of resource (each impact category is given a unitary weighting factor). Being so, the characterization factors for the energy sources are divided in five impact categories: Non renewable, fossil; Non renewable, nuclear; Renewable, biomass; Renewable, wind , solar geothermal; Renewable, water [54, 43].

In order to give a picture of the aircraft life cycle impact assessment in terms of energy demand, the Cumulative Energy Demand was used.

Ecological Footprint

The Ecological Footprint (EF) represents the biologically productive land and sea area that a human population requires in order to regenerate the resources it consumes, and to absorb part of the waste generated by fossil and nuclear fuel consumption. Being so, it is a measure of human demand on the Earth's ecosystems. In the context of LCA, the ecological footprint of a product is defined as the sum of time integrated direct and indirect land occupation, related to nuclear energy use and to CO_2 emissions from fossil energy use. The ecological footprint is then calculated according to:

$$EF = EF_{direct} + EF_{CO_2} + EF_{nuclear} \tag{5.1}$$

Moreover, in the Simapro Ecological Footprint method, normalization is not included, while each impact category is expressed in the same unit with a unitary weighting factor, except for the substance "Carbon dioxide" which is weighted with a 2.6722 factor regarding the impact category "carbon dioxide" [43].

5.2 Life Cycle Impact Assessment Results

After the environmental assessment methods have been briefly described, the results obtained will be shown in this *Section*. The Simapro allows the user to create a network, in which all processes are linked in a flow diagram. Due to the complexity of the aircraft, it is difficult to analyse such network with all the existing processes, and for that reason, this section is divided into three sections correspondent to the three cycles of the aircraft life: manufacturing phase, active life, and end-of-life scenario. For each of these life cycle phases, various environmental assessment methods have been used. However, in order to give a general idea of the network obtained for the whole life cycle, *Figure* 5.2 is shown. This network was acquired with the ReCiPe Midpoint method, for Climate change and the characterization step, which was used to give the first perspective of the results.

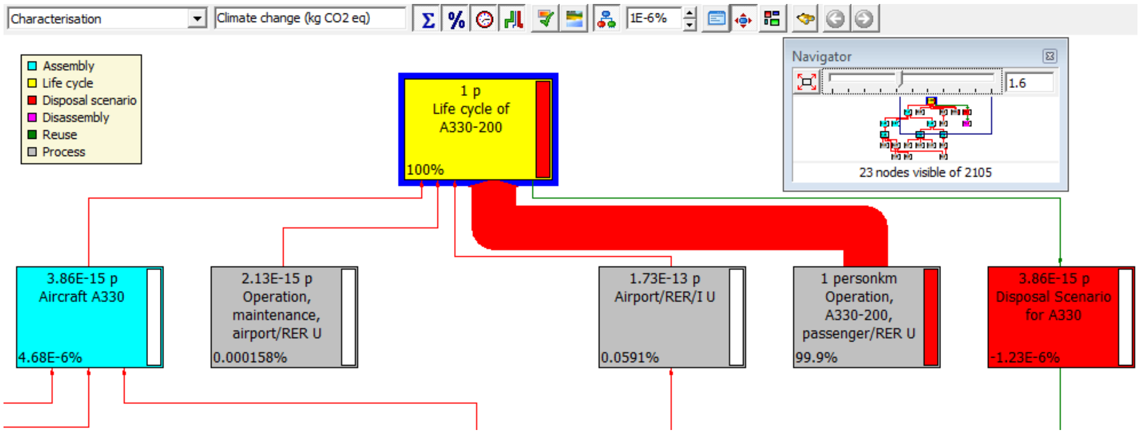
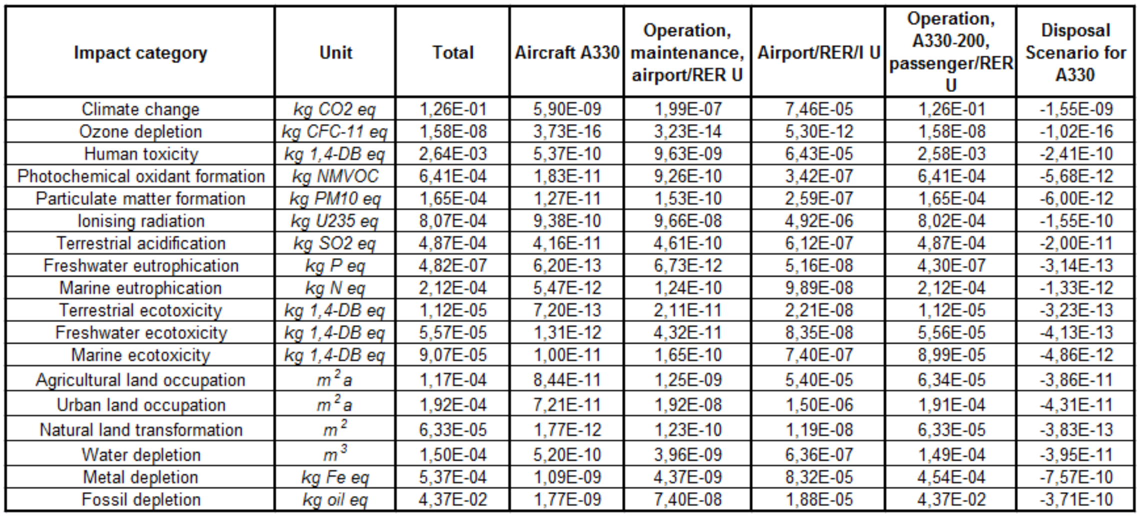


Figure 5.2: Network of the A330-200 aircraft life cycle obtained with the Simapro software, using the ReCiPe midpoint method, for the Climate Change environmental category.

In *Figure* 5.2 several information is shown, even though it may not be clear to those who are not familiar with the Simapro software. First, it can be seen that the cut-off has been set to 4×10^{-7}%, so that all life cycle phases could be seen, and only 38 nodes are visible, out of 2100, as shown on the Navigator window). The 'Navigator' window shows the network overview, in which a blue rectangle indicates the visible nodes. Moreover, a button has been selected (and will always be, for all the networks hereby displayed) to 'show flow indicator in line width', meaning that (for the environmental impact assessment method chosen) the width of the lines reflect environmental impact of the flow. Moreover, each box (see legend on the figure's left corner) indicates its contribution to the total environmental load in the bottom left corner of each box, which can be in given percentage or in absolute values, being that the vertical bar on the right side of the boxes also indicate such percentage. Finally, on the top of each box is the quantity concerning each box, which depends what the box represents (e. g., assemblies unit is 'part' - p).

It can be seen in *Figure* 5.2 that the operation life cycle, namely the fuel burn process ('$Operation, A330-200, passenger/RER\,U$') represents the majority of the aircraft environmental load (around 99,9%), completely dominating over the rest of the life cycle phases. Being so, the manufacturing phase is only responsible for 4.68×10^{-6}% of the total aircraft climate change impact, while the end-of-life scenario, modelled according to the Airbus PAMELA project, results in a positive contribution, taking 1.23×10^{-6}% out of the total impact. Using the Ecoinvent processes regarding Airport construction ($Airport/RER/I\,U$) and aircraft maintenance ($Operation$, $maintenance$, $airport/RER\,U$), it can be seen that their contribution is $5.91 \times 10^{-2}\%$ and$1.58 \times 10^{-4}\%$, respectively. Somewhat surprisingly, according to *Figure* 5.2 both these contributions contribute more to climate change than the manufacturing of the A330-200 aircraft, but still it should be mentioned that these Ecoinvent processes have a great uncertainty, namely regarding the expected life span of the airport, the flights frequency and travelled distance per flight, taking place at the airport.

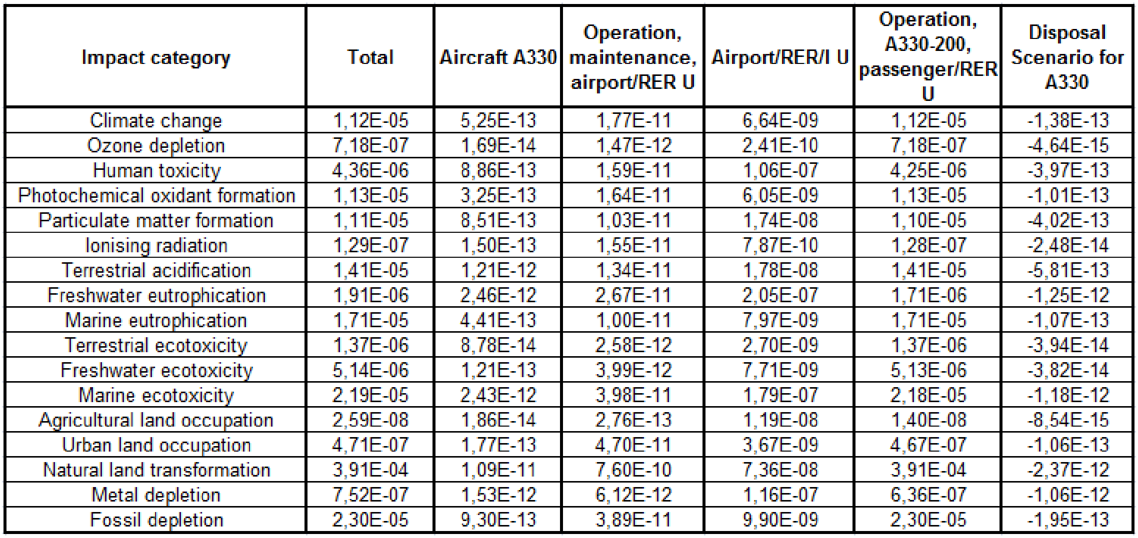


Impact category	Unit	Total	Aircraft A330	Operation, maintenance, airport/RER U	Airport/RER/I U	Operation, A330-200, passenger/RER U	Disposal Scenario for A330
Climate change	*kg CO2 eq*	1,26E-01	5,90E-09	1,99E-07	7,46E-05	1,26E-01	-1,55E-09
Ozone depletion	*kg CFC-11 eq*	1,58E-08	3,73E-16	3,23E-14	5,30E-12	1,58E-08	-1,02E-16
Human toxicity	*kg 1,4-DB eq*	2,64E-03	5,37E-10	9,63E-09	6,43E-05	2,58E-03	-2,41E-10
Photochemical oxidant formation	*kg NMVOC*	6,41E-04	1,83E-11	9,26E-10	3,42E-07	6,41E-04	-5,68E-12
Particulate matter formation	*kg PM10 eq*	1,65E-04	1,27E-11	1,53E-10	2,59E-07	1,65E-04	-6,00E-12
Ionising radiation	*kg U235 eq*	8,07E-04	9,38E-10	9,66E-08	4,92E-06	8,02E-04	-1,55E-10
Terrestrial acidification	*kg SO2 eq*	4,87E-04	4,16E-11	4,61E-10	6,12E-07	4,87E-04	-2,00E-11
Freshwater eutrophication	*kg P eq*	4,82E-07	6,20E-13	6,73E-12	5,16E-08	4,30E-07	-3,14E-13
Marine eutrophication	*kg N eq*	2,12E-04	5,47E-12	1,24E-10	9,89E-08	2,12E-04	-1,33E-12
Terrestrial ecotoxicity	*kg 1,4-DB eq*	1,12E-05	7,20E-13	2,11E-11	2,21E-08	1,12E-05	-3,23E-13
Freshwater ecotoxicity	*kg 1,4-DB eq*	5,57E-05	1,31E-12	4,32E-11	8,35E-08	5,56E-05	-4,13E-13
Marine ecotoxicity	*kg 1,4-DB eq*	9,07E-05	1,00E-11	1,65E-10	7,40E-07	8,99E-05	-4,86E-12
Agricultural land occupation	m^2a	1,17E-04	8,44E-11	1,25E-09	5,40E-05	6,34E-05	-3,86E-11
Urban land occupation	m^2a	1,92E-04	7,21E-11	1,92E-08	1,50E-06	1,91E-04	-4,31E-11
Natural land transformation	m^2	6,33E-05	1,77E-12	1,23E-10	1,19E-08	6,33E-05	-3,83E-13
Water depletion	m^3	1,50E-04	5,20E-10	3,96E-09	6,36E-07	1,49E-04	-3,95E-11
Metal depletion	*kg Fe eq*	5,37E-04	1,09E-09	4,37E-09	8,32E-05	4,54E-04	-7,57E-10
Fossil depletion	*kg oil eq*	4,37E-02	1,77E-09	7,40E-08	1,88E-05	4,37E-02	-3,71E-10

Table 5.3: Emission factors for the A330-200 aircraft Life cycle, using the ReCiPe Midpoint method (Characterisation results).

In *Table* 5.3 the emission factors are shown for all ReCiPe Midpoint impact categories, regarding the different life cycle phases of the aircraft. It can be noted that the operation phase remains the major responsible for the aircraft environmental impacts across all impact categories. Naturally, the '$Operation\,A330-200,\ passenger/RER\,U$' contribution comes almost entirely from the crude oil production process, across all environmental impact categories. Being so, it becomes evident that the fuel burn process, through its fuel consumption and atmospheric emissions, is by far the most environmental harmful process throughout the aircraft life cycle, a conclusion already predicted at the beginning of this work.

However, the construction of the airport plays an important role on four impact categories, namely 'Agricultural land occupation' (46% of the total life cycle phases contribution), 'Metal depletion' (15,5%), 'Freshwater eutrophication' (10.7%), and finally 'Human toxicity' (2.43%), being that this strong airport construction contribution is mainly due to the use of copper, except for 'Agricultural land occupation' (here, the contribution mainly comes from the use of sawn timber).



Impact category	Total	Aircraft A330	Operation, maintenance, airport/RER U	Airport/RER/I U	Operation, A330-200, passenger/RER U	Disposal Scenario for A330
Climate change	1,12E-05	5,25E-13	1,77E-11	6,64E-09	1,12E-05	-1,38E-13
Ozone depletion	7,18E-07	1,69E-14	1,47E-12	2,41E-10	7,18E-07	-4,64E-15
Human toxicity	4,36E-06	8,86E-13	1,59E-11	1,06E-07	4,25E-06	-3,97E-13
Photochemical oxidant formation	1,13E-05	3,25E-13	1,64E-11	6,05E-09	1,13E-05	-1,01E-13
Particulate matter formation	1,11E-05	8,51E-13	1,03E-11	1,74E-08	1,10E-05	-4,02E-13
Ionising radiation	1,29E-07	1,50E-13	1,55E-11	7,87E-10	1,28E-07	-2,48E-14
Terrestrial acidification	1,41E-05	1,21E-12	1,34E-11	1,78E-08	1,41E-05	-5,81E-13
Freshwater eutrophication	1,91E-06	2,46E-12	2,67E-11	2,05E-07	1,71E-06	-1,25E-12
Marine eutrophication	1,71E-05	4,41E-13	1,00E-11	7,97E-09	1,71E-05	-1,07E-13
Terrestrial ecotoxicity	1,37E-06	8,78E-14	2,58E-12	2,70E-09	1,37E-06	-3,94E-14
Freshwater ecotoxicity	5,14E-06	1,21E-13	3,99E-12	7,71E-09	5,13E-06	-3,82E-14
Marine ecotoxicity	2,19E-05	2,43E-12	3,98E-11	1,79E-07	2,18E-05	-1,18E-12
Agricultural land occupation	2,59E-08	1,86E-14	2,76E-13	1,19E-08	1,40E-08	-8,54E-15
Urban land occupation	4,71E-07	1,77E-13	4,70E-11	3,67E-09	4,67E-07	-1,06E-13
Natural land transformation	3,91E-04	1,09E-11	7,60E-10	7,36E-08	3,91E-04	-2,37E-12
Metal depletion	7,52E-07	1,53E-12	6,12E-12	1,16E-07	6,36E-07	-1,06E-12
Fossil depletion	2,30E-05	9,30E-13	3,89E-11	9,90E-09	2,30E-05	-1,95E-13

Table 5.4: Normalisation results for the A330-200 aircraft Life cycle, using the ReCiPe Midpoint method.

Analyzing *Table* 5.3 and the normalisation results of the aircraft impact assessment, in *Table* 5.4, an important conclusion arises: besides climate change, other environmental categories suffer significant impacts from the air transportation of passengers. However it should be clearly noted that the results of normalisation (for both midpoint and endpoint methods) increases the uncertainty level, lacking the same scientific basis than characterization. Thus, dividing the results from characterization with an average of the European citizen yearly environmental impact in each environmental category, the normalisation results are obtained, being that one should consider the limitations of such results.

As it has been said in *Section* 5.1, it can be insightful to measure the environmental impacts from a more tangible approach, using environmental damage categories, even though these methods are characterised by an inherent subjectivity and uncertainty. Being so, *Table* 5.5 is shown, which has the obtained results for the environmental damage assessment of the aircraft life cycle, using the ReCiPe Endpoint method. In this *Table* it can be seen that the fuel burn process remains the most harmful, and 'Particulate matter formation', Human toxicity', 'Natural land transformation' and 'Fossil depletion'. In addi-

Damage category	Unit	Total	Aircraft A330	Operation, maintenance, airport/RER U	Airport/RER/I U	Operation, A330-200, passenger/RER U	Disposal Scenario for A330
Climate change Human Health	DALY	1,77E-07	8,26E-15	2,79E-13	1,04E-10	1,76E-07	-2,17E-15
Ozone depletion	DALY	4,18E-11	8,19E-19	8,59E-17	1,32E-14	4,18E-11	-2,11E-19
Human toxicity	DALY	1,85E-09	3,76E-16	6,74E-15	4,51E-11	1,80E-09	-1,69E-16
Photochemical oxidant formation	DALY	2,50E-11	7,15E-19	3,61E-17	1,33E-14	2,50E-11	-2,21E-19
Particulate matter formation	DALY	4,29E-08	3,30E-15	3,98E-14	6,74E-11	4,28E-08	-1,56E-15
Ionising radiation	DALY	1,32E-11	1,54E-17	1,58E-15	8,07E-14	1,31E-11	-2,55E-18
Climate change Ecosystems	species.yr	1,00E-09	4,68E-17	1,58E-15	5,91E-13	9,99E-10	-1,23E-17
Terrestrial acidification	species.yr	2,83E-12	2,41E-19	2,68E-18	3,55E-15	2,82E-12	-1,16E-19
Freshwater eutrophication	species.yr	2,12E-14	2,72E-20	2,96E-19	2,27E-15	1,89E-14	-1,38E-20
Terrestrial ecotoxicity	species.yr	1,43E-12	9,14E-20	2,68E-18	2,81E-15	1,43E-12	-4,10E-20
Freshwater ecotoxicity	species.yr	1,45E-14	3,41E-22	1,12E-20	2,17E-17	1,45E-14	-1,07E-22
Marine ecotoxicity	species.yr	7,25E-17	8,03E-24	1,32E-22	5,93E-19	7,19E-17	-3,89E-24
Agricultural land occupation	species.yr	1,32E-12	9,46E-19	1,40E-17	6,06E-13	7,18E-13	-4,33E-19
Urban land occupation	species.yr	3,71E-12	1,39E-18	3,70E-16	2,89E-14	3,68E-12	-8,32E-19
Natural land transformation	species.yr	8,92E-11	2,87E-18	1,91E-16	1,72E-14	8,92E-11	-6,02E-19
Metal depletion	$	3,84E-05	7,80E-11	3,13E-10	5,94E-06	3,25E-05	-5,41E-11
Fossil depletion	$	7,03E-01	2,84E-08	1,19E-06	3,03E-04	7,02E-01	-5,97E-09

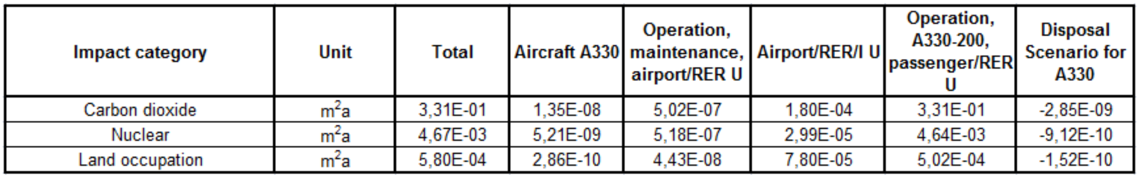
Table 5.5: Characterisation results of the life cycle impact assessment, using the ReCiPe Endpoint method.

Damage category	Unit	Total	Aircraft A330	Operation, maintenance, airport/RER U	Airport/RER/I U	Operation, A330-200, passenger/RER U	Disposal Scenario for A330
Non renewable, fossil	MJ eq	1,84E+00	7,43E-08	3,11E-06	7,91E-04	1,84E+00	-1,56E-08
Non-renewable, nuclear	MJ eq	2,38E-02	2,70E-08	2,65E-06	1,52E-04	2,37E-02	-4,67E-09
Non-renewable, biomass	MJ eq	2,49E-06	1,29E-13	2,50E-12	2,91E-09	2,48E-06	-4,07E-14
Renewable, biomass	MJ eq	1,13E-03	8,18E-10	2,77E-08	2,33E-04	8,98E-04	-4,91E-10
Renewable, wind, solar, geothe	MJ eq	4,40E-04	1,46E-10	8,25E-09	1,23E-06	4,39E-04	-4,49E-11
Renewable, water	MJ eq	2,87E-03	6,13E-09	4,80E-07	8,30E-05	2,78E-03	-3,13E-09

Table 5.6: Impact assessment of the A330-200 aircraft, using the Cumulative Energy Demand method, Characterisation.

tion to this, the manufacturing phase remains less harmful than the airport construction in every environmental category analysed here.

In order to have an idea of the aircraft life cycle energy demand, as usual with reference to the functional unit, the Cumulative Energy Demand [54] environmental assessment method was used (see *Section* 5.1). Thus, it is possible to have a generic idea of the different types of energy used throughout the aircraft life cycle, as well as the quantification of each energy type demand. The result obtained can be seen on *Table* 5.6. A simple calculation indicates that 99,8% of the energy used during the aircraft life cycle comes from non-renewable sources which comes from fossil fuels (fossil energy corresponds to 97,8% of the total non-renewable energy), whilst only 0,2% of the total energy demand has its origin on renewable sources of energy. This was to do with the fact that the aircraft fuel is



Impact category	Unit	Total	Aircraft A330	Operation, maintenance, airport/RER U	Airport/RER/I U	Operation, A330-200, passenger/RER U	Disposal Scenario for A330
Carbon dioxide	m^2a	3,31E-01	1,35E-08	5,02E-07	1,80E-04	3,31E-01	-2,85E-09
Nuclear	m^2a	4,67E-03	5,21E-09	5,18E-07	2,99E-05	4,64E-03	-9,12E-10
Land occupation	m^2a	5,80E-04	2,86E-10	4,43E-08	7,80E-05	5,02E-04	-1,52E-10

Table 5.7: Impact assessment of the A330-200 aircraft, using the Ecological Footprint method, Characterisation.

kerosene, which comes from a non-renewable fossil energy, crude oil, which dominates over the rest of the energy demands of the aircraft life cycle.

One last environmental impact assessment method has been used, the Ecological Footprint (see *Section* 5.1). Being so, the results shown on *Figure* 5.7 merely serve as a illustration of the life cycle impact. The Ecological Footprint has the advantage of assessing an impact through a more tangible measure, the necessary land area to compensate the environmental impact of the process under analysis. Thus, this method has become very popular, due to being easily understandable by laymen. However, the scientific nature of the method is questionable and the results presented should serve as merely an idea, lacking the accuracy and a full scientific basis. The most significant impact category is Carbon dioxide, which stand for 98.4% of the total impact. It should be noted that the carbon dioxide is a pollutant directly connected with global warming, a very discussed and relevant environmental concern. The ecological footprint of nuclear power[1] is 1.39%, being the contribution of land occupation is only 0.172%. Thus, the activities of the nuclear energy industry and the land occupation do not stand as a significant contribution compared to the total Ecological footprint of the aircraft life cycle.

The life cycle assessment can not only be used to evaluate the environmental impacts of a product and suggest improvements, but it can also be used to compare the environmental performance of different products, under the same functional unit. Being so, the environmental performance of the A330-200 aircraft over its life cycle was compared to different types of transportation, namely road and rail transportation of passengers. In order to accomplish such measurement, the processes $'Transport, passenger\, car/RER\, U'$ and $'Transport, long-distance\, train, SBB\, mix/CH\, U'$ were used, to account respectively for

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[1] The inclusion of nuclear energy is the Ecological Footprint has been under discussion by the scientific community, and a consensus has not yet been achieved. Yet, besides the fact that it seems to be taken out of the Ecological Footprint calculation, since the Simapro software accounts for the nuclear contribution, it was decided to remain present and discussed in this work.

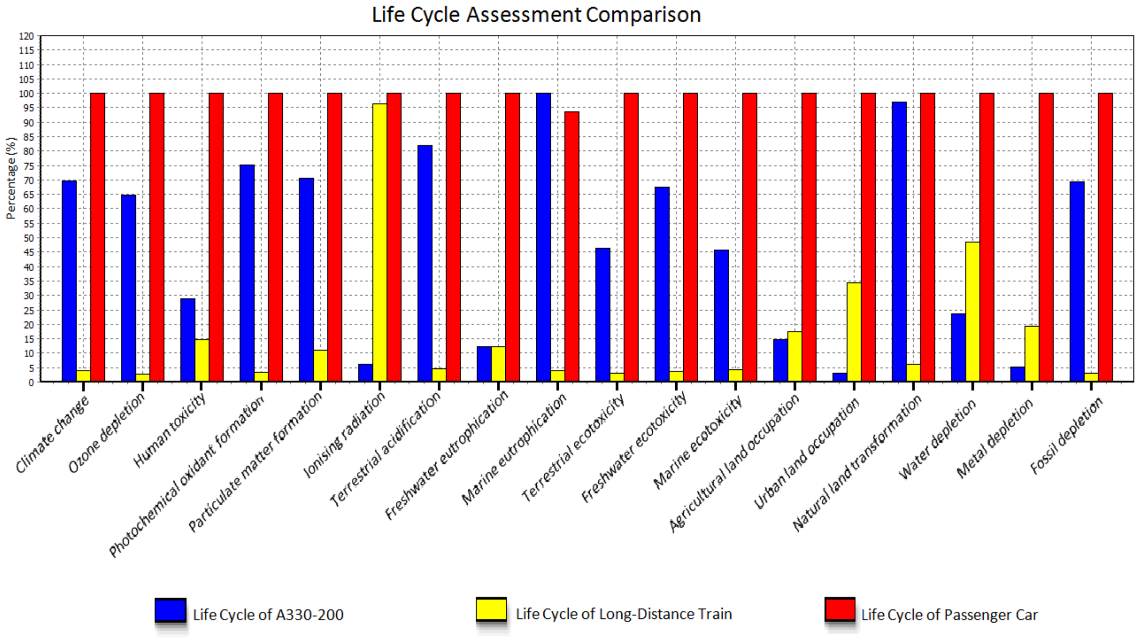


Figure 5.3: Comparison of the Life Cycle Impacts of three different types of transportation, using the ReCiPe Midpoint method (Characterisation).

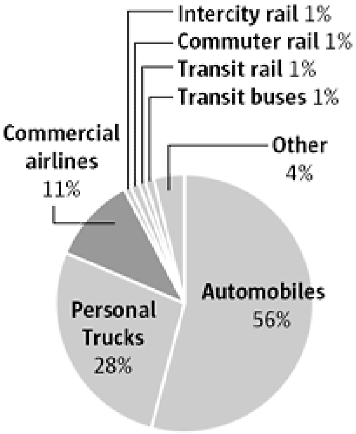
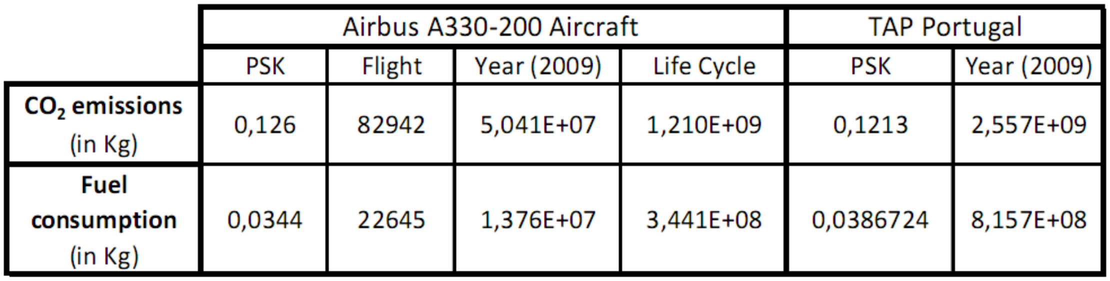


Figure 5.4: Different contributions of greenhouse gas emissions for the transportation sector in the U.S. (source: [5])

road and rail transportation. Being so, the results are shown on *Figure* 5.3, using the ReCiPe Midpoint method. Analysing this figure, the life cycle of the passenger car stands as the most environmental harmful process of all (except on Marine eutrophication), while the rail transportation of one passenger has the lowest impact on the environmental on most impact categories. Moreover, in terms of climate change, the passenger car emission factor is 0,181 $kg\,CO_2\,eq$, slightly more than the A330-200 aircraft (0,126 $kg\,CO_2\,eq$), and much more than the case of the long distance train (0,00704 $kg\,CO_2\,eq$). The transportation sector accounts for a big share of the total climate change impact of the anthropogenic activities, and it can be seen that the aviation environmental performance stands between the road and rail transportation sectors, as shown on *Figure* 5.4.

Finally, *Table* 5.8 shows some of the A330-200 aircraft LCA results regarding CO_2 emissions and fuel consumption were extrapolated to an average flight distance and to a whole year in operation (knowing the average number of flights per year), according to the confidential information provided by an airliner. Moreover, given the 24 years estimate of the aircraft life cycle, there were also results obtained for its life cycle. This way, the obtained results can be compared not only to other aircrafts, but also to any activity with a certain quantity of CO_2 emissions or fuel consumption. In addition, the TAP Sustainability report for 2009 [44] was also used to compare the values obtained for the A330-200 aircraft with the information released by TAP for the year 2009. Thus, it can be seen that the generic



	Airbus A330-200 Aircraft				TAP Portugal	
	PSK	Flight	Year (2009)	Life Cycle	PSK	Year (2009)
CO_2 emissions (in Kg)	0,126	82942	5,041E+07	1,210E+09	0,1213	2,557E+09
Fuel consumption (in Kg)	0,0344	22645	1,376E+07	3,441E+08	0,0386724	8,157E+08

Table 5.8: CO_2 emissions and fuel consumption for the A330-200 aircraft and the 'TAP Portugal' results, for 2009.

CO_2 emissions and fuel consumption per PSK, by the whole TAP fleet, are higher than the emissions and fuel consumption of the A330-200 aircraft, despite the values similarity. Also, knowing that the TAP fleet is composed of 55 aircrafts, one A330-200 aircraft corresponds to 1,81% (1/55, in percentage) of the airliner's fleet. Dividing the obtained yearly fuel consumption and CO_2 emissions results for TAP (in *Table* 5.8) with the annual results of TAP we have that the average contribution of one A330-200 aircraft is 1.69% for fuel consumption and 1.971% for CO_2 emissions. Thus, it can be concluded that the A330-200 aircraft, despite consuming less fuel than the average value for the TAP fleet, have higher CO_2 emissions than the TAP fleet average.

5.2.1 Manufacturing Phase of the A330-200 Aircraft

The manufacturing phase of the aircraft was the first to be modelled. Thus, the necessary data (see *Section* 4.2.2) was gathered in order to model the manufacturing of the aircraft, and then the data was inserted in Simapro, the software used to perform the LCA of the aircraft and model its life cycle. The data regarding the materials and respective weights in each component can be found on *Appendix B*, and components transportation to the final assembly line is given in *Table* 4.7.

In addition, the network for the A330-200 manufacturing phase can be found in *Figure* 5.5, using the ReCiPe Midpoint (H) method, being that the impacts (bottom left corner of boxes, in percentage) refer to *Single score*, expressed in *Pt*. It can be seen that the most important aircraft parts are the wings (35,9%), followed by the engines (27%) and the fuselage (19,5%). Moreover, the impact on climate change of CFRP stands as the most environmental harmful process of the manufacturing phase (56,6% in relation to the global processes contribution), despite being far less used that aluminium or steel (CFRP represents 9% of the aircraft weight; see *Figure* 4.4), that have a combined contribution of 21.6% to the total process contribution.

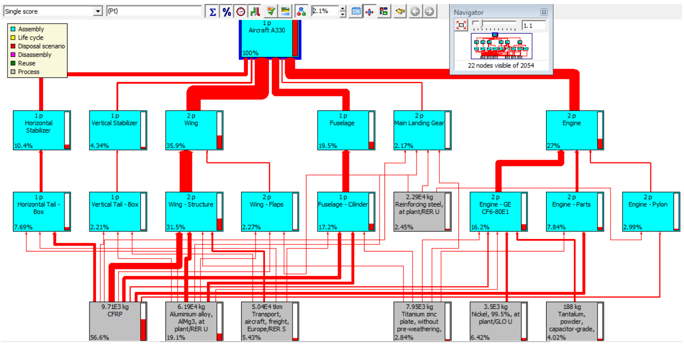
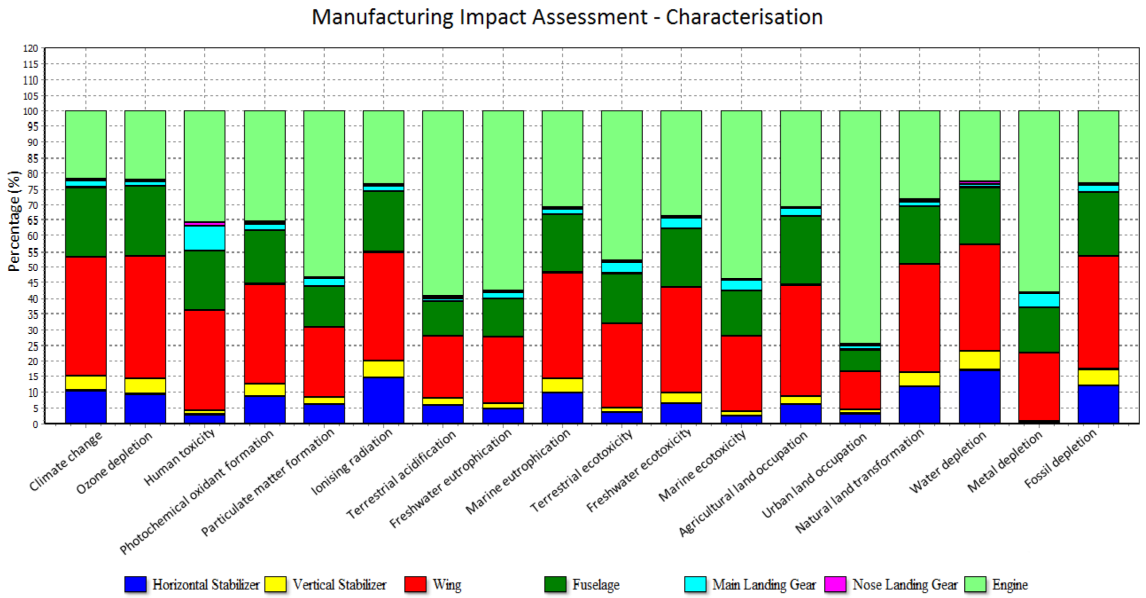


Figure 5.5: Manufacturing network model of the A330-200 aircraft, using Simapro through the ReCiPe Midpoint method, and

In *Figure* 5.6 we can see the contribution of each aircraft component manufacturing to different environmental impact categories, using the ReCiPe Midpoint method. Being so, despite representing only 17% of the total aircraft weight, the engine structure emerges as having the largest contribution for many environmental impact categories, such as particulate matter formation (53,5%), freshwater eutrophication (57,8%), marine ecotoxicity (54%), metal depletion (58,2%) and urban land occupation (75%). Analysing the contribution of the engine for each material, it was seen that the use of nickel endorses large environmental loads in several categories: 32,2% contribution (regarding all the manufacturing processes), for freshwater eutrophication; 34,7% for particulate matter formation; 31,2% for marine ecotoxicity. Moreover, another material responsible for great contributions in some environmental categories is tantalum, which in the case of 'urban land transformation' is responsible for 63,6% of the impact regarding all manufacturing processes. Thus, given the existence such environmental harmful materials in the engine as nickel and tantalum, it becomes clear the strong contribution of the engine structure to the total manufacturing environmental load. Moreover, apart from the engine itself, the pylons and other engine parts (fan cowl, thrust reverser, etc) do not have a significant part in comparison to the GE CF6-E1 engine.

The wing structure is also greatly responsible for manufacturing environmental impacts, whether sharing protagonist with the engine, namely in impact categories such as natural



Analysing 1 p 'Aircraft A330';
Method: ReCiPe Midpoint (H) V1.04 / Europe ReCiPe H / Characterisation / Excluding long-term emissions

Figure 5.6: Manufacturing impact assessment of the A330-200 aircraft, using the ReCiPe midpoint method, Characterization.

land transformation (34,9% for wing, 28,7% for engine), human toxicity (32 % for wing, 26% for engine), marine eutrophication (34% for wing, 31% for engine) and fossil depletion (37% for wing, 23% for engine), or standing as the most environmental harmful structure, as in climate change (39%), ozone depletion (40%) and fossil depletion (37%). In the case of climate change and fossil depletion, the wing strong contribution has its origin mainly on the use of CFRP and its inherent necessary electricity production in order to be manufactured (according to the Japanese electricity mix, in the Ecoinvent database).

Besides, the fuselage is responsible for an average of approximately 20% regarding most of the impact categories (it is mainly composed of aluminium, which has a low environmental impact compared to other materials in the aircraft). The horizontal stabilizer impact tends to vary between 14,5% (for ionising radiation) and 2,6% (for marine ecotoxicity) and the vertical stabilizer impact is even lower, varying between 5,6% (for ionising radiation) and 1,1% (for marine ecotoxicity). Regarding the main landing gear, its impact its also overall quite low despite being almost 10 times heavier than the vertical stabilizer (see *Figure* 4.3), representing only for the ionising radiation impact category, a contribution bigger than 5%. The reason main reason behind the main landing gear low impact is the fact that it is mainly made out of steel (*Table* 4.6), which is less environmental harmful than other materials in use (2,43% contribution to the total process contribution, according to *Figure* 5.5).

In *Figure* 5.6 the contribution of each aircraft component is visible for every environmental category, but however, it is important to know the importance of each category so that the manufacturing phase is properly analysed. In order to give such measure of each impact category importance, further LCIA steps were made (description in *Section* 3.3.3), and the results are shown in *Figure* 5.7, regarding normalisation using ReCiPe Midpoint method. In addition to this, the ReCiPe Endpoint method has also been used, in order to give a measure of the damage categories, in *Figure* 5.9 (characterization), *Figure* 5.10 (normalisation) and *Figure* 5.11 (single score). However, it should be remembered once again that the normalisation comprises significant uncertainties that should be taken into account, when Analysing the normalisation results. Moreover, the single score results for the endpoint method, being the output of a series of calculations with subjective and uncertain nature, merely provide an idea of the impacts in the three damage categories addressed in the ReCiPe Endpoint method. Moreover, even though the characterization for the midpoint and endpoint methods analyse basically the same impact categories, its calculation is performed through different environmental pathways that produce different results [4].

Being so, in *Figure* 5.7 the normalisation results are shown, using the ReCiPe Midpoint, being that the normalisation refers to the average yearly impact of an European citizen. This means, for the case of the category with the higher value, 'Natural land transformation', its total value indicates that the manufacturing of the A330-200 aircraft is equivalent to the Natural land transformation impact of 2850 European citizens during one year. Analysing the reasons behind this value, with the exception of the engine contribution, it was seen that it is due to the use of CFRP, which through the use of Japanese electricity production mix (60,2% to the total processes contribution), uses pipelines to transport natural gas, endorsing a strong natural land transformation impact (39% of the total processes contribution). In the case of the engine (28,6% of the total aircraft components contribution), its natural land transformation impact comes mainly (besides the use of CFRP) from the utilisation of tantalum (10,7% of the total processes contribution).

Still referring to the ReCiPe midpoint normalisation results, it is important to analyse with special detail the case of climate change. In order to do so, *Figure* 5.8 is shown,

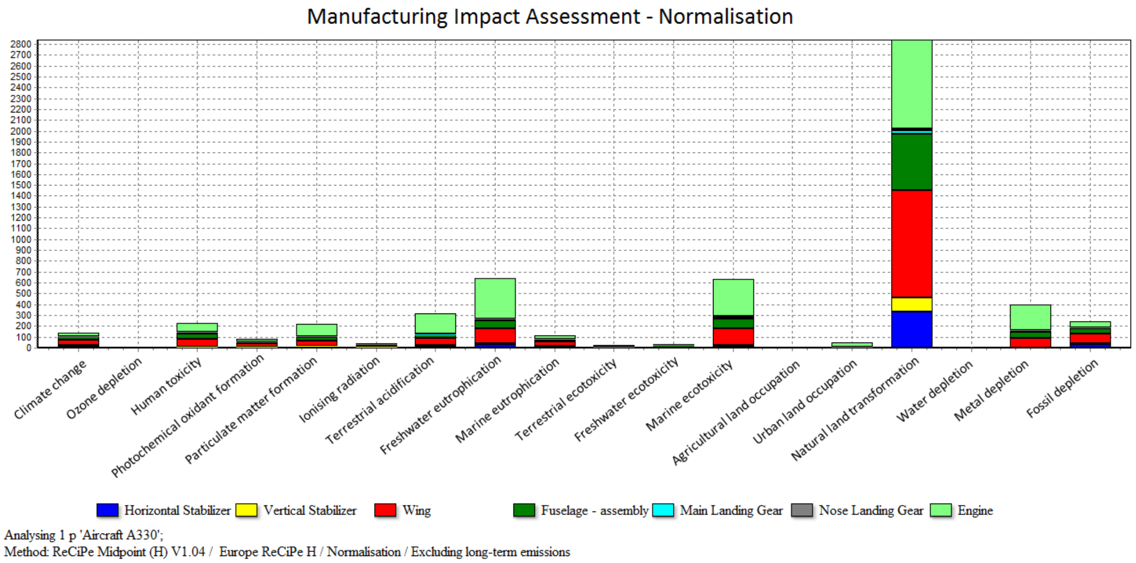


Figure 5.7: Manufacturing impact assessment of the A330-200 aircraft, using the ReCiPe midpoint method, Normalisation

which corresponds to the network of the aircraft manufacturing process, showing results for the climate change impact category, through the use of the ReCiPe Midpoint method. Being so, the CFRP is the process with the largest contribution to climate change (57,6% of the total process contribution), even though its use is far less than aluminium alloy or steel. The latter represents a surprising low contribution (2,16%) taking into account that it is the second most used material (see *Figure* 4.4 for information regarding the weight of each material used in the A330-200 aircraft). Being so, on *Figure* 5.8 it can be seen that the wing is the biggest contributor (38,6% of the total component contribution) to climate change, although it must be kept in mind that it is the heaviest component as well. This fact is also due to the wing being the component with the largest quantity of composites, namely CFRP (see *Table* 4.6). Moreover, the engine is composed of materials such as CFRP, tantalum and nickel that, despite not being used extensively compared to other components weights, are responsible for a great contribution to climate change. Thus, the engine structure is responsible for 21,9% of the total components contribution to climate change. Finally, and the analysis of the results using the ReCiPe Endpoint method that follows next, *Table* 5.9 shows the contribution of each aircraft component both in absolute and relative values. Furthermore, the values of $Kg\,CO_2\,eq$ can be compared to

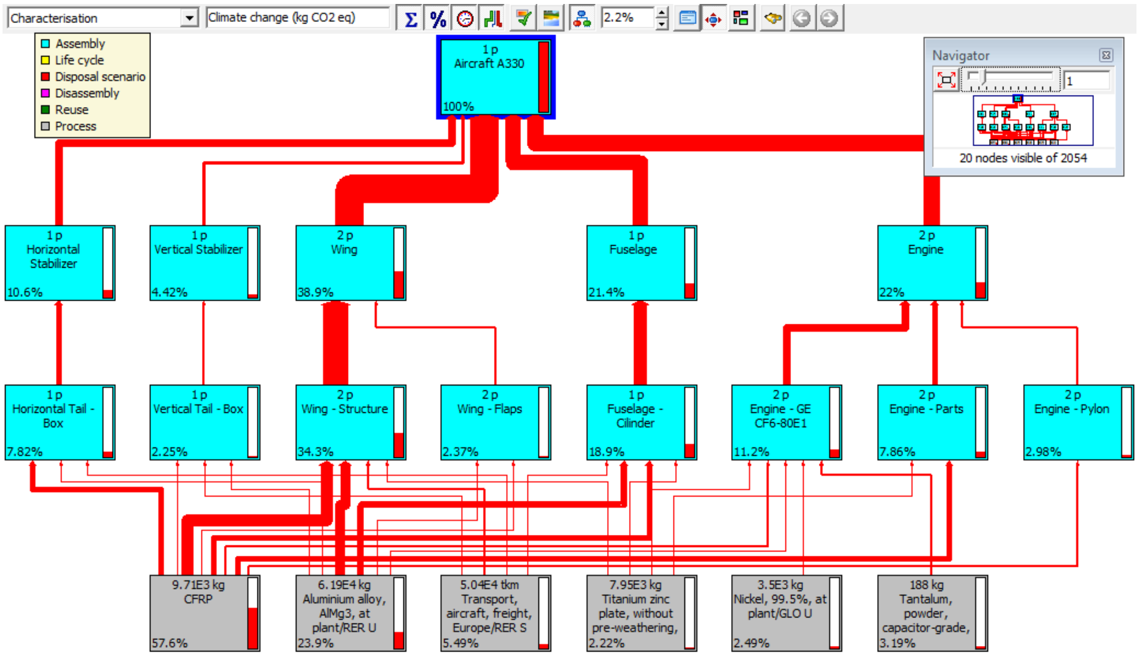


Figure 5.8: Manufacturing network model of the A330-200 aircraft, using Simapro through the ReCiPe Midpoint, with reference to the climate change impact category

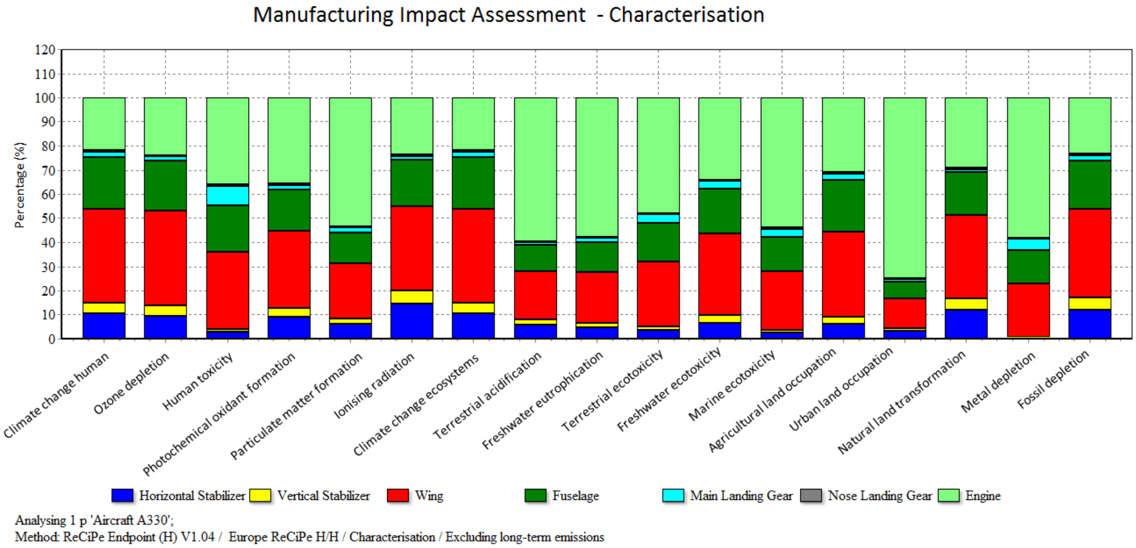
the manufacturing of other aircrafts, or any other process that for some reason should be compared to the manufacturing process of the A330-200 Airbus aircraft.

Using endpoint indicators have an increased uncertainty and subjectivity, but on the other hand provide a more understandable and tangible result, through a quantification of damage categories. In *Figure* 5.9 we can the characterisation for the manufacturing process, using the ReCiPe Endpoint method. Comparing this results with the characterisation using the midpoint method (*Figure* 5.6), it becomes clear that the results are basically the same, and that the impact categories are similar, yet with small differences. Namely, in the endpoint method the climate change category is divided into 'climate change human' and 'climate change ecosystem'.

The normalisation for the ReCiPe endpoint method is substantially different from what has been obtained with the midpoint method, and it is shown in *Figure* 5.10. Being so, there are four categories that emerge as the most important: climate change human, climate change ecosystems, particulate matter formation and fossil depletion.

		Horizontal Tail	Vertical Tail	Wing	Fuselage	MLG	NLG	Engines	Total
ReCiPe Midpoint Method	in $Kg\,CO_2\,eq$	$1,62\times10^5$	$6,73\times10^4$	$5,92\times10^5$	$3,39\times10^5$	$3,39\times10^4$	$9,13\times10^3$	$3,37\times10^5$	$1,54\times10^6$
	in percentage	10,5%	4,57%	38,6%	22%	2,03%	0,592%	21,9%	100%

Table 5.9: Life cycle impact assessment results for the impact category 'Climate Change', using the ReCiPe Midpoint method.


Manufacturing Impact Assessment - Characterisation

Analysing 1 p 'Aircraft A330';
Method: ReCiPe Endpoint (H) V1.04 / Europe ReCiPe H/H / Characterisation / Excluding long-term emissions

Figure 5.9: Manufacturing impact assessment of the A330-200 aircraft, using the ReCiPe endpoint method, Characterization.

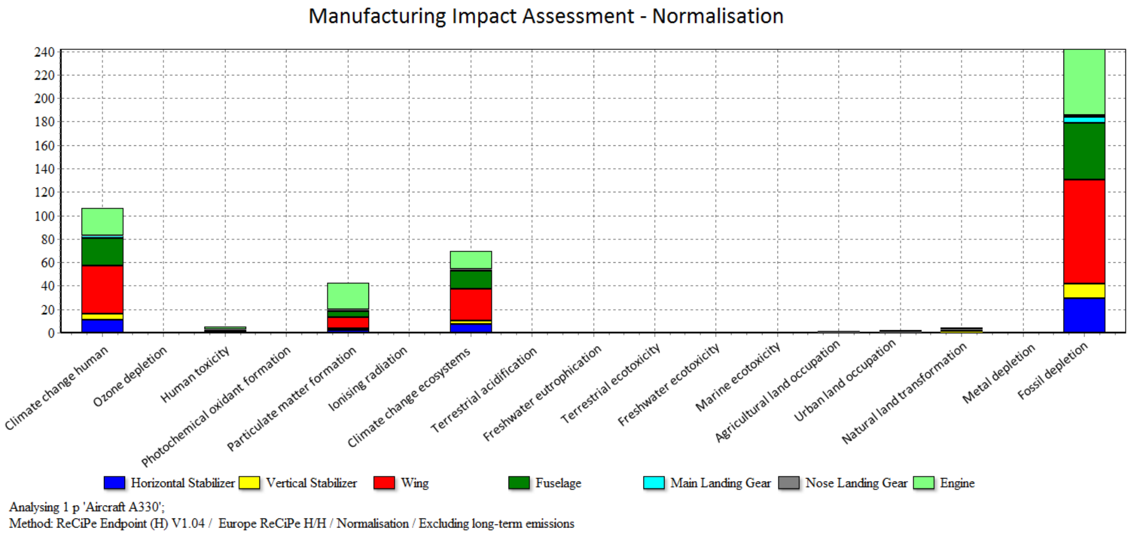
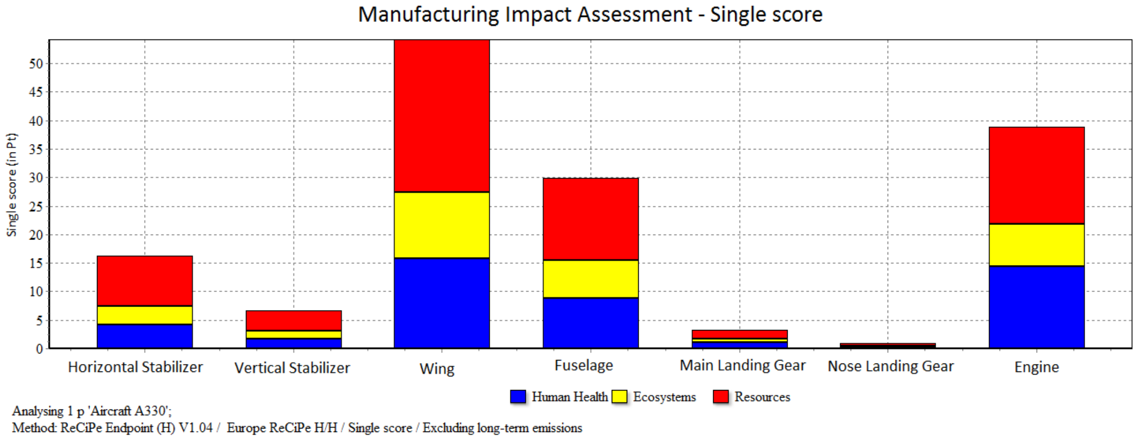


Figure 5.10: Manufacturing impact assessment of the A330-200 aircraft, using the ReCiPe endpoint method, Normalisation.

Thus, in *Figure* 5.10 it can be seen that (in comparison to the impact average of a European citizen during one year) the fossil depletion is the most affected damage category, mainly due to the wing (value of 88), engine (value of 56,5) and fuselage (48,1). Moreover, as expected the climate change to both humans and ecosystems emerge as very important categories, once more due to the wing, fuselage and engine contribution. Besides these three categories, only particulate matter formation stand has a significant impact category while the other only have residual values.

In order to analyse the contribution of each aircraft component on damage categories through endpoint indicators, *Figure* 5.11 is shown using single scores (in kPt). These single score values, as previously mentioned, has a highly subjective and uncertain nature, being that for instance, the weighting for each category greatly depends on what is regarded as a more important damage impact (which is subjective). It can be observed that the wing is indeed the most environmental harmful aircraft component (it is the heaviest aircraft part). Thus, wings impact on resources is the highest one, mainly due to fuel depletion (impact category), while its impact on ecosystems derives mainly from its Climate change on ecosystems and its impact on human health from Climate change affecting human health and the Particulate matter formation impact categories.

What may come is a surprise is the high contribution of the engine (second most harmful aircraft structure, according to the single score values), which represents only 17,3% of the aircraft total weight. As the rest of the aircraft components, its greater contribution is to the resources damage category, followed by damage to human health and lastly, damage to ecosystems. Another interesting result is the fact that the landing gears combined representing a small impact comparing to their weight (12,7% of the aircraft weight). As it can be identified in *Figure* 5.5, this is due to the fact that steel is the main material in its composition (see *Table* 4.6) and it has a small environmental impact in comparison to other materials in use. In fact, there is around 25100 *kg* of steel in the whole aircraft, representing a total of 2,43% of the total impact (in terms of processes), while for instance nickel represents 5,2% of the total impact, despite only around 3500 *kg* are used. This, along with the use of other materials such as tantalum, explain why the engine has a high impact/weight ratio.



Analysing 1 p 'Aircraft A330';
Method: ReCiPe Endpoint (H) V1.04 / Europe ReCiPe H/H / Single score / Excluding long-term emissions

Figure 5.11: Manufacturing impact assessment of the A330-200 aircraft, using the ReCiPe endpoint method, Single score.

5.3 Uncertainty Analysis

In order to perform an assessment of the uncertainties regarding the calculation of the values used to model the A330-200 aircraft life cycle, an uncertainty analysis has been performed. In order to do so, normal distributions were made, regarding the number of passengers per flight (standard deviation of 2234), the travelled distance per flight (standard deviation of 254 *nm*) and the number of flights per month (standard deviation of 51), and each of them

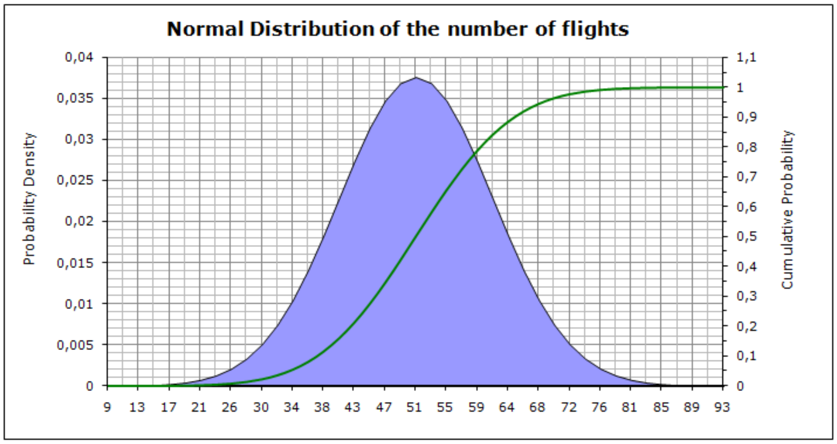


Figure 5.12: Normal distribution of the number of flights per month, for the entire airliner A330-200 fleet

are shown in *Figures* 5.14, 5.13 and 5.12.

Two scenarios have been characterized, Scenario 1 ('*sc*1') consists on a pessimist scenario, resulting in a higher fuel consumption, and Scenario 2 ('*sc*2'), modelled according to a more optimistic perspective. Thus, the average values of each distribution were used to model the aircraft life cycle, and the standard deviation for each distribution was subtracted or added to each average, depending on the scenario. A brief characterisation of each scenario is shown on *Table* 5.10, in which the operations performed are easily understood. According to the obtained fuel consumptions and the total number of passenger times the total travelled distance of the aircraft throughout its life cycle, these scenarios were inserted in the Simapro software. Being so, the modelling comprised also the difference in emissions to air between the case that had been modelled for this study, assuming a linear relation between the fuel consumption and the emissions to air.

	Number of pass.	Distance per flight (nm)	Flight count	Fuel consumption (kg/km)	Total pass.km
average	9477	3507	51	0,034383	2,6E+14
sc1	7242,5	3252,8	40,41	0,03551	1,5E+14
sc2	11711,5	3762	61,59	0,033469	4,2E+14

Table 5.10: Characterisation of the 'sc1' and 'sc2' scenarios.

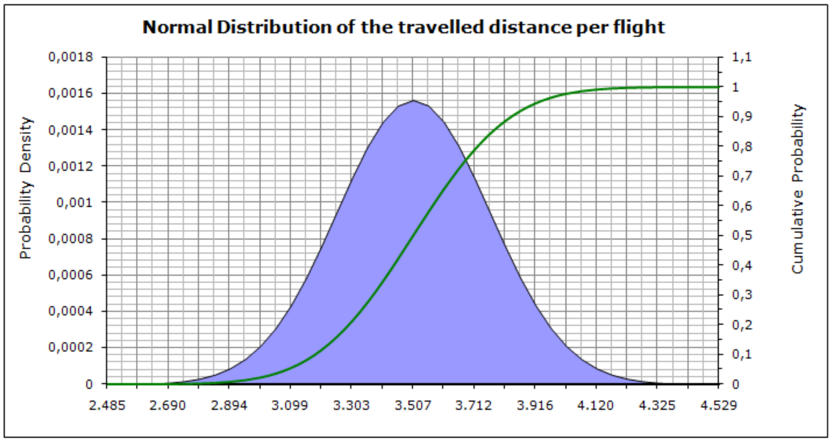


Figure 5.13: Normal distribution of the average travelled distance per flight during one year, for the entire airliner A330-200 fleet

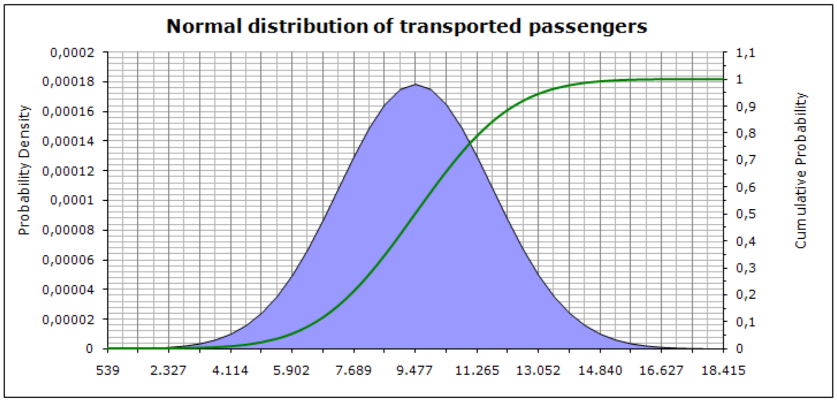
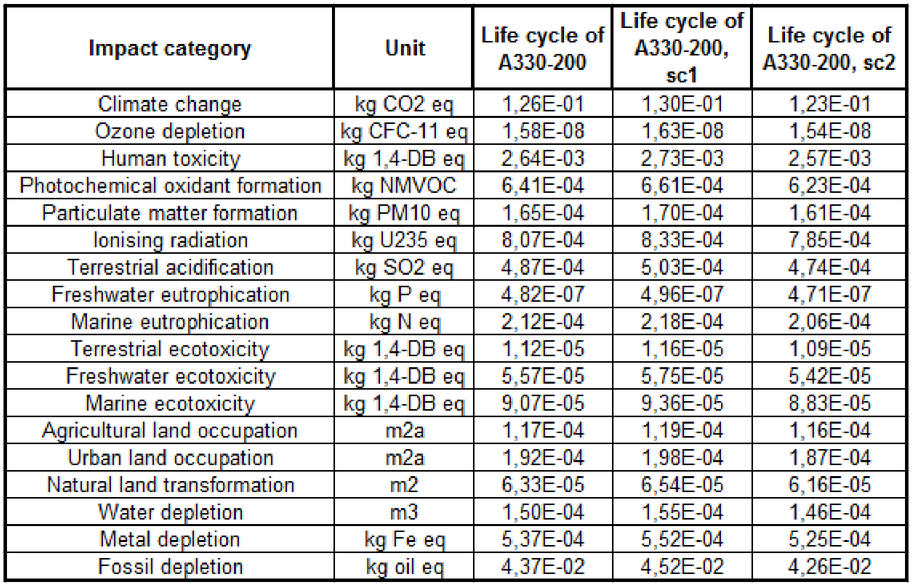


Figure 5.14: Normal distribution of the number of passengers during one year, for the entire airliner A330-200 fleet



Impact category	Unit	Life cycle of A330-200	Life cycle of A330-200, sc1	Life cycle of A330-200, sc2
Climate change	kg CO2 eq	1,26E-01	1,30E-01	1,23E-01
Ozone depletion	kg CFC-11 eq	1,58E-08	1,63E-08	1,54E-08
Human toxicity	kg 1,4-DB eq	2,64E-03	2,73E-03	2,57E-03
Photochemical oxidant formation	kg NMVOC	6,41E-04	6,61E-04	6,23E-04
Particulate matter formation	kg PM10 eq	1,65E-04	1,70E-04	1,61E-04
Ionising radiation	kg U235 eq	8,07E-04	8,33E-04	7,85E-04
Terrestrial acidification	kg SO2 eq	4,87E-04	5,03E-04	4,74E-04
Freshwater eutrophication	kg P eq	4,82E-07	4,96E-07	4,71E-07
Marine eutrophication	kg N eq	2,12E-04	2,18E-04	2,06E-04
Terrestrial ecotoxicity	kg 1,4-DB eq	1,12E-05	1,16E-05	1,09E-05
Freshwater ecotoxicity	kg 1,4-DB eq	5,57E-05	5,75E-05	5,42E-05
Marine ecotoxicity	kg 1,4-DB eq	9,07E-05	9,36E-05	8,83E-05
Agricultural land occupation	m2a	1,17E-04	1,19E-04	1,16E-04
Urban land occupation	m2a	1,92E-04	1,98E-04	1,87E-04
Natural land transformation	m2	6,33E-05	6,54E-05	6,16E-05
Water depletion	m3	1,50E-04	1,55E-04	1,46E-04
Metal depletion	kg Fe eq	5,37E-04	5,52E-04	5,25E-04
Fossil depletion	kg oil eq	4,37E-02	4,52E-02	4,26E-02

Table 5.11: Comparison between the life cycle impact assessment results for three different scenarios

The Simapro was then used to compare the total life cycle impact assessment results, using the ReCiPe Midpoint Method, and the results can be seen in *Table* 5.11. The results obtained are very satisfactory, being that for the climate change the uncertainty range is between -2.38% and 3.17%, regarding the 0,126 $KgCO_2$ used to model the aircraft in the previous *Subsections*.

Chapter 6

Conclusions and Future Work

This thesis was carried out in collaboration with the Portuguese company '3 Drivers - Inovação, Engenharia e Ambiente', and it consists in a Life Cycle Assessment (LCA) of the Airbus A330-200 aircraft, which is an evaluation of the environmental impacts of the aircraft over its life cycle. This study required a large amount of data, given the complexity of the aircraft itself, and all the processes inherent to the different life cycles phases of the aircraft, namely operational data. In order to gather such information, several visits to the Portuguese airliner 'TAP Portugal' took place, and many A330-200 manuals were provided. However, the aircraft manufacturing information required, weight and material composition of each aircraft component, was not given directly in any aircraft manual. Being so, the data from a weight description manual (Weight and Balance Manual) had to be matched with a material composition manual (Structure Repair Manual), which turned out to be a very laborious and time-consuming process. In the future, in order for life cycle assessments to be more easily and quickly performed, it is recommended that Airbus issues a manual in which the weight of every material that constitutes each aircraft structural component is clearly presented. In addition, if such manual contained also the transportation of the components to the final assembly line, and the energy inputs necessary to manufacture each aircraft component, the accuracy and reliability of the aircrafts LCA results would be further improved.

Being that it is nearly impossible to, during the time period in which this work was developed, account for all information and processes concerning the aircraft life cycle, this work made certain assumptions clearly described during this work. Moreover, given the extensive information regarding the manufacturing phase of the aircraft, this life cycle stage has been modelled with in much detail. Being so, the LCA results for the manufacturing phase, in *Chapter* 5, were carefully analysed, despite its environmental impact over the entire aircraft life cycle being very small compared to the operation phase. In addition, the manufacturing phase was given a special attention since the process of manufacturing an aircraft in the Ecoinvent database is very simple, comprising only two materials: aluminium and polyethylene. Thus, the manufacturing process modelled in this work can be used by LCA practitioners in the future, instead of the less realistic air transportation of passengers process present in the Ecoinvent Database.

In reference to the functional unit adopted ($passenger.km$), and accounting for the manufacturing, operation, and end-of-life phases of the A330-200 aircraft life cycle, it became clear that the fuel burn process is by far the most harmful process across all environmental categories analysed (approximately $99,9\%$ of the total process contribution to climate change). Somewhat surprisingly, the aircraft maintenance process and the airport construction (adapted from the processes in the Ecoinvent database) are both more significant ($1,58 \times 10^{-4}\%$ and $5,91 \times 10^{-2}\%$, respectively, for climate change), across all environmental impact categories analysed, than the manufacturing phase of the aircraft ($4,68 \times 10^{-6}\%$, for climate change). However, the interpretation of such result must take into account the assumptions and uncertainties of the adapted Ecoinvent processes used to model the aircraft maintenance and airport construction. In addition, the end-of-life scenario resulted in a negative contribution (environmental benefit) for all environmental categories, mainly due to the aluminium recycling process in the wings and fuselage, and to the re-use of the engine. Furthermore, a uncertainty analysis was performed, and resulted in a reasonable uncertainty rage of -2.38% to 3.17% regarding the CO_2 emission factor obtained (0,126 $Kg\,CO_2\,eq$) in the life cycle impact assessment results of the A330-200 aircraft.

Although climate change is the most discussed environmental category concerning the environmental concerns of aviation, other categories were analysed in order to have an idea of their importance. Being so, the research regarding the aviation impacts on the environment which has been performed and discussed throughout *Chapter* 2 clearly indicated that the impacts of carbon dioxide emissions and climate change have been extensively studied by the scientific community, and a good level of scientific knowledge has been achieved. However, other aviation environmental consequences must be further studied and accounted for. Thus, other environmental impact categories have proven to be relevant in the aircraft life cycle, such as Particulate matter formation and Human toxicity (see *Tables* 5.3, 5.4 and 5.5).

The life cycle assessment results for the manufacturing phase revealed that the most environmental harmful aircraft components are the wing (38,6% of the total components contribution to climate change), engines structure (21,9%) and fuselage (22%). In addition, Carbon Fiber Reinforced Plastic (CFRP) emerges as the larger material contributor to the total climate change of the manufacturing process (57,6%), even though it only represents around 9% of the aircraft total weight (see *Figure* 4.4), followed by aluminium alloy (24%), which is the most used material in the aircraft (58% of the total aircraft weight).

The disposal scenario of the aircraft was modelled according to the Airbus Project for Advanced Management of End of Life of Aircraft (PAMELA) results (see *Table* 4.8). Being so, the overall contribution of the end-of-life scenario is beneficial to the environment, mainly due to the contribution of the aluminium recycling (64.2% of the total benefit end-of-life contribution to climate change), being that the recycling of steel contribution is much smaller $(1,7\%)$. Moreover, in the aircraft disposal scenario, the wing has the highest beneficial contribution regarding climate change $(33,8\%$ of the total component contribution), followed by the engine (32.1%) and the fuselage $(26,8\%)$. Despite the very small contribution of the disposal scenario to the holistic aircraft environmental performance, Airbus has a budget of 3.242.694 *Euros* for the PAMELA project, given the fact that over 6000 aircrafts will be inoperative over the next 20 years [41]. This project by Airbus shows the importance of a life cycle approach when addressing the environmental performance of aircrafts, despite the end-of-life small contribution to environmental impacts.

Since the majority of the environmental impacts of the aircraft comes from the consumption of kerosene and its airborne emissions (fuel burn process), it becomes evident that the most effective way to improve aviation environmental performance is improve engine's CO_2 emissions, or using alternative fuels. The American airliner Boeing has estimated that mixing the kerosene with algae fuels could reduce the GHG emissions by 60 to 80 percent [5], and the International Air Transport Association (IATA) has set the goal for its members to use 10% alternative fuels by 2017 [55].

Thus, this work addressed the environmental concerns regarding the aviation sector, using the Life Cycle Assessment approach to analyse the environmental performance of the Airbus A330-200 aircraft.

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Appendix A

Life Cycle Inventory of the A330-220 Aircraft

Number	Category	Substance	Unit	Total
1	Raw material inputs	Air	kg	1,396E-09
2	Raw material inputs	Aluminium, 24% in bauxite, 11% in crude ore, in ground	kg	3,274E-06
3	Raw material inputs	Anhydrite, in ground	kg	1,023E-10
4	Raw material inputs	Barite, 15% in crude ore, in ground	kg	1,928E-04
5	Raw material inputs	Basalt, in ground	kg	1,389E-06
6	Raw material inputs	Biomass, feedstock	MJ	1,674E-18
7	Raw material inputs	Borax, in ground	kg	7,906E-11
8	Raw material inputs	Bromine, 0.0023% in water	kg	1,048E-11
9	Raw material inputs	Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	kg	6,499E-10
10	Raw material inputs	Calcite, in ground	kg	3,064E-04
11	Raw material inputs	Calcium chloride	kg	4,463E-22
12	Raw material inputs	Carbon dioxide, in air	kg	1,184E-04
13	Raw material inputs	Carbon, in organic matter, in soil	kg	3,587E-08
14	Raw material inputs	Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	kg	8,405E-07
15	Raw material inputs	Chromium, in ground	kg	3,594E-17
16	Raw material inputs	Chrysotile, in ground	kg	3,501E-10
17	Raw material inputs	Cinnabar, in ground	kg	3,257E-11
18	Raw material inputs	Clay, bentonite, in ground	kg	1,450E-05
19	Raw material inputs	Clay, unspecified, in ground	kg	1,508E-04
20	Raw material inputs	Coal, brown, in ground	kg	1,058E-03
21	Raw material inputs	Coal, hard, unspecified, in ground	kg	8,233E-04
22	Raw material inputs	Cobalt, in ground	kg	1,587E-11
23	Raw material inputs	Colemanite, in ground	kg	3,766E-09
24	Raw material inputs	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	kg	1,663E-07
25	Raw material inputs	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	kg	9,201E-07
26	Raw material inputs	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	kg	2,441E-07
27	Raw material inputs	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	kg	1,211E-06
28	Raw material inputs	Copper, in ground	kg	3,621E-16
29	Raw material inputs	Diatomite, in ground	kg	2,217E-13
30	Raw material inputs	Dolomite, in ground	kg	8,808E-07
31	Raw material inputs	Energy, from coal	MJ	1,690E-10
32	Raw material inputs	Energy, from coal, brown	MJ	1,050E-10
33	Raw material inputs	Energy, from gas, natural	MJ	1,896E-09
34	Raw material inputs	Energy, from oil	MJ	1,585E-09
35	Raw material inputs	Energy, from peat	MJ	1,602E-12
36	Raw material inputs	Energy, from uranium	MJ	3,701E-10
37	Raw material inputs	Energy, from wood	MJ	1,065E-14
38	Raw material inputs	Energy, geothermal, converted	MJ	1,841E-12
39	Raw material inputs	Energy, gross calorific value, in biomass	MJ	1,131E-03
40	Raw material inputs	Energy, gross calorific value, in biomass, primary forest	MJ	2,487E-06
41	Raw material inputs	Energy, kinetic (in wind), converted	MJ	4,336E-04
42	Raw material inputs	Energy, potential (in hydropower reservoir), converted	MJ	2,865E-03
43	Raw material inputs	Energy, solar, converted	MJ	6,252E-06
44	Raw material inputs	Feldspar, in ground	kg	1,090E-12
45	Raw material inputs	Fluorine, 4.5% in apatite, 1% in crude ore, in ground	kg	1,042E-07
46	Raw material inputs	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	kg	4,595E-08
47	Raw material inputs	Fluorspar, 92%, in ground	kg	3,016E-06
48	Raw material inputs	Gallium, 0.014% in bauxite, in ground	kg	1,772E-14

49	Raw material inputs	Gas, mine, off-gas, process, coal mining/m3	m3	8,037E-06
50	Raw material inputs	Gas, natural, in ground	m3	1,940E-03
51	Raw material inputs	Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	kg	5,510E-13
52	Raw material inputs	Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	kg	1,010E-12
53	Raw material inputs	Gold, Au 1.4E-4%, in ore, in ground	kg	1,210E-12
54	Raw material inputs	Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	kg	1,848E-12
55	Raw material inputs	Gold, Au 4.3E-4%, in ore, in ground	kg	4,580E-13
56	Raw material inputs	Gold, Au 4.9E-5%, in ore, in ground	kg	1,097E-12
57	Raw material inputs	Gold, Au 6.7E-4%, in ore, in ground	kg	1,698E-12
58	Raw material inputs	Gold, Au 7.1E-4%, in ore, in ground	kg	1,915E-12
59	Raw material inputs	Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	kg	1,147E-13
60	Raw material inputs	Gold, in ground	kg	1,659E-22
61	Raw material inputs	Granite, in ground	kg	2,060E-15
62	Raw material inputs	Gravel, in ground	kg	1,557E-03
63	Raw material inputs	Gypsum, in ground	kg	9,875E-10
64	Raw material inputs	Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground	kg	1,171E-11
65	Raw material inputs	Iodine, 0.03% in water	kg	3,864E-12
66	Raw material inputs	Iron, 46% in ore, 25% in crude ore, in ground	kg	3,036E-04
67	Raw material inputs	Kaolinite, 24% in crude ore, in ground	kg	1,136E-08
68	Raw material inputs	Kieserite, 25% in crude ore, in ground	kg	7,908E-11
69	Raw material inputs	Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	kg	1,183E-07
70	Raw material inputs	Lead, in ground	kg	3,799E-15
71	Raw material inputs	Lithium, 0.15% in brine, in ground	kg	1,038E-14
72	Raw material inputs	Magnesite, 60% in crude ore, in ground	kg	3,966E-06
73	Raw material inputs	Magnesium chloride	kg	1,811E-13
74	Raw material inputs	Magnesium, 0.13% in water	kg	4,371E-11
75	Raw material inputs	Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore,	kg	3,523E-07
76	Raw material inputs	Manganese, in ground	kg	4,173E-16
77	Raw material inputs	Metamorphous rock, graphite containing, in ground	kg	4,754E-09
78	Raw material inputs	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	kg	2,250E-08
79	Raw material inputs	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	kg	3,206E-09
80	Raw material inputs	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	kg	5,810E-09
81	Raw material inputs	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	kg	1,175E-08
82	Raw material inputs	Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	kg	1,172E-08
83	Raw material inputs	Molybdenum, in ground	kg	5,690E-19
84	Raw material inputs	Natural aggregate	kg	4,437E-13
85	Raw material inputs	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in	kg	3,561E-09
86	Raw material inputs	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	kg	4,404E-06
87	Raw material inputs	Nickel, in ground	kg	6,792E-17
88	Raw material inputs	Nitrogen, in air	kg	3,456E-20
89	Raw material inputs	Occupation, arable, non-irrigated	m2a	2,456E-07
90	Raw material inputs	Occupation, construction site	m2a	4,362E-06
91	Raw material inputs	Occupation, dump site	m2a	5,620E-06
92	Raw material inputs	Occupation, dump site, benthos	m2a	1,418E-05
93	Raw material inputs	Occupation, forest, intensive	m2a	1,371E-06
94	Raw material inputs	Occupation, forest, intensive, normal	m2a	1,141E-04
95	Raw material inputs	Occupation, forest, intensive, short-cycle	m2a	6,238E-07

96	Raw material inputs	Occupation, industrial area	m2a	1,188E-04
97	Raw material inputs	Occupation, industrial area, benthos	m2a	1,088E-07
98	Raw material inputs	Occupation, industrial area, built up	m2a	4,694E-06
99	Raw material inputs	Occupation, industrial area, vegetation	m2a	2,891E-06
100	Raw material inputs	Occupation, mineral extraction site	m2a	1,057E-05
101	Raw material inputs	Occupation, permanent crop, fruit, intensive	m2a	8,966E-07
102	Raw material inputs	Occupation, shrub land, sclerophyllous	m2a	1,440E-07
103	Raw material inputs	Occupation, traffic area, rail embankment	m2a	1,322E-06
104	Raw material inputs	Occupation, traffic area, rail network	m2a	1,462E-06
105	Raw material inputs	Occupation, traffic area, road embankment	m2a	1,454E-06
106	Raw material inputs	Occupation, traffic area, road network	m2a	2,672E-05
107	Raw material inputs	Occupation, urban, discontinuously built	m2a	3,601E-09
108	Raw material inputs	Occupation, water bodies, artificial	m2a	1,126E-05
109	Raw material inputs	Occupation, water courses, artificial	m2a	1,099E-05
110	Raw material inputs	Oil, crude, in ground	kg	3,793E-02
111	Raw material inputs	Olivine, in ground	kg	3,600E-11
112	Raw material inputs	Oxygen, in air	kg	-4,959E-13
113	Raw material inputs	Palladium, in ground	kg	5,656E-23
114	Raw material inputs	Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	4,734E-11
115	Raw material inputs	Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	1,138E-10
116	Raw material inputs	Peat, in ground	kg	1,192E-08
117	Raw material inputs	Phosphorus, 18% in apatite, 12% in crude ore, in ground	kg	1,833E-07
118	Raw material inputs	Phosphorus, 18% in apatite, 4% in crude ore, in ground	kg	4,167E-07
119	Raw material inputs	Phosphorus, in ground	kg	3,513E-18
120	Raw material inputs	Platinum, in ground	kg	6,795E-22
121	Raw material inputs	Potassium chloride	kg	6,289E-20
122	Raw material inputs	Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	1,134E-12
123	Raw material inputs	Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	4,067E-12
124	Raw material inputs	Pumice, in ground	kg	4,368E-18
125	Raw material inputs	Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	1,087E-12
126	Raw material inputs	Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	3,403E-12
127	Raw material inputs	Rhenium, in crude ore, in ground	kg	1,530E-12
128	Raw material inputs	Sand, unspecified, in ground	kg	1,007E-08
129	Raw material inputs	Shale, in ground	kg	2,895E-10
130	Raw material inputs	Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	kg	1,409E-11
131	Raw material inputs	Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore, in	kg	1,008E-11
132	Raw material inputs	Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	kg	9,286E-13
133	Raw material inputs	Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	kg	2,121E-12
134	Raw material inputs	Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	kg	2,079E-12
135	Raw material inputs	Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	kg	1,372E-12
136	Raw material inputs	Silver, in ground	kg	2,854E-20
137	Raw material inputs	Slate, in ground	kg	3,934E-25
138	Raw material inputs	Sodium chloride, in ground	kg	2,338E-05
139	Raw material inputs	Sodium nitrate, in ground	kg	5,686E-15
140	Raw material inputs	Sodium sulphate, various forms, in ground	kg	8,647E-07
141	Raw material inputs	Soil, unspecified, in ground	kg	1,865E-13

142	Raw material inputs	Stibnite, in ground	kg	2,304E-14
143	Raw material inputs	Sulfur, in ground	kg	4,157E-09
144	Raw material inputs	Sylvite, 25 % in sylvinite, in ground	kg	2,697E-08
145	Raw material inputs	Talc, in ground	kg	1,200E-09
146	Raw material inputs	Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground	kg	1,115E-11
147	Raw material inputs	Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground	kg	1,512E-12
148	Raw material inputs	Tin, 79% in cassiterite, 0.1% in crude ore, in ground	kg	1,029E-09
149	Raw material inputs	Tin, in ground	kg	3,781E-28
150	Raw material inputs	TiO2, 54% in ilmenite, 2.6% in crude ore, in ground	kg	1,729E-06
151	Raw material inputs	TiO2, 95% in rutile, 0.40% in crude ore, in ground	kg	3,882E-13
152	Raw material inputs	Titanium, in ground	kg	1,419E-16
153	Raw material inputs	Transformation, from arable	m2	3,425E-09
154	Raw material inputs	Transformation, from arable, non-irrigated	m2	4,538E-07
155	Raw material inputs	Transformation, from arable, non-irrigated, fallow	m2	3,972E-10
156	Raw material inputs	Transformation, from dump site, inert material landfill	m2	1,478E-08
157	Raw material inputs	Transformation, from dump site, residual material landfill	m2	1,319E-08
158	Raw material inputs	Transformation, from dump site, sanitary landfill	m2	7,168E-10
159	Raw material inputs	Transformation, from dump site, slag compartment	m2	8,854E-11
160	Raw material inputs	Transformation, from forest	m2	4,875E-05
161	Raw material inputs	Transformation, from forest, extensive	m2	9,127E-07
162	Raw material inputs	Transformation, from forest, intensive, clear-cutting	m2	2,228E-08
163	Raw material inputs	Transformation, from industrial area	m2	1,992E-08
164	Raw material inputs	Transformation, from industrial area, benthos	m2	9,240E-12
165	Raw material inputs	Transformation, from industrial area, built up	m2	1,487E-10
166	Raw material inputs	Transformation, from industrial area, vegetation	m2	2,537E-10
167	Raw material inputs	Transformation, from mineral extraction site	m2	6,584E-08
168	Raw material inputs	Transformation, from pasture and meadow	m2	8,057E-08
169	Raw material inputs	Transformation, from pasture and meadow, intensive	m2	3,703E-10
170	Raw material inputs	Transformation, from sea and ocean	m2	1,418E-05
171	Raw material inputs	Transformation, from shrub land, sclerophyllous	m2	4,268E-08
172	Raw material inputs	Transformation, from tropical rain forest	m2	2,228E-08
173	Raw material inputs	Transformation, from unknown	m2	1,000E-06
174	Raw material inputs	Transformation, to arable	m2	6,490E-08
175	Raw material inputs	Transformation, to arable, non-irrigated	m2	4,541E-07
176	Raw material inputs	Transformation, to arable, non-irrigated, fallow	m2	9,820E-10
177	Raw material inputs	Transformation, to dump site	m2	4,168E-08
178	Raw material inputs	Transformation, to dump site, benthos	m2	1,418E-05
179	Raw material inputs	Transformation, to dump site, inert material landfill	m2	1,478E-08
180	Raw material inputs	Transformation, to dump site, residual material landfill	m2	1,319E-08
181	Raw material inputs	Transformation, to dump site, sanitary landfill	m2	7,168E-10
182	Raw material inputs	Transformation, to dump site, slag compartment	m2	8,854E-11
183	Raw material inputs	Transformation, to forest	m2	4,201E-08
184	Raw material inputs	Transformation, to forest, intensive	m2	9,132E-09
185	Raw material inputs	Transformation, to forest, intensive, clear-cutting	m2	2,228E-08
186	Raw material inputs	Transformation, to forest, intensive, normal	m2	8,818E-07
187	Raw material inputs	Transformation, to forest, intensive, short-cycle	m2	2,228E-08
188	Raw material inputs	Transformation, to heterogeneous, agricultural	m2	2,267E-06
189	Raw material inputs	Transformation, to industrial area	m2	9,686E-08
190	Raw material inputs	Transformation, to industrial area, benthos	m2	4,743E-09
191	Raw material inputs	Transformation, to industrial area, built up	m2	1,253E-07
192	Raw material inputs	Transformation, to industrial area, vegetation	m2	8,989E-08
193	Raw material inputs	Transformation, to mineral extraction site	m2	4,667E-05

194	Raw material inputs	Transformation, to pasture and meadow	m2	3,102E-09
195	Raw material inputs	Transformation, to permanent crop, fruit, intensive	m2	1,262E-08
196	Raw material inputs	Transformation, to sea and ocean	m2	9,240E-12
197	Raw material inputs	Transformation, to shrub land, sclerophyllous	m2	2,877E-08
198	Raw material inputs	Transformation, to traffic area, rail embankment	m2	3,076E-09
199	Raw material inputs	Transformation, to traffic area, rail network	m2	3,381E-09
200	Raw material inputs	Transformation, to traffic area, road embankment	m2	9,633E-09
201	Raw material inputs	Transformation, to traffic area, road network	m2	3,054E-07
202	Raw material inputs	Transformation, to unknown	m2	2,408E-08
203	Raw material inputs	Transformation, to urban, discontinuously built	m2	7,173E-11
204	Raw material inputs	Transformation, to water bodies, artificial	m2	1,033E-07
205	Raw material inputs	Transformation, to water courses, artificial	m2	1,019E-07
206	Raw material inputs	Ulexite, in ground	kg	7,948E-10
207	Raw material inputs	Uranium, in ground	kg	4,253E-08
208	Raw material inputs	Vermiculite, in ground	kg	1,892E-10
209	Raw material inputs	Volume occupied, final repository for low-active radioactive	m3	8,761E-11
210	Raw material inputs	Volume occupied, final repository for radioactive waste	m3	2,213E-11
211	Raw material inputs	Volume occupied, reservoir	m3y	5,084E-05
212	Raw material inputs	Volume occupied, underground deposit	m3	4,217E-10
213	Raw material inputs	Water, cooling, unspecified natural origin/m3	m3	2,500E-04
214	Raw material inputs	Water, lake	m3	1,991E-07
215	Raw material inputs	Water, river	m3	4,592E-05
216	Raw material inputs	Water, salt, ocean	m3	1,458E-05
217	Raw material inputs	Water, salt, sole	m3	3,011E-05
218	Raw material inputs	Water, turbine use, unspecified natural origin	m3	2,344E-02
219	Raw material inputs	Water, unspecified natural origin/kg	kg	2,427E-10
220	Raw material inputs	Water, unspecified natural origin/m3	m3	9,699E-05
221	Raw material inputs	Water, well, in ground	m3	6,823E-06
222	Raw material inputs	Wood, hard, standing	m3	2,667E-08
223	Raw material inputs	Wood, primary forest, standing	m3	2,307E-10
224	Raw material inputs	Wood, soft, standing	m3	8,302E-08
225	Raw material inputs	Wood, unspecified, standing/m3	m3	8,335E-13
226	Raw material inputs	Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	kg	6,830E-07
227	Raw material inputs	Zinc, in ground	kg	9,995E-16
228	Raw material inputs	Zirconium, 50% in zircon, 0.39% in crude ore, in ground	kg	1,337E-11
229	Releases to air	1-Butanol	kg	7,062E-16
230	Releases to air	1-Pentanol	kg	1,962E-16
231	Releases to air	1-Pentene	kg	1,483E-16
232	Releases to air	1-Propanol	kg	8,510E-14
233	Releases to air	1,4-Butanediol	kg	7,831E-15
234	Releases to air	2-Aminopropanol	kg	6,138E-17
235	Releases to air	2-Butene, 2-methyl-	kg	3,289E-20
236	Releases to air	2-Methyl-1-propanol	kg	9,393E-16
237	Releases to air	2-Nitrobenzoic acid	kg	1,098E-16
238	Releases to air	2-Propanol	kg	5,977E-11
239	Releases to air	Acenaphthene	kg	7,384E-15
240	Releases to air	Acetaldehyde	kg	1,747E-09
241	Releases to air	Acetic acid	kg	1,671E-08
242	Releases to air	Acetone	kg	1,841E-09
243	Releases to air	Acetonitrile	kg	2,422E-11
244	Releases to air	Acidity, unspecified	kg	1,580E-20
245	Releases to air	Acrolein	kg	3,445E-12
246	Releases to air	Acrylic acid	kg	1,550E-13

247	Releases to air	Acrylonitrile	kg	8,286E-17
248	Releases to air	Actinides, radioactive, unspecified	Bq	7,382E-07
249	Releases to air	Aerosols, radioactive, unspecified	Bq	1,861E-05
250	Releases to air	Aldehydes, unspecified	kg	1,213E-10
251	Releases to air	Aluminium	kg	1,519E-07
252	Releases to air	Ammonia	kg	2,925E-07
253	Releases to air	Ammonium carbonate	kg	2,479E-12
254	Releases to air	Ammonium, ion	kg	6,429E-22
255	Releases to air	Aniline	kg	1,582E-14
256	Releases to air	Anthracene	kg	4,805E-21
257	Releases to air	Anthranilic acid	kg	8,019E-17
258	Releases to air	Antimony	kg	1,026E-10
259	Releases to air	Antimony-124	Bq	9,663E-11
260	Releases to air	Antimony-125	Bq	1,008E-09
261	Releases to air	Argon-41	Bq	9,788E-03
262	Releases to air	Arsenic	kg	1,486E-09
263	Releases to air	Arsenic trioxide	kg	1,555E-23
264	Releases to air	Arsine	kg	1,808E-18
265	Releases to air	Barium	kg	4,301E-10
266	Releases to air	Barium-140	Bq	6,559E-08
267	Releases to air	Benzal chloride	kg	1,258E-19
268	Releases to air	Benzaldehyde	kg	1,577E-12
269	Releases to air	Benzene	kg	9,294E-07
270	Releases to air	Benzene, 1-methyl-2-nitro-	kg	9,481E-17
271	Releases to air	Benzene, 1,2-dichloro-	kg	2,215E-15
272	Releases to air	Benzene, 1,3,5-trimethyl-	kg	1,752E-23
273	Releases to air	Benzene, ethyl-	kg	5,044E-08
274	Releases to air	Benzene, hexachloro-	kg	2,704E-12
275	Releases to air	Benzene, pentachloro-	kg	5,830E-14
276	Releases to air	Benzo(a)anthracene	kg	2,417E-21
277	Releases to air	Benzo(a)pyrene	kg	6,561E-11
278	Releases to air	Benzo(b)fluoranthene	kg	4,313E-21
279	Releases to air	Benzo(ghi)perylene	kg	2,157E-21
280	Releases to air	Beryllium	kg	1,395E-12
281	Releases to air	Boron	kg	2,720E-08
282	Releases to air	Boron trifluoride	kg	2,472E-20
283	Releases to air	Bromine	kg	3,016E-09
284	Releases to air	Butadiene	kg	6,498E-07
285	Releases to air	Butane	kg	2,230E-06
286	Releases to air	Butene	kg	5,040E-08
287	Releases to air	Butyrolactone	kg	9,791E-16
288	Releases to air	Cadmium	kg	2,054E-09
289	Releases to air	Calcium	kg	9,751E-09
290	Releases to air	Carbon-14	Bq	7,599E-02
291	Releases to air	Carbon dioxide, biogenic	kg	1,144E-04
292	Releases to air	Carbon dioxide, fossil	kg	1,240E-01
293	Releases to air	Carbon dioxide, land transformation	kg	5,526E-07
294	Releases to air	Carbon disulfide	kg	1,688E-08
295	Releases to air	Carbon monoxide, biogenic	kg	2,054E-08
296	Releases to air	Carbon monoxide, fossil	kg	1,525E-04
297	Releases to air	Cerium-141	Bq	1,590E-08
298	Releases to air	Cesium-134	Bq	7,618E-10
299	Releases to air	Cesium-137	Bq	1,350E-08

300	Releases to air	Chloramine	kg	8,152E-16
301	Releases to air	Chloride	kg	1,338E-16
302	Releases to air	Chlorine	kg	1,101E-08
303	Releases to air	Chloroacetic acid	kg	1,727E-13
304	Releases to air	Chloroform	kg	1,014E-12
305	Releases to air	Chlorosilane, trimethyl-	kg	6,891E-13
306	Releases to air	Chlorosulfonic acid	kg	7,372E-16
307	Releases to air	Chromium	kg	5,615E-09
308	Releases to air	Chromium-51	Bq	1,019E-09
309	Releases to air	Chromium VI	kg	7,975E-11
310	Releases to air	Chromium, ion	kg	4,755E-21
311	Releases to air	Chrysene	kg	5,938E-21
312	Releases to air	Cobalt	kg	1,681E-09
313	Releases to air	Cobalt-58	Bq	1,419E-09
314	Releases to air	Cobalt-60	Bq	1,253E-08
315	Releases to air	Copper	kg	6,458E-08
316	Releases to air	Cumene	kg	2,540E-09
317	Releases to air	Cyanide	kg	1,755E-10
318	Releases to air	Cyanoacetic acid	kg	6,038E-16
319	Releases to air	Cyclohexane	kg	1,551E-20
320	Releases to air	Dibenz(a,h)anthracene	kg	1,344E-21
321	Releases to air	Diethanolamine	kg	1,544E-26
322	Releases to air	Diethylamine	kg	7,051E-15
323	Releases to air	Dimethyl malonate	kg	7,571E-16
324	Releases to air	Dinitrogen monoxide	kg	1,332E-06
325	Releases to air	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	3,490E-15
326	Releases to air	Dipropylamine	kg	4,470E-15
327	Releases to air	Ethane	kg	8,030E-07
328	Releases to air	Ethane, 1,1-difluoro-, HFC-152a	kg	2,301E-12
329	Releases to air	Ethane, 1,1,1-trichloro-, HCFC-140	kg	7,126E-15
330	Releases to air	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	3,915E-10
331	Releases to air	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	kg	7,354E-15
332	Releases to air	Ethane, 1,2-dichloro-	kg	2,254E-10
333	Releases to air	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	3,085E-11
334	Releases to air	Ethane, hexafluoro-, HFC-116	kg	7,059E-11
335	Releases to air	Ethanol	kg	2,842E-09
336	Releases to air	Ethene	kg	1,086E-07
337	Releases to air	Ethene, chloro-	kg	8,199E-11
338	Releases to air	Ethene, tetrachloro-	kg	1,728E-14
339	Releases to air	Ethyl acetate	kg	2,848E-10
340	Releases to air	Ethyl cellulose	kg	5,623E-13
341	Releases to air	Ethylamine	kg	4,610E-16
342	Releases to air	Ethylene diamine	kg	4,758E-15
343	Releases to air	Ethylene oxide	kg	6,282E-06
344	Releases to air	Ethyne	kg	3,343E-10
345	Releases to air	Fluoranthene	kg	1,565E-20
346	Releases to air	Fluorene	kg	4,965E-20
347	Releases to air	Fluoride	kg	5,779E-17
348	Releases to air	Fluorine	kg	1,300E-10
349	Releases to air	Fluosilicic acid	kg	8,184E-11
350	Releases to air	Formaldehyde	kg	5,423E-06
351	Releases to air	Formamide	kg	3,588E-16
352	Releases to air	Formic acid	kg	1,623E-10

353	Releases to air	Furan	kg	4,600E-11
354	Releases to air	Heat, waste	MJ	1,816E+00
355	Releases to air	Helium	kg	9,107E-08
356	Releases to air	Heptane	kg	5,040E-07
357	Releases to air	Hexamethylene diamine	kg	3,519E-23
358	Releases to air	Hexane	kg	1,085E-06
359	Releases to air	Hydrocarbons, aliphatic, alkanes, cyclic	kg	4,688E-11
360	Releases to air	Hydrocarbons, aliphatic, alkanes, unspecified	kg	1,101E-07
361	Releases to air	Hydrocarbons, aliphatic, unsaturated	kg	6,712E-09
362	Releases to air	Hydrocarbons, aromatic	kg	1,670E-08
363	Releases to air	Hydrocarbons, chlorinated	kg	1,018E-10
364	Releases to air	Hydrogen	kg	8,309E-08
365	Releases to air	Hydrogen-3, Tritium	Bq	4,393E-01
366	Releases to air	Hydrogen bromide	kg	1,524E-19
367	Releases to air	Hydrogen chloride	kg	3,435E-07
368	Releases to air	Hydrogen cyanide	kg	3,155E-20
369	Releases to air	Hydrogen fluoride	kg	5,213E-08
370	Releases to air	Hydrogen iodide	kg	1,644E-22
371	Releases to air	Hydrogen peroxide	kg	4,211E-13
372	Releases to air	Hydrogen sulfide	kg	1,621E-08
373	Releases to air	Indeno(1,2,3-cd)pyrene	kg	1,605E-21
374	Releases to air	Iodine	kg	1,596E-09
375	Releases to air	Iodine-129	Bq	7,686E-05
376	Releases to air	Iodine-131	Bq	3,873E-03
377	Releases to air	Iodine-133	Bq	1,669E-07
378	Releases to air	Iodine-135	Bq	1,918E-07
379	Releases to air	Iron	kg	1,144E-08
380	Releases to air	Isocyanic acid	kg	4,038E-11
381	Releases to air	Isoprene	kg	2,135E-12
382	Releases to air	Isopropylamine	kg	1,292E-16
383	Releases to air	Krypton-85	Bq	3,064E-02
384	Releases to air	Krypton-85m	Bq	1,464E-03
385	Releases to air	Krypton-87	Bq	5,826E-04
386	Releases to air	Krypton-88	Bq	5,691E-04
387	Releases to air	Krypton-89	Bq	1,424E-04
388	Releases to air	Lactic acid	kg	3,501E-15
389	Releases to air	Lanthanum-140	Bq	5,606E-09
390	Releases to air	Lead	kg	6,894E-09
391	Releases to air	Lead-210	Bq	4,202E-04
392	Releases to air	Lead compounds	kg	2,067E-23
393	Releases to air	m-Xylene	kg	8,359E-11
394	Releases to air	Magnesium	kg	1,751E-09
395	Releases to air	Manganese	kg	8,956E-10
396	Releases to air	Manganese-54	Bq	5,218E-10
397	Releases to air	Mercury	kg	7,794E-10
398	Releases to air	Methane	kg	4,422E-13
399	Releases to air	Methane, biogenic	kg	1,497E-07
400	Releases to air	Methane, bromo-, Halon 1001	kg	2,877E-20
401	Releases to air	Methane, bromochlorodifluoro-, Halon 1211	kg	2,167E-11
402	Releases to air	Methane, bromotrifluoro-, Halon 1301	kg	1,304E-09
403	Releases to air	Methane, chlorodifluoro-, HCFC-22	kg	8,611E-11
404	Releases to air	Methane, chlorotrifluoro-, CFC-13	kg	6,536E-19
405	Releases to air	Methane, dichloro-, HCC-30	kg	1,981E-13

406	Releases to air	Methane, dichlorodifluoro-, CFC-12	kg	2,243E-13
407	Releases to air	Methane, dichlorofluoro-, HCFC-21	kg	7,978E-17
408	Releases to air	Methane, fossil	kg	6,584E-05
409	Releases to air	Methane, monochloro-, R-40	kg	1,989E-13
410	Releases to air	Methane, tetrachloro-, CFC-10	kg	1,864E-11
411	Releases to air	Methane, tetrafluoro-, CFC-14	kg	6,304E-10
412	Releases to air	Methane, trichlorofluoro-, CFC-11	kg	1,344E-16
413	Releases to air	Methane, trifluoro-, HFC-23	kg	2,538E-14
414	Releases to air	Methanesulfonic acid	kg	6,101E-16
415	Releases to air	Methanol	kg	1,033E-08
416	Releases to air	Methyl acetate	kg	2,542E-17
417	Releases to air	Methyl acrylate	kg	1,759E-13
418	Releases to air	Methyl amine	kg	2,970E-15
419	Releases to air	Methyl borate	kg	7,716E-17
420	Releases to air	Methyl ethyl ketone	kg	2,848E-10
421	Releases to air	Methyl formate	kg	7,754E-16
422	Releases to air	Methyl lactate	kg	3,844E-15
423	Releases to air	Molybdenum	kg	7,747E-10
424	Releases to air	Monoethanolamine	kg	3,295E-11
425	Releases to air	Naphthalene	kg	5,045E-19
426	Releases to air	Nickel	kg	2,713E-08
427	Releases to air	Niobium-95	Bq	6,194E-11
428	Releases to air	Nitrate	kg	1,106E-10
429	Releases to air	Nitric oxide	kg	1,210E-21
430	Releases to air	Nitrobenzene	kg	2,125E-14
431	Releases to air	Nitrogen	kg	2,575E-14
432	Releases to air	Nitrogen oxides	kg	5,423E-04
433	Releases to air	NMVOC, non-methane volatile organic compounds, unspecified	kg	6,417E-05
434	Releases to air	Noble gases, radioactive, unspecified	Bq	7,386E+02
435	Releases to air	Octane	kg	4,547E-17
436	Releases to air	Oxygen	kg	5,837E-14
437	Releases to air	Ozone	kg	2,634E-08
438	Releases to air	PAH, polycyclic aromatic hydrocarbons	kg	1,560E-09
439	Releases to air	Palladium	kg	1,235E-26
440	Releases to air	Particulates, < 10 um	kg	1,885E-15
441	Releases to air	Particulates, < 2.5 um	kg	7,187E-06
442	Releases to air	Particulates, > 10 um	kg	4,847E-06
443	Releases to air	Particulates, > 2.5 um, and < 10um	kg	1,864E-06
444	Releases to air	Pentane	kg	2,748E-06
445	Releases to air	Phenanthrene	kg	1,585E-19
446	Releases to air	Phenol	kg	2,309E-10
447	Releases to air	Phenol, 2,4-dichloro-	kg	2,435E-15
448	Releases to air	Phenol, pentachloro-	kg	2,095E-11
449	Releases to air	Phosphine	kg	1,339E-16
450	Releases to air	Phosphorus	kg	2,613E-10
451	Releases to air	Platinum	kg	1,103E-15
452	Releases to air	Plutonium-238	Bq	1,048E-11
453	Releases to air	Plutonium-alpha	Bq	2,403E-11
454	Releases to air	Polonium-210	Bq	7,400E-04
455	Releases to air	Polychlorinated biphenyls	kg	4,691E-12
456	Releases to air	Potassium	kg	1,683E-08
457	Releases to air	Potassium-40	Bq	9,404E-05
458	Releases to air	Propanal	kg	1,626E-12

459	Releases to air	Propane	kg	2,261E-06
460	Releases to air	Propene	kg	1,028E-07
461	Releases to air	Propionic acid	kg	1,708E-10
462	Releases to air	Propylamine	kg	1,136E-16
463	Releases to air	Propylene oxide	kg	1,152E-10
464	Releases to air	Protactinium-234	Bq	1,044E-05
465	Releases to air	Radioactive species, other beta emitters	Bq	3,561E-04
466	Releases to air	Radium-226	Bq	4,479E-04
467	Releases to air	Radium-228	Bq	4,835E-05
468	Releases to air	Radon-220	Bq	4,173E-03
469	Releases to air	Radon-222	Bq	3,312E+01
470	Releases to air	Rhodium	kg	1,193E-26
471	Releases to air	Ruthenium-103	Bq	1,361E-11
472	Releases to air	Scandium	kg	9,328E-13
473	Releases to air	Selenium	kg	1,323E-09
474	Releases to air	Silicon	kg	7,450E-09
475	Releases to air	Silicon tetrafluoride	kg	3,150E-12
476	Releases to air	Silver	kg	3,721E-13
477	Releases to air	Silver-110	Bq	1,349E-10
478	Releases to air	Sodium	kg	3,542E-08
479	Releases to air	Sodium chlorate	kg	3,500E-11
480	Releases to air	Sodium dichromate	kg	1,213E-11
481	Releases to air	Sodium formate	kg	2,116E-13
482	Releases to air	Sodium hydroxide	kg	1,561E-12
483	Releases to air	Strontium	kg	4,373E-10
484	Releases to air	Styrene	kg	3,409E-11
485	Releases to air	Sulfate	kg	9,440E-08
486	Releases to air	Sulfur dioxide	kg	1,827E-04
487	Releases to air	Sulfur hexafluoride	kg	3,964E-10
488	Releases to air	Sulfur trioxide	kg	1,711E-13
489	Releases to air	Sulfuric acid	kg	3,321E-13
490	Releases to air	t-Butyl methyl ether	kg	2,765E-12
491	Releases to air	t-Butylamine	kg	5,226E-16
492	Releases to air	Tellurium	kg	6,339E-22
493	Releases to air	Terpenes	kg	2,018E-11
494	Releases to air	Thallium	kg	2,359E-12
495	Releases to air	Thorium	kg	8,351E-13
496	Releases to air	Thorium-228	Bq	1,980E-05
497	Releases to air	Thorium-230	Bq	4,432E-05
498	Releases to air	Thorium-232	Bq	3,007E-05
499	Releases to air	Thorium-234	Bq	1,044E-05
500	Releases to air	Tin	kg	1,409E-10
501	Releases to air	Tin oxide	kg	1,798E-24
502	Releases to air	Titanium	kg	1,585E-10
503	Releases to air	Toluene	kg	3,190E-07
504	Releases to air	Toluene, 2-chloro-	kg	6,385E-15
505	Releases to air	Trimethylamine	kg	4,526E-17
506	Releases to air	Tungsten	kg	3,119E-14
507	Releases to air	Uranium	kg	7,553E-13
508	Releases to air	Uranium-234	Bq	1,271E-04
509	Releases to air	Uranium-235	Bq	5,891E-06
510	Releases to air	Uranium-238	Bq	2,011E-04
511	Releases to air	Uranium alpha	Bq	5,675E-04

512	Releases to air	Used air	kg	1,124E-09
513	Releases to air	Vanadium	kg	3,972E-08
514	Releases to air	VOC, volatile organic compounds	kg	5,412E-16
515	Releases to air	Water	kg	4,264E-02
516	Releases to air	Xenon-131m	Bq	2,671E-03
517	Releases to air	Xenon-133	Bq	8,476E-02
518	Releases to air	Xenon-133m	Bq	3,688E-04
519	Releases to air	Xenon-135	Bq	3,477E-02
520	Releases to air	Xenon-135m	Bq	2,048E-02
521	Releases to air	Xenon-137	Bq	3,905E-04
522	Releases to air	Xenon-138	Bq	3,465E-03
523	Releases to air	Xylene	kg	2,221E-07
524	Releases to air	Zinc	kg	4,414E-08
525	Releases to air	Zinc-65	Bq	2,606E-09
526	Releases to air	Zinc oxide	kg	3,597E-24
527	Releases to air	Zirconium	kg	5,339E-12
528	Releases to air	Zirconium-95	Bq	2,547E-09
529	Releases to water	1-Butanol	kg	1,035E-12
530	Releases to water	1-Pentanol	kg	4,709E-16
531	Releases to water	1-Pentene	kg	3,558E-16
532	Releases to water	1,4-Butanediol	kg	3,132E-15
533	Releases to water	2-Aminopropanol	kg	1,542E-16
534	Releases to water	2-Methyl-1-propanol	kg	2,254E-15
535	Releases to water	2-Methyl-2-butene	kg	7,893E-20
536	Releases to water	2-Propanol	kg	7,152E-16
537	Releases to water	4-Methyl-2-pentanone	kg	7,464E-16
538	Releases to water	Acenaphthene	kg	1,505E-11
539	Releases to water	Acenaphthylene	kg	9,412E-13
540	Releases to water	Acetaldehyde	kg	2,255E-12
541	Releases to water	Acetic acid	kg	5,542E-10
542	Releases to water	Acetone	kg	5,197E-14
543	Releases to water	Acetonitrile	kg	5,056E-16
544	Releases to water	Acetyl chloride	kg	3,699E-16
545	Releases to water	Acidity, unspecified	kg	4,282E-10
546	Releases to water	Acrylate, ion	kg	3,668E-13
547	Releases to water	Acrylonitrile	kg	2,065E-21
548	Releases to water	Actinides, radioactive, unspecified	Bq	1,248E-04
549	Releases to water	Aluminium	kg	2,035E-07
550	Releases to water	Americium-241	Bq	7,647E-13
551	Releases to water	Ammonia	kg	2,464E-14
552	Releases to water	Ammonium, ion	kg	1,729E-07
553	Releases to water	Aniline	kg	3,802E-14
554	Releases to water	Anthracene	kg	1,092E-19
555	Releases to water	Antimony	kg	5,372E-10
556	Releases to water	Antimony-122	Bq	3,896E-08
557	Releases to water	Antimony-124	Bq	2,033E-05
558	Releases to water	Antimony-125	Bq	1,854E-05
559	Releases to water	AOX, Adsorbable Organic Halogen as Cl	kg	1,960E-09
560	Releases to water	Arsenic, ion	kg	5,238E-09
561	Releases to water	Barite	kg	8,835E-06
562	Releases to water	Barium	kg	2,111E-06
563	Releases to water	Barium-140	Bq	1,706E-07
564	Releases to water	Benzene	kg	1,698E-07

565	Releases to water	Benzene, 1,2-dichloro-	kg	4,670E-13
566	Releases to water	Benzene, chloro-	kg	9,541E-12
567	Releases to water	Benzene, ethyl-	kg	5,807E-08
568	Releases to water	Benzo(a)anthracene	kg	8,353E-20
569	Releases to water	Benzo(b)fluoranthene	kg	9,220E-20
570	Releases to water	Beryllium	kg	1,098E-11
571	Releases to water	BOD5, Biological Oxygen Demand	kg	5,227E-04
572	Releases to water	Borate	kg	4,193E-14
573	Releases to water	Boron	kg	2,783E-08
574	Releases to water	Bromate	kg	1,844E-09
575	Releases to water	Bromide	kg	1,108E-11
576	Releases to water	Bromine	kg	1,699E-06
577	Releases to water	Butene	kg	7,467E-13
578	Releases to water	Butyl acetate	kg	1,343E-12
579	Releases to water	Butyrolactone	kg	2,350E-15
580	Releases to water	Cadmium	kg	9,526E-18
581	Releases to water	Cadmium, ion	kg	4,846E-10
582	Releases to water	Calcium, ion	kg	7,606E-05
583	Releases to water	Carbon-14	Bq	3,871E-11
584	Releases to water	Carbon disulfide	kg	1,938E-14
585	Releases to water	Carbonate	kg	2,692E-09
586	Releases to water	Carboxylic acids, unspecified	kg	1,049E-05
587	Releases to water	Cerium-141	Bq	6,823E-08
588	Releases to water	Cerium-144	Bq	2,077E-08
589	Releases to water	Cesium	kg	2,420E-09
590	Releases to water	Cesium-134	Bq	1,710E-05
591	Releases to water	Cesium-136	Bq	1,211E-08
592	Releases to water	Cesium-137	Bq	1,436E-02
593	Releases to water	Chloramine	kg	7,339E-15
594	Releases to water	Chlorate	kg	1,588E-08
595	Releases to water	Chloride	kg	1,228E-03
596	Releases to water	Chlorinated solvents, unspecified	kg	9,414E-12
597	Releases to water	Chlorine	kg	1,023E-10
598	Releases to water	Chloroacetic acid	kg	1,053E-11
599	Releases to water	Chloroacetyl chloride	kg	2,056E-16
600	Releases to water	Chloroform	kg	2,082E-14
601	Releases to water	Chlorosulfonic acid	kg	1,839E-15
602	Releases to water	Chromium	kg	3,509E-17
603	Releases to water	Chromium-51	Bq	2,162E-05
604	Releases to water	Chromium VI	kg	1,483E-08
605	Releases to water	Chromium, ion	kg	6,190E-09
606	Releases to water	Chrysene	kg	4,706E-19
607	Releases to water	Cobalt	kg	6,413E-10
608	Releases to water	Cobalt-57	Bq	3,844E-07
609	Releases to water	Cobalt-58	Bq	1,618E-04
610	Releases to water	Cobalt-60	Bq	1,266E-04
611	Releases to water	COD, Chemical Oxygen Demand	kg	5,264E-04
612	Releases to water	Copper	kg	4,500E-17
613	Releases to water	Copper, ion	kg	1,850E-09
614	Releases to water	Cresol	kg	1,547E-22
615	Releases to water	Cumene	kg	6,103E-09
616	Releases to water	Curium alpha	Bq	1,014E-12
617	Releases to water	Cyanide	kg	5,792E-09

618	Releases to water	Decane	kg	7,379E-16
619	Releases to water	Dichromate	kg	4,500E-11
620	Releases to water	Diethylamine	kg	1,692E-14
621	Releases to water	Dimethylamine	kg	1,166E-14
622	Releases to water	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	4,136E-31
623	Releases to water	Dipropylamine	kg	1,073E-14
624	Releases to water	DOC, Dissolved Organic Carbon	kg	1,579E-04
625	Releases to water	Ethane, 1,2-dichloro-	kg	2,335E-11
626	Releases to water	Ethanol	kg	2,611E-12
627	Releases to water	Ethene	kg	2,527E-09
628	Releases to water	Ethene, chloro-	kg	8,458E-13
629	Releases to water	Ethyl acetate	kg	1,814E-14
630	Releases to water	Ethylamine	kg	1,106E-15
631	Releases to water	Ethylene diamine	kg	1,146E-14
632	Releases to water	Ethylene oxide	kg	2,417E-13
633	Releases to water	Fluoranthene	kg	9,864E-20
634	Releases to water	Fluoride	kg	1,782E-07
635	Releases to water	Fluorine	kg	3,703E-19
636	Releases to water	Fluosilicic acid	kg	1,473E-10
637	Releases to water	Formaldehyde	kg	3,282E-10
638	Releases to water	Formamide	kg	8,612E-16
639	Releases to water	Formate	kg	1,611E-13
640	Releases to water	Formic acid	kg	2,500E-16
641	Releases to water	Glutaraldehyde	kg	1,091E-09
642	Releases to water	Heat, waste	MJ	3,142E-02
643	Releases to water	Hexane	kg	1,819E-23
644	Releases to water	Hydrocarbons, aliphatic, alkanes, unspecified	kg	3,145E-07
645	Releases to water	Hydrocarbons, aliphatic, unsaturated	kg	2,903E-08
646	Releases to water	Hydrocarbons, aromatic	kg	1,291E-06
647	Releases to water	Hydrocarbons, unspecified	kg	1,751E-07
648	Releases to water	Hydrogen-3, Tritium	Bq	3,290E+01
649	Releases to water	Hydrogen chloride	kg	5,174E-21
650	Releases to water	Hydrogen fluoride	kg	1,930E-20
651	Releases to water	Hydrogen peroxide	kg	6,481E-12
652	Releases to water	Hydrogen sulfide	kg	2,847E-10
653	Releases to water	Hydroxide	kg	1,371E-11
654	Releases to water	Hypochlorite	kg	1,773E-09
655	Releases to water	Iodide	kg	2,421E-07
656	Releases to water	Iodine-129	Bq	1,106E-10
657	Releases to water	Iodine-131	Bq	3,688E-06
658	Releases to water	Iodine-133	Bq	1,071E-07
659	Releases to water	Iron	kg	1,912E-14
660	Releases to water	Iron-59	Bq	2,945E-08
661	Releases to water	Iron, ion	kg	2,016E-06
662	Releases to water	Isopropylamine	kg	3,100E-16
663	Releases to water	Lactic acid	kg	8,404E-15
664	Releases to water	Lanthanum-140	Bq	1,818E-07
665	Releases to water	Lead	kg	9,334E-09
666	Releases to water	Lead-210	Bq	1,369E-03
667	Releases to water	Lithium, ion	kg	1,914E-10
668	Releases to water	m-Xylene	kg	6,297E-15
669	Releases to water	Magnesium	kg	1,316E-05
670	Releases to water	Manganese	kg	1,214E-07

671	Releases to water	Manganese-54	Bq	9,951E-06
672	Releases to water	Mercury	kg	4,575E-11
673	Releases to water	Methane, dibromo-	kg	3,644E-24
674	Releases to water	Methane, dichloro-, HCC-30	kg	2,846E-08
675	Releases to water	Methane, monochloro-, R-40	kg	3,962E-20
676	Releases to water	Methanol	kg	3,133E-10
677	Releases to water	Methyl acetate	kg	6,102E-17
678	Releases to water	Methyl acrylate	kg	3,435E-12
679	Releases to water	Methyl amine	kg	7,128E-15
680	Releases to water	Methyl formate	kg	3,096E-16
681	Releases to water	Molybdenum	kg	3,427E-09
682	Releases to water	Molybdenum-99	Bq	6,266E-08
683	Releases to water	Naphthalene	kg	1,241E-17
684	Releases to water	Nickel	kg	5,910E-17
685	Releases to water	Nickel, ion	kg	2,617E-09
686	Releases to water	Niobium-95	Bq	1,551E-06
687	Releases to water	Nitrate	kg	3,389E-07
688	Releases to water	Nitrite	kg	3,692E-10
689	Releases to water	Nitrobenzene	kg	8,516E-14
690	Releases to water	Nitrogen	kg	1,338E-07
691	Releases to water	Nitrogen, organic bound	kg	4,413E-07
692	Releases to water	o-Xylene	kg	3,928E-15
693	Releases to water	Oils, unspecified	kg	1,651E-04
694	Releases to water	PAH, polycyclic aromatic hydrocarbons	kg	1,414E-08
695	Releases to water	Particulates, < 10 um	kg	9,275E-21
696	Releases to water	Particulates, > 10 um	kg	3,012E-13
697	Releases to water	Phenol	kg	2,306E-07
698	Releases to water	Phosphate	kg	1,251E-06
699	Releases to water	Phosphorus	kg	1,218E-08
700	Releases to water	Plutonium-alpha	Bq	3,043E-12
701	Releases to water	Polonium-210	Bq	1,994E-03
702	Releases to water	Potassium	kg	8,410E-18
703	Releases to water	Potassium-40	Bq	3,692E-04
704	Releases to water	Potassium, ion	kg	1,073E-05
705	Releases to water	Propanal	kg	6,817E-16
706	Releases to water	Propane, 1,2-dichloro-	kg	2,824E-26
707	Releases to water	Propanol	kg	1,355E-15
708	Releases to water	Propene	kg	2,506E-09
709	Releases to water	Propionic acid	kg	6,173E-15
710	Releases to water	Propylamine	kg	2,727E-16
711	Releases to water	Propylene oxide	kg	2,771E-10
712	Releases to water	Protactinium-234	Bq	1,925E-04
713	Releases to water	Radioactive species, alpha emitters	Bq	3,555E-06
714	Releases to water	Radioactive species, Nuclides, unspecified	Bq	7,486E-02
715	Releases to water	Radium-224	Bq	1,210E-01
716	Releases to water	Radium-226	Bq	3,148E-01
717	Releases to water	Radium-228	Bq	2,420E-01
718	Releases to water	Rubidium	kg	2,420E-08
719	Releases to water	Ruthenium-103	Bq	1,322E-08
720	Releases to water	Ruthenium-106	Bq	7,647E-13
721	Releases to water	Scandium	kg	2,050E-10
722	Releases to water	Selenium	kg	7,930E-10
723	Releases to water	Silicon	kg	2,389E-07

724	Releases to water	Silver-110	Bq	1,180E-04
725	Releases to water	Silver, ion	kg	1,938E-09
726	Releases to water	Sodium-24	Bq	4,741E-07
727	Releases to water	Sodium formate	kg	5,084E-13
728	Releases to water	Sodium, ion	kg	7,388E-04
729	Releases to water	Solids, inorganic	kg	4,064E-06
730	Releases to water	Solved solids	kg	2,577E-07
731	Releases to water	Strontium	kg	4,392E-06
732	Releases to water	Strontium-89	Bq	2,111E-06
733	Releases to water	Strontium-90	Bq	1,071E-01
734	Releases to water	Sulfate	kg	2,164E-05
735	Releases to water	Sulfide	kg	2,801E-09
736	Releases to water	Sulfite	kg	4,815E-09
737	Releases to water	Sulfur	kg	4,427E-07
738	Releases to water	Suspended solids, unspecified	kg	3,396E-05
739	Releases to water	t-Butyl methyl ether	kg	5,266E-09
740	Releases to water	t-Butylamine	kg	1,254E-15
741	Releases to water	Technetium-99m	Bq	1,452E-06
742	Releases to water	Tellurium-123m	Bq	2,209E-06
743	Releases to water	Tellurium-132	Bq	3,628E-09
744	Releases to water	Thallium	kg	9,976E-12
745	Releases to water	Thorium-228	Bq	4,839E-01
746	Releases to water	Thorium-230	Bq	2,627E-02
747	Releases to water	Thorium-232	Bq	4,204E-05
748	Releases to water	Thorium-234	Bq	1,925E-04
749	Releases to water	Tin	kg	6,724E-22
750	Releases to water	Tin, ion	kg	1,840E-11
751	Releases to water	Titanium	kg	1,471E-18
752	Releases to water	Titanium, ion	kg	3,824E-10
753	Releases to water	TOC, Total Organic Carbon	kg	1,582E-04
754	Releases to water	Toluene	kg	3,055E-07
755	Releases to water	Toluene, 2-chloro-	kg	1,324E-14
756	Releases to water	Tributyltin compounds	kg	2,336E-09
757	Releases to water	Triethylene glycol	kg	1,730E-10
758	Releases to water	Trimethylamine	kg	1,086E-16
759	Releases to water	Tungsten	kg	3,172E-10
760	Releases to water	Uranium-234	Bq	2,310E-04
761	Releases to water	Uranium-235	Bq	3,812E-04
762	Releases to water	Uranium-238	Bq	1,279E-03
763	Releases to water	Uranium alpha	Bq	1,109E-02
764	Releases to water	Urea	kg	8,407E-16
765	Releases to water	Vanadium	kg	1,067E-17
766	Releases to water	Vanadium, ion	kg	1,232E-09
767	Releases to water	VOC, volatile organic compounds, unspecified origin	kg	8,473E-07
768	Releases to water	Xylene	kg	2,479E-07
769	Releases to water	Zinc	kg	1,830E-16
770	Releases to water	Zinc-65	Bq	6,428E-06
771	Releases to water	Zinc, ion	kg	6,018E-07
772	Releases to water	Zirconium-95	Bq	7,444E-08
773	Solid waste	Calcium fluoride waste	kg	7,328E-17
774	Solid waste	Construction waste	kg	2,681E-13
775	Solid waste	Mineral waste, from mining	kg	1,640E-10
776	Solid waste	Radioactive tailings	kg	1,284E-13

777	Solid waste	Rejects	kg	2,904E-13
778	Solid waste	Slag (uranium conversion)	kg	4,853E-16
779	Solid waste	Slags	kg	9,227E-15
780	Solid waste	Waste returned to mine	kg	1,608E-16
781	Solid waste	Waste, nuclear, unspecified/kg	kg	1,415E-15
782	Releases to soil	2,4-D	kg	8,125E-12
783	Releases to soil	Aclonifen	kg	9,197E-13
784	Releases to soil	Aldrin	kg	4,002E-15
785	Releases to soil	Aluminium	kg	1,126E-06
786	Releases to soil	Ammonia	kg	4,318E-15
787	Releases to soil	Antimony	kg	3,499E-15
788	Releases to soil	Arsenic	kg	4,503E-10
789	Releases to soil	Atrazine	kg	1,050E-15
790	Releases to soil	Barium	kg	5,621E-07
791	Releases to soil	Benomyl	kg	5,179E-14
792	Releases to soil	Bentazone	kg	4,694E-13
793	Releases to soil	Boron	kg	1,155E-08
794	Releases to soil	Bromide	kg	1,271E-18
795	Releases to soil	Cadmium	kg	1,921E-12
796	Releases to soil	Calcium	kg	4,525E-06
797	Releases to soil	Carbetamide	kg	1,705E-13
798	Releases to soil	Carbofuran	kg	2,840E-11
799	Releases to soil	Carbon	kg	3,381E-06
800	Releases to soil	Chloride	kg	4,280E-06
801	Releases to soil	Chlorothalonil	kg	4,291E-12
802	Releases to soil	Chromium	kg	5,644E-09
803	Releases to soil	Chromium VI	kg	1,726E-09
804	Releases to soil	Chromium, ion	kg	5,246E-23
805	Releases to soil	Cobalt	kg	1,706E-12
806	Releases to soil	Copper	kg	1,141E-09
807	Releases to soil	Cypermethrin	kg	4,013E-12
808	Releases to soil	Decane	kg	4,286E-17
809	Releases to soil	Fenpiclonil	kg	2,006E-13
810	Releases to soil	Fluoride	kg	5,737E-08
811	Releases to soil	Glyphosate	kg	1,535E-10
812	Releases to soil	Heat, waste	MJ	2,902E-04
813	Releases to soil	Iron	kg	2,427E-06
814	Releases to soil	Lead	kg	2,230E-11
815	Releases to soil	Linuron	kg	7,086E-12
816	Releases to soil	Magnesium	kg	9,024E-07
817	Releases to soil	Mancozeb	kg	5,573E-12
818	Releases to soil	Manganese	kg	4,684E-08
819	Releases to soil	Mercury	kg	2,684E-14
820	Releases to soil	Metaldehyde	kg	3,320E-14
821	Releases to soil	Metolachlor	kg	5,129E-11
822	Releases to soil	Metribuzin	kg	1,962E-13
823	Releases to soil	Molybdenum	kg	3,743E-13
824	Releases to soil	Napropamide	kg	5,874E-14
825	Releases to soil	Nickel	kg	1,164E-11
826	Releases to soil	Oils, biogenic	kg	2,264E-09
827	Releases to soil	Oils, unspecified	kg	1,745E-04
828	Releases to soil	Orbencarb	kg	1,060E-12
829	Releases to soil	Phosphate	kg	2,473E-15

830	Releases to soil	Phosphorus	kg	5,710E-08
831	Releases to soil	Pirimicarb	kg	4,440E-14
832	Releases to soil	Potassium	kg	3,984E-07
833	Releases to soil	Silicon	kg	1,202E-07
834	Releases to soil	Sodium	kg	2,249E-06
835	Releases to soil	Strontium	kg	1,132E-08
836	Releases to soil	Sulfate	kg	1,368E-16
837	Releases to soil	Sulfide	kg	8,206E-16
838	Releases to soil	Sulfur	kg	6,754E-07
839	Releases to soil	Sulfuric acid	kg	2,009E-16
840	Releases to soil	Tebutam	kg	1,392E-13
841	Releases to soil	Teflubenzuron	kg	1,308E-14
842	Releases to soil	Thiram	kg	9,189E-14
843	Releases to soil	Tin	kg	1,592E-13
844	Releases to soil	Titanium	kg	1,261E-10
845	Releases to soil	Vanadium	kg	3,609E-12
846	Releases to soil	Zinc	kg	1,809E-08

Appendix B
Material Composition of the A330-200 Aircraft

ENGINE STRUCTURE					
Assembly name (Simapro)	**Part name**	**Total weight (in Kg)**	**MATERIAL COMPOSITION**		
			Name	**Simapro Material**	**Weight (in kg)**
GE CF6-80E1	GE CF6-80E1	676	Iron-nickel-chromium alloy	Iron-nickel-chromium alloy, at plant/RER U	864
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	465
			CFRP	CFRP	216
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	1310
			Nickel	Nickel, 99,5%, at plant/DE U	1474
			GFRP	Chromium, at regional storage/RER U	447
			Aluminium alloy	Molybdenite, at plant/GLO U	76
			Iron	Cast iron, at plant/GLO U	456
			Niobium + tantalum	Tantalum, powder, capacitor-grade, at regional storage/GLO	94
Parts	inlet cowl	281	CFRP	CFRP	140,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	140,5
	fan cowl	125	CFRP	CFRP	62,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	62,5
	thrust reverser	703	CFRP	CFRP	351,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	351,5
	core cowl	61	CFRP	CFRP	30,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	30,5
	primary nozzle	79	CFRP	CFRP	39,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	39,5
Pylon	removable leading edge	2563	steel	Reinforcing steel, at plant/RER U	2179
			CFRP	CFRP	192
			GFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	192

LANDING GEAR STRUCURE					
Assembly name (Simapro)	**Part name**	**Total weight (in Kg)**	**MATERIAL COMPOSITION**		
			Name	**Simapro Material**	**Weight (in kg)**
Main Landing Gear - Structure	main landing gear	4086	steel	Reinforcing steel, at plant/RER U	3677,4
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	204,3
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	204,3
	MLG sidestray assembly inc. locking system	178,8	steel	Reinforcing steel, at plant/RER U	161
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	8,9
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	8,9
	MLG retraction actuator (wet)	85	steel	Reinforcing steel, at plant/RER U	85
	MLG leg fairing	34,4	CFRP	CFRP	34,4
	MLG outer hinged doors	15,4	CFRP	CFRP	15,4
	MLG wheels (4 off) with tires brakes and fans	1748,2	steel	Reinforcing steel, at plant/RER U	1573,4
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	87,4
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	87,4
Nose Landing Gear - Structure	nose landing gear	747,5	steel	Reinforcing steel, at plant/RER U	672,8
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	37,4
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	37,4
	NLG telescopic strut	146,1	steel	Reinforcing steel, at plant/RER U	131,5
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	7,3
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	7,3
	NLG retraction actuator	26,2	steel	Reinforcing steel, at plant/RER U	26,2
	NLG leg fairing	5	CFRP	CFRP	5
	NLG hinged doors forward (2 off)	56	CFRP	CFRP	56
	NLG wheels (2 off) with tires	210,7	steel	Reinforcing steel, at plant/RER U	189,7
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	10,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	10,5

FUSELAGE STRUCURE

Assembly name (Simapro)	Part name	Total weight (in Kg)	MATERIAL COMPOSITION		
			Name	**Simapro Material**	**Weight (in kg)**
Fuselage - Cilinder	cilinder	25000	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	22500
			CFRP	CFRP	1250
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	1250
	belly fairing	250	CFRP	CFRP	125
			GFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	125
	radome	28	QFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	28
Fuselage - Cabin Doors	cabin door FWD	131	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	131
	cabin door MID	124	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	124
	cabin door AFT	125	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	125
	emergency exit	68	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	68
Fuselage - Cargo Doors	cargo door FWD	190	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	190
	cargo door AFT	201	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	201
	bulk cargo door	34	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	34
Fuselage - Landing Gear Doors	main landing gear doors	344	CFRP	CFRP	326,8
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	17,2
	nose landing gear main and intermediate doors	58	steel	Reinforcing steel, at plant/RER U	58
Fuselage - Control units flap and slat	control unit, flap	42	steel	Reinforcing steel, at plant/RER U	42
	control unit, slat	40	steel	Reinforcing steel, at plant/RER U	40
Fuselage - Actuator Trimmable Horizontal Stabilizer	actuator, trimmable horizontal stabilizer	107	steel	Reinforcing steel, at plant/RER U	107

ENGINE STRUCTURE					
Assembly name (Simapro)	**Part name**	**Total weight (in Kg)**	**MATERIAL COMPOSITION**		
			Name	**Simapro Material**	**Weight (in kg)**
GE CF6-80E1	GE CF6-80E1	676	Iron-nickel-chromium alloy	Iron-nickel-chromium alloy, at plant/RER U	864
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	465
			CFRP	CFRP	216
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	1310
			Nickel	Nickel, 99,5%, at plant/DE U	1474
			GFRP	Chromium, at regional storage/RER U	447
			Aluminium alloy	Molybdenite, at plant/GLO U	76
			Iron	Cast iron, at plant/GLO U	456
			Niobium + tantalum	Tantalum, powder, capacitor-grade, at regional storage/GLO	94
Parts	inlet cowl	281	CFRP	CFRP	140,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	140,5
	fan cowl	125	CFRP	CFRP	62,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	62,5
	thrust reverser	703	CFRP	CFRP	351,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	351,5
	core cowl	61	CFRP	CFRP	30,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	30,5
	primary nozzle	79	CFRP	CFRP	39,5
			Titanium alloy	Titanium zinc plate, without pre-weathering, at plant/DE U	39,5
Pylon	removable leading edge	2563	steel	Reinforcing steel, at plant/RER U	2179
			CFRP	CFRP	192
			GFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	192

VERTICAL STABILIZER STRUCURE					
Assembly name (Simapro)	**Part name**	**Total weight (in Kg)**	**MATERIAL COMPOSITION**		
			Name	**Simapro Material**	**Weight (in kg)**
Vertical Tail - Box	box	676	CFRP	CFRP	321,1
			GFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	321,1
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	33,8
Vertical Tail - Rudder	rudder	335	CFRP	CFRP	335
Vertical Tail - Removable leading edge	removable leading edge	134	GFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	127
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	6,7
Vertical Tail - Tip	tip	17	GFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	17
Vertical Tail - Fuselage fairing	fuselage fairing	30	GFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	30

HORIZONTAL STABILIZER STRUCURE					
Assembly name (Simapro)	**Part name**	**Total weight (in Kg)**	**MATERIAL COMPOSITION**		
			Name	**Simapro Material**	**Weight (in kg)**
Horizontal Tail - Box	box	1337	CFRP	CFRP	1270
			Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	67
Horizontal Tail - Elevator	elevator	270	CFRP	CFRP	270
Horizontal Tail - Removable leading edge	removable leading edge	182	CFRP	CFRP	182
Horizontal Tail - Tip	tip	34	Aluminium alloy	Aluminium alloy, AlMg3, at plant/RER U	34
Horizontal Tail - Tailplane fuselage fairing	Tail fuselage fairing	54	GFRP	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	54