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Project

Department of Automotive and Aeronautical Engineering

Creating a Life-Cycle Assessment of an Aircraft

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Delivery date: 12 July 2012

Abstract

This project addresses the environmental concerns of the aviation sector with a full life-cycle approach. The impact of aviation on the environment has been studied. Many emissions come from fuel combustion. Greenhouse gasses and other criteria air pollutants from aviation have environmental effects. According to the U.S. Environmental Protection Agency, Cabon-dioxide (CO2), sulphur dioxide (SO2), carbon monoxide (CO), nitrogen oxides (NOx), Volatile Organic Compounds (VOC), particles (PM) and lead (Pb) are the most common air pollutants. Different LCA tools have been investigated and GaBi has been chosen to perform the life-cycle inventory assessment of the A320. A literature research of already existing life-cycle assessments of aircraft was needed to find out if previous life-cycle attempts have been made. Most studies of aircraft have been at the cruise phase. Also the landing-takeoff cycle and components of aircraft are studied. According to the literature research in this work, only Chester (2008) and Lopes (2010) have completed a comprehensive Life-Cycle Inventory of infrastructure and fuel associated with aircraft. These have been compared. It is decided to follow the method of Chester because his cruise inventory is more accurate and the manufacturing phase is less time-consuming with fewer assumptions. A LCA of a paperclip has been conducted to familiarize with GaBi and learn more about life-cycle assessment. Then a basic life-cycle assessment could be generated for the A320. The goal and scope was defined in the beginning. An inventory is made from the manufacturing phase and the operational phase. The assessment is conducted in GaBi. The results are comparable with the Boeing 737 of Chester.

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DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

Creating a Life-Cycle Assessment of an Aircraft

Task for a *project*

Background

A Life-Cycle Assessment (LCA) examines the environmental impacts from all stages of life of a product. Environmental impacts include all resources from the environment and all emissions into the environment. A LCA allows realistic comparisons of the environmental impacts of different products. The creation of LCAs is standardized by ISO 14040/4 and separated into four phases. This project is concentrated on the second phase (life-cycle inventory analysis) for commercial aircrafts.

Task

The task consists of creating a basic life-cycle assessment for an aircraft. This includes:

- Literature research for already existing life-cycle assessments of aircraft.
- What methods were used to create these LCAs?
- What were the results of these LCAs?
- How can we easily create a basic life-cycle assessment for an aircraft?
- Collection of the relevant data for the LCA
- Generation of an LCA.

The report has to be written in English based on German or international standards on report writing.

Declaration

This project work is entirely my own work. Where use has been made of the work of others, it has been totally acknowledged and referenced.

2012-07-19

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Date Signature

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List of Symbols

I/O_{β}^{α}	Input or Output for component (α) and functional unit (β)
$	2002 U.S. dollars unless year stated otherwise
m	mass

Subscripts

$(\ )_{PL}$	payload
$(\ )_{pax}$	passengers
$(\ )_{baggage}$	baggage
$(\ )_{cargo}$	cargo

List of Abbreviations

Acare	Advisory Council for Aeronautics Research in Europe
AEDT	Aviation Environmental Design Tool
agg	system proces
AIC	Aviation Induced Cloudiness
AP	Acidification Potential
aps	avoided product system
APU	Auxillary Power Unit
CFRP	Carbon Fiber Reinforced Polymer
CML	Institute of Environmental Sciences
EASA	European Aviation Safety Agency
EI	Emission Index
EIO-LCA	Economic Input-Output Life-cycle Assessment
EDMS	Emission Data Modelling Software
EP	Eutrophication Potential
eq.	equivalent
EU	European Union
FAA	Federal Aviation Authority
FDR	Flight Data Recorder
FKT	Freight Kilometers Travelled
FMC	Flight Management Computer
GE	General Electric
GGE	Greenhouse Gas Equivalence (KgCO2Eq.)
GHG	Greenhouse Gasses
GPU	Ground Power Unit
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GWP	Global Warming Potential
HAP	Hazardous Air Pollutants
HC	Hydrocarbons
HFC	Hydrofluorcarbons
ICAO	International Civil Aviation Organisation
IPC	Illustrated Parts Catalog
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
LCA	Life-Cycle Assessment
LCI	Life-Cycle inventory
LCIA	Life-Cycle Impact Assessment
LCM	List of Consumable Materials
NICETRIP	Novel Innovative Competitive Effective Tilt Rotor Integrated Project

NM	Nautical Miles
p-agg	partly terminated system
PAMELA	Process for the Advanced Management of End-of-Life Aircraft
Pb	Lead
PFC	Perfluorcarbons
PKT	Passenger Kilometers Travelled
PM	Particulate Matter
PM10	Particles that are smaller than 10 micrometer
PM2,5	Particles that are smaller than 2,5 micrometer
POCP	Photochemical Ozone Creation Potential
POH	Pilot Operating Handbook
RCRA	Resource Conservation and Recovery Act
RER	Processes that are valid for the situation in Europe.
RF	Radiadative Forcing
SRM	Structural Repair Manual
TRACEY	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (US Environmental Protection Agency Methodology)
TSFC	Thrust Specific Fuel Consumption
u-bb	process black box
UK	United Kingdom
US	United States
u-so	unit process single operation
VKT	Vehicle Kilometers Travelled
VOC	Volatile Organic Compounds
W&B	Weight and Balance

Terms and Definitions

Greenhouse effect

„The Sun powers Earth's climate, radiating energy at very short wavelengths, predominately in the visible or near-visible (e.g., ultraviolet) part of the spectrum. Roughly one-third of the solar energy that reaches the top of Earth's atmosphere is reflected directly back to space. The remaining two-thirds is absorbed by the surface and, to a lesser extent, by the atmosphere. To balance the absorbed incoming energy, the Earth must, on average, radiate the same amount of energy back to space. Because the Earth is much colder than the Sun, it radiates at much longer wavelengths, primarily in the infrared part of the spectrum (see Figure 1). Much of this thermal radiation emitted by the land and ocean is absorbed by the atmosphere, including clouds, and reradiated back to Earth. This is called the greenhouse effect. However, human activities, primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural greenhouse effect, causing global warming. "(**IPCC 2012a**)

Greenhouse gasses

Gases that trap heat in the atmosphere are called greenhouse gases (**EPA 2012b**). According to **EPA 2012b** the principal gasses are:

- Carbon dioxide (CO2),
- Methane (CH_4),
- Nitrous oxide (N_2O),
- Fluorinated gases.

Radiative forcing

"The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say, a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave, in Wm-2) at the tropopause AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values." (**IPCC 2012b**)

1 Introduction

1.1 Motivation

Aviation is an important industry for the economy, transporting goods and people around the world. At the 37th annual Federal Aviation Authority (FAA) forecast conference is predicted that airline passenger miles will nearly double in the next two decades, from 815 billion in 2011 to 1.57 trillion in 2032. The Advisory Council for Aeronautics Research in Europe (Acare) has set ambiguous goals to cut down aviation emissions to reduce the environmental effects created by aircraft life-cycle. The life-cycle of an aircraft can be divided into four main phases:

- Design and development,
- Production,
- Operation,
- End-of-life.

These phases have environmental impacts, which are: Consumption of raw materials from the ecosphere and production of gaseous, liquid or solid releases.

However, the impact of aviation has a small overall contribution. In 2004 the impact of aviation was only 2 % compared to other industries (refer to section 2.4). The problem for aviation should be seen over the last forty years. During this time engines have been improved and consume 60 % more efficient fuel. Aircrafts are significantly more eco-friendly than forty years ago. By continuing ecological improvements, aircrafts should meet Acare environmental objectives.

Butyniec, the CEO of Magellan Aerospace said: “The alignment of our strategy with the direction of our customers and the global industry has never been stronger. Investment driven by knowledge and a culture committed to meeting customer requirements has been the key to our success. Achieving and sustaining operational excellence is essential.”

This project work, *Creating a Life-Cycle Assessmen of an Aircraft*, is a research of life-cycle assessment of aircraft wich leads to a better knowledge of LCA and a possible method to perform this on aircrafts.

1.2 Objectives

The aim of this work is to investigate if it is possible to make a LCA of an aircraft. How can this be done? Have there been previous attempts before? The eventual goal is to create a basic life-cycle for an aircraft. Therefore life-cycle assessment is explained. The basis lies in applying this for the A320. In order to make a LCA, previous methods have to be considered. Enough relevant data has to be gathered to generate the LCA. The objective of this work is more directed to the aircraft.

1.3 Structure of the Work

This report is structured in six chapters as follows:

Chapter 2 Explains the impact of aviation on the environment. The emissions of concern for the LCA are determined and explained.

Chapter 3 Explains what life-cycle assessment is. Many terms are explained and a comparison of LCA tools is given. A LCA of a paperclip is conducted to familiarize with Gabi.

Chapter 4 Gives an overview of LCA's of aircraft and summarizes the results.

Chapter 5 Compares the results of chapter 4. The tool EIO-LCA (Economic Input-Output Life-cycle Assessment) is used.

Chapter 6 A basic life-cycle assessment of the A320-200 is made in following phases: goal and scope, inventory and assessment.

2 Impact of Aviation on the Environment

2.1 Emissions from Aviation

In flight aircraft produce emissions from fuel combustion. These are amongst others Carbon dioxide (CO2), water (H2O), nitrogen oxides (NOx), carbon monoxide (CO), sulphur oxides (SOx), Hydrocarbons (HC) (or Volatile Organic Compounds (VOC)) and particles. A subset of VOC and particles are considered as hazardous air pollutants (HAP). It is a good idea to differentiate emissions close to the ground (landing and take-off) from emissions in cruise because cruise emissions contribute primarily to global warming and „lower“ emissions can be seen as local air pollutants. Also water in the aircraft exhaust at altitude has a greenhouse effect and occasionally this water produces contrails that also have a positive warming effect (**Avstop 2012**). At last, the operation of the airport has an impact on the environment. For example the use of an auxiliary power unit (APU) or ground power unit (GPU) and shuttle services uses fuel. De-icing uses contaminating fluids etc.

2.1.1 Emissions from Fuel Combustion

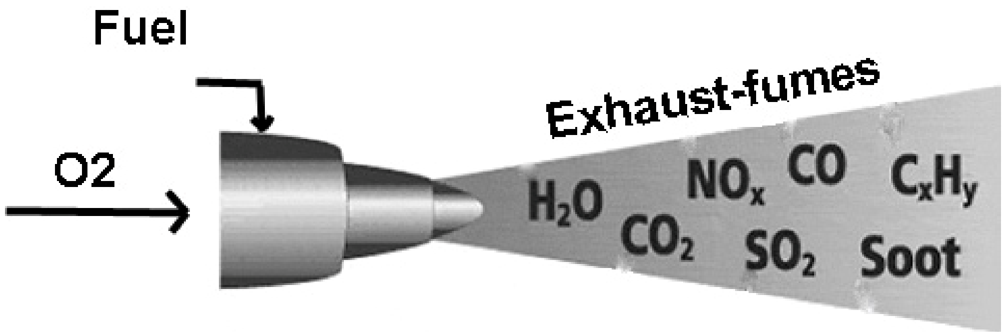


Figure 2.1 Fuel combustion emissions

CO2 and H2O are the products of complete combustion of hydrocarbon fuels, like jet A1. NOx are produced when nitrogen and oxygen are present in high temperature and pressure. HC are emitted due to incomplete fuel combustion. They are also referred to as VOC. CO is also formed due to the incomplete combustion of the carbon in the fuel. SOx are produced when small quantities of sulphur, present in essentially all hydrocarbon fuels, combine with oxygen from the air during combustion. Particulates are form as a result of incomplete combustion, and are small enough to be inhaled. They can be solid or liquid. Ozone (O3) is not emitted directly into the air but is formed by the reaction of VOC and NOx in the presence of heat and sunlight (**Avstop 2012**).

2.2 Emission Index

The Emission Index (EI) [g/kg fuel] is used to indicate the quantity of pollutant per kg 100 kg of burned fuel (**Schmitt 2009**).

For 1 kg burned kerosene about 4,4 kg engine exhaust-fumes are produced. These emissions are (**Environment 2009)**:

- 3,16 kg CO2 (destroys ozone and methane),
- 1,24 kg H2O,
- 14 g NOx,
- 3 g CO
- 0,8 g SO2,
- 0,4 g HC,
- 0,025 g soot particles,
- OH, Methane and lubricant,
- Linear contrails.

Kerosene combustion by-products depend on:
- Operating conditions,
- Altitude,
- Humidity,
- Temperature.

2.3 Radiative Forcing

Radiative Forcing (RF) is the irradiance per kg atmosphere presented in Watts per square meter per kilogram [W/m²/kg]. Integration of RF results in absolute global warming potential [J/m²/kg].

$$GWP_{absolute} = \int_{horizon} RF(t)dt \tag{2.1}$$

If you consider the Earth's heat-capacity then RF has a Global temperature change potential presented in Kelvin per kilogram [K/kg]. This eventually leads to a global temperature change. For long-sustaining gasses (CO2 ≃ 100 years) following model applies:

$$\Delta T \cong \lambda \cdot RF \tag{2.2}$$

This general agreement is supported by many experiments which suggest a linear relationship between the global ground temperature change and radiative forcing. $\lambda\left[\frac{K}{w \times m^2}\right]$ is dependent from the model and the gas (**Lopes 2010, Schmitt 2009**).

The fuel is combusted in the engine and emitted in the atmosphere. Aircraft emissions alter the composition of the atmosphere by direct emissions and atmospheric processes. This changes the radiative forcing of the environment, which potentially leads to climate change and that can impact human health, ecosystems, etc. This eventually damages the social welfare and costs. Figure 2.2 illustrates this.

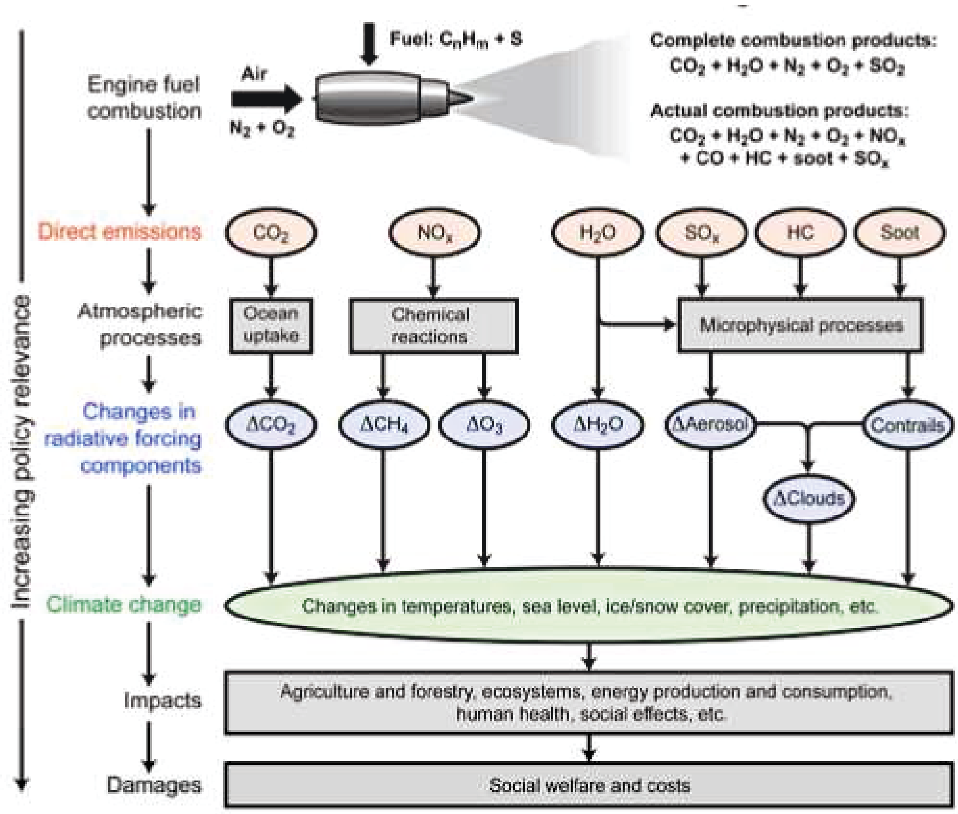


Figure 2.2 Aircraft emissions and climate change (Global 2009)

Aviation changes the concentration of Greenhouse Gasses (GHG) that affects RF. A positive value entails a warming effect, a negative value entails a cooling effect. According to **Global 2009** aviation has following impacts on RF:

- Emissions of CO2, that result in a positive RF,
- Emissions of NOx, resulting in the formation of tropospheric O3 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 O3 (negative RF, cooling effect),
- Emissions of H2O (positive RF),

- Formation of persistent linear contrails that, depending on the weather conditions, may be formed in the wake of an aircraft (positive effect),
- Emissions of sulphate particles (SOx) caused by the existence of sulphur in the fuel (negative RF),
- Emission of soot particles (negative RF),
- Aviation-induced cloudiness (AIC, potentially a positive RF).

It is well known that aviation has an impact on climate change. This has been a subject of great research. An important study is "Aviation and the global atmosphere" (**IPCC 1999**). The study estimates that non-CO2 emissions are responsible for 63 % of the total RF-effect.

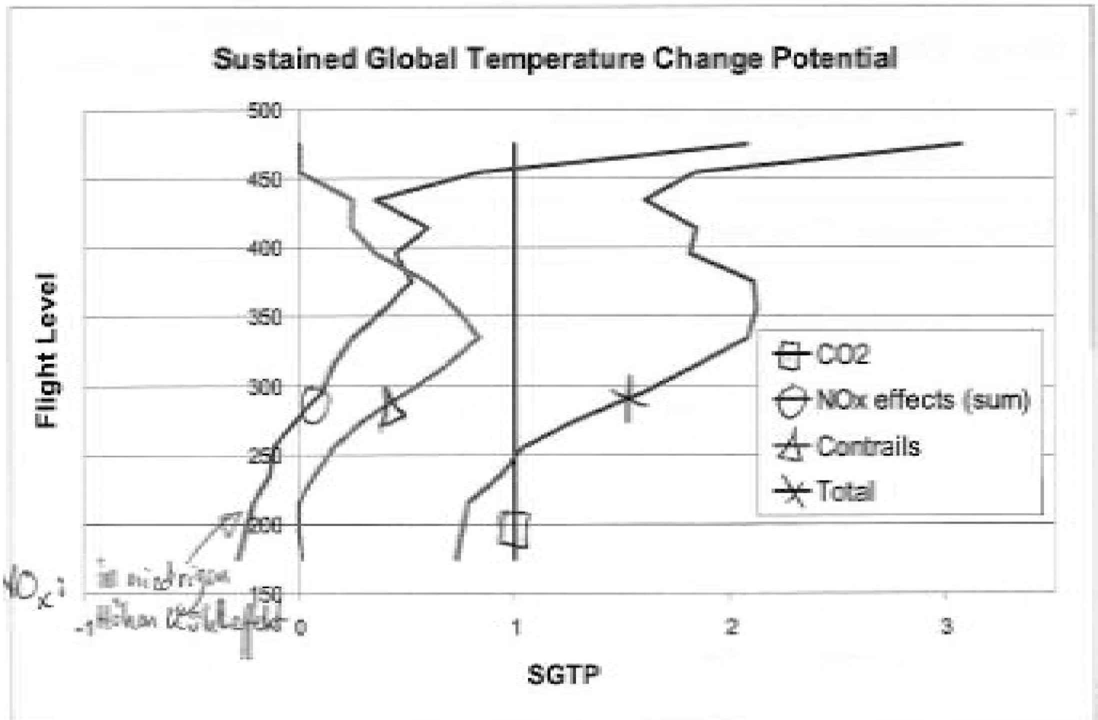


Figure 2.3 Impact of emissions on global warming, Low Emission Effect Aircraft project (**LEEA 2006**) (adapted from **Schmitt 2009)**

Statistics of Figure 2.3 are based on continuous emissions. Output: change of temperature normalized to CO2 (GGE). NOx effects: Formation of ozone, methane destruction, and feedback on methane concentration of ozone interference.

Aviation emissions in cruise are dispersed between 8 and 12 Km. This has a direct impact on the atmosphere composition. Therefore it is important to know what routes airplanes follow and how much time they spend in the cruise phase. CO2 has a long atmospheric residence and will stay in the air for many years. Other gasses and particle have a shorter atmospheric residence time, these gasses may cause problems close to the ground. This means that regions close to an airport will excess more RF. That is why it is a good idea to differentiate emissions close to the airport from cruise emissions.

2.4 Comparison with other Polluters

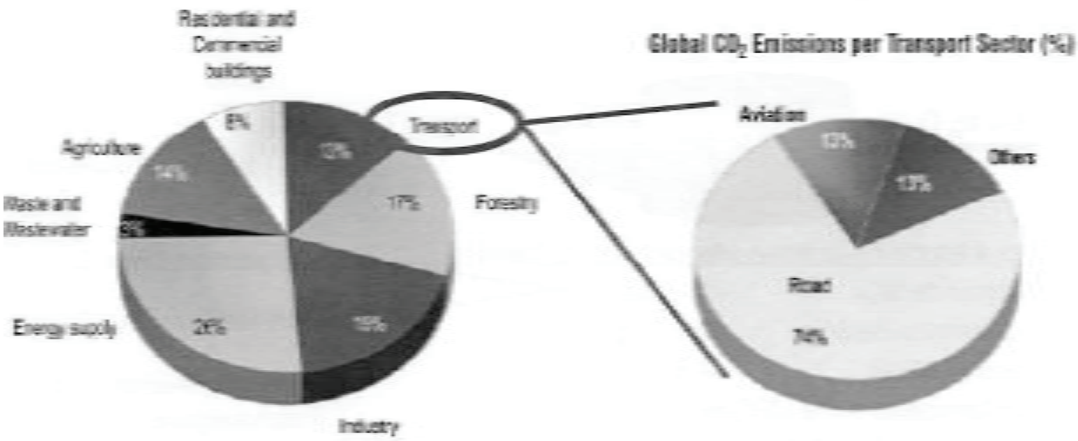


Figure 2.4 Impact of aviation on global CO2-emission in 2004 **(Schmitt 2009)**

In 2004, aviation had a share of 2 % of the global CO2 emission. It seems that aviation has a small overall contribution. But if you consider the time that an average person travels by air each year then aviation has huge emissions compared to the time he invests in other transportation modes.

2.5 Environmental Effects Included

The emissions of concern to the environment are (**EPA 2008a, EPA 2008b**):

- Greenhouse gasses – traps heat in the atmosphere,
- Sulphur Dioxide (SO2) – is bad for the respiratory system and can aggravate existing pulmonary and cardiovascular conditions. When SO2 is emitted to air, it can dissolve into water droplets or into the ground. This affects vegetation and animals,
- Carbon Monoxide (CO) – low exposure leads to hypoxia, angina, impaired vision and reduced brain function. High concentrations cause asphyxiation,
- Nitrogen Oxides (NOx) – Short term exposures of NO2 causes inreceased respiratory symptoms. NOx together with VOCs and sunlight it forms ozone which can damage lung tissues an aggregate respiratory symptoms. It increases the nitrogen loading in water which the disturbs the ecosystem, and reacts with common organic chemicals in the atmosphere to produce toxic products,
- Volatile Organic Compounds (VOC) - VOC means any organic compound having an initial boiling point less than or equal to 250°C measured at a standard pressure of 101,3 kPa. (**EUR-LEX 2012)** The toxic VOCs can cause eye, nose and throat irritation, central nervous system damage and cancer. In presence with NOx and sunlight it forms O3,

- Particulate Matter (PM) – Particles that are smaller than 10 micrometer (PM_{10}) in diameter can easily pass through the throat and enter the lungs. This can cause serious health effects like decreased lung function, nonfatal heart attacks and premature death. The modes of transport differ from the particle size. Some can easily enter the bloodstream. Fine particles ($PM_{2,5}$) reduce the visibility. Particles can be transported over long distances before they settle. The effect of this settling can damage the ecosystem,
- Lead (Pb) – The major sources of lead emissions to the air today are ore and metals processing and piston-engine aircraft operating on leaded aviation gasoline. Others are utilities and lead-acid battery manufacturers. Lead can affect the nervous system, kidney function, immune system, reproductive and developmental systems and the cardiovascular system.

3 Life-Cycle Assessment

A life-cycle assessment is defined in **ISO 14040** and **ISO 14044**. An LCA of a product are all the inputs and outputs through its life-cycle that are evaluated in the assessment and their impact on the environment.

The inputs are the resources required and the outputs are the emissions to the air, land, sea…
An LCA of a product can be used for:

- Planning environmental Strategies,
- Product Development,
- Marketing,
- Comparisons,
- Follow Legislation,
- Ecolabeling.

3.1 Four Main Phases

An LCA consist out of four main phases:

- Goal and scope,
- Life-cycle Inventory,
- Life-cycle Inventory assessment (LCIA),
- Interpretation.

3.1.1 Goal and Scope

In the goal are a number of questions answered. What is the reason why we want to do an LCA and what is the overall goal that we want to accomplish? The target group for the LCA report is defined. This could be the industry that wants to do the LCA. And a final question that must be answered is if the study is a comparative study or not.

For the scope a **product description** must be given. The function of an aircraft is to transport passengers. What are the demands for the aircraft? The **functional unit** of an aircraft can be transporting a passenger 1 km.

After defining the functional unit a **reference flow** must be defined. A reference flow is a unit that could represent how many planes I need to achieve to one functional unit. This depends on the type of plane.

Assumptions of the result have to be made. Also the **system boundaries** have to be defined. Maybe it is useful for a LCA to omit phases of the life-cycle that have no or low relative impact on the environment.

The **Impact categories** have to be defined. Impact categories can be for example the ecological footprint, CO2 equivalent (eq.) or global warning impact potential. The quality requirements for the data have to be defined.

A methodology to set up the product system must be defined by **cut off criteria**. The cut off criteria can for example be defined by mass. If the mass is less than 5 kg then it can be excluded from the system. Also systems that have no impact on LCA can be neglected.

System Boundaries have to be made. The boundaries for a natural system can be:

- Cradle to Gate (resources),
- Gate to Gate (manufacturing),
- Gate to Grave (use),
- And Cradle to Grave.

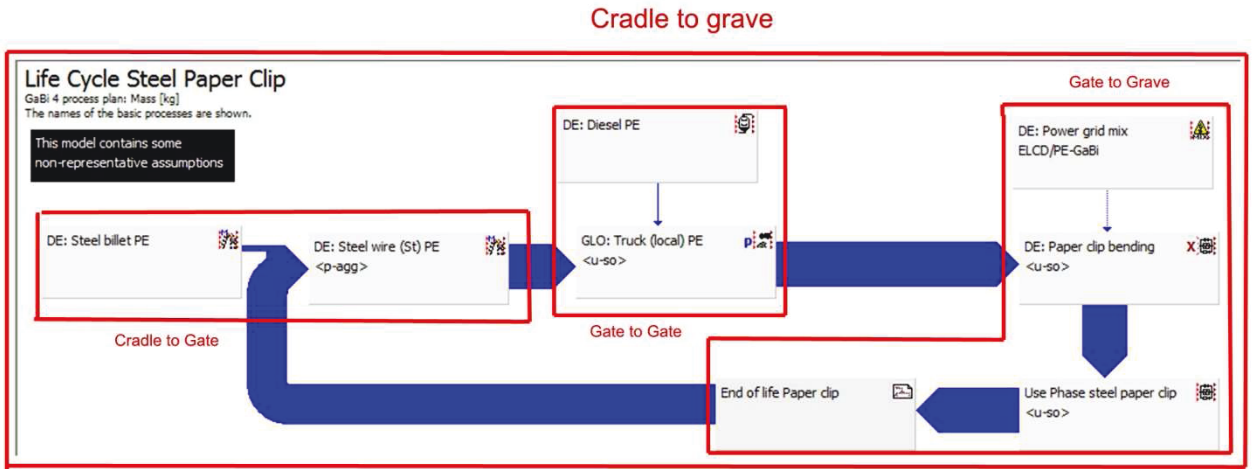


Figure 3.1 System boundaries of a life-cycle Steel Paper Clip (see also section 3.4)

3.1.2 Life-Cycle Inventory

The Life-Cycle Inventory (LCI) is the most time consuming part of LCA. In the LCI quantitive and qualitative data from the product is collected. Data can be gathered by plant visits, this is named primary data, or by literature research and databases, named secondary data. Primary data is more accurate but also more time consuming.

After validation of/and allocation of the data the boundaries can be redefinitionned. This is why LCA is an iterative process.

When all the data of the system is available, the modelling of the system can be made (LCI modelling). Figure 3.2 represents a model of a paperclip. The LCI is in fact a Table containing all the input and output flows.

Inputs ☑ Just elementary flows ☑ separate IO tables Diagram -

	Life Cycle Stee
Flows	17,9
Resources	17,9

Outputs Diagram -

	Life Cycle Stee
Flows	4,29
Resources	2,13
Emissions to air	2,16
Emissions to fresh water	0,00356
Emissions to sea water	0,000239
Emissions to industrial soil	5,38E-006

Figure 3.2 Life cycle inventory table example

3.1.3 Life-Cycle Inventory Assessment

The LCIA consists out of four steps:

1. Classification (mandatory)
2. Characterisation (mandatory)
3. Normalisation (optional)
4. Evaluation (optional)

With classification, all the outputs are classified to their impact category. Some emissions have one impact category and others have multiple. In the characterization phase, factors are given to each emission, representing the contribution to a category. Characterisation factors are determined by different scientific groups based on different methodology and philosophical views of the problems. The most widely used methodologies are in the United States (US): Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

(TRACEY) and in the European Union (EU): Institute of Environmental Sciences (CML) (website **GaBi 2012a)**. An example is given in Figure 3.3.

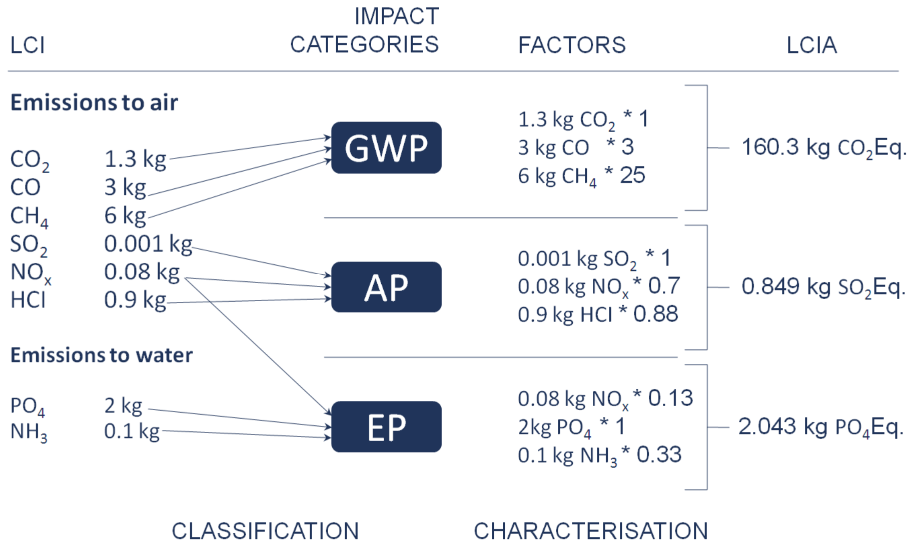


Figure 3.3 Classification and characterisation example (**GaBi 2012**)

LCIA methods exist either for midpoint or for endpoint and both for integrated LCIA methodologies. They have advantages and disadvantages. In general midpoint assessments are classified to a higher number of impact categories (average around 10) and the results are more accurate than the endpoint assessments. In Figure 3.4 the weighing factors are not shown and they can start from either midpoints or endpoints. (**EC 2010**)

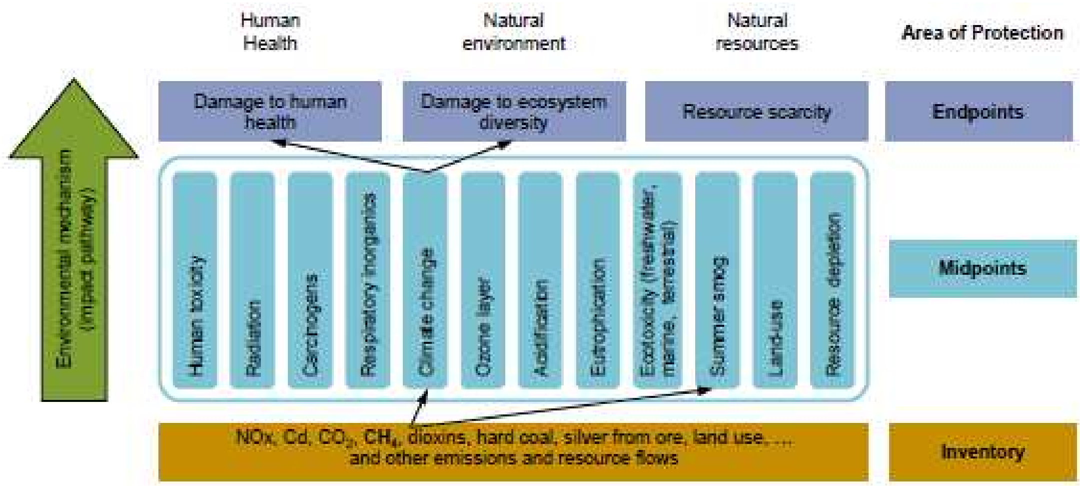


Figure 3.4 Life cycle impact assessment. Schematic steps from inventory to category Endpoints (**EC 2010)**

3.1.4 Interpretation

The final step is the interpretation of the results. This is a very important step. What are the environmental hot spots? The results must therefore be checked with the goal and scope definition. This phase is also an iterative procedure. In the evaluation three important aspects have to be checked. First any missing or incomplete methods have to be added. Second the uncertainty effect has to be checked. How sensitive are the results to certain assumptions? Third, the information has to be consistent, i.e. no allocation or wrong data.

The goal of the LCA is to draw a conclusion. The study can be documented in an LCA report, which is specified by **ISO 14044**. The layout of the document should contain the same components. Before the publication of the report a critical review is required.

3.2 LCA Terms

I order to work with GaBi some LCA terms have to be understood.

Within a **plan** the system is made up from processes and flows. This represents the system with its boundary's. **Flows** consist out of all the inputs and outputs of the system. They connect plans or processes. From a plan, a balance calculation can be made by GaBi. This results in a complete list of input and output flow, named **LCI** and eventually the LCIA. A **process** is a system with in- and outputs. **Elementary flows** are the flows that leave or enter the system from the natural environment. As defined by **EC 2010** elementary flows are: *"single substance or energy entering the system being studied that has been drawn from the ecosphere without previous human transformation, or single substance or energy leaving the system being studied that is released into the ecosphere without subsequent human transformation"*.
In the database flows can be found. Resources and emissions to air are examples of elementary flows. These contain classification and characterization factors. A flow can be determined as an input, output or both. The technical system is also called the **technosphere**. Elementary flows enter or exit the technosphere. **Track flows** include valuable substances that can be used into other processes. These flows stay in the technosphere. **Waste flows** are used in the end of life scenario.

Every process has its inputs and outputs. Multiple inputs and outputs can be assigned in GaBi. For example Steel wire has two inputs. Witch processes that have to be added are defined in the Goal and Scope. There are 5 types of processes:

A **unit process single operation (u-so)** contains only the process, no LCI data. A Unit **process black box (u-bb)** is a unit operation with multifunctional processes, process chain or plant level. A LCI result contains all the data (aggregated dataset) from cradle to gate or grave. This is named a **System process (agg). Partly terminated system (p-agg)** is a unit process with at least one product flow requiring modelling. **Avoided product system (aps)** is a unit process with negative flows or outputs converted to inputs and vice versa.

3.3 LCA Tools

LCA tools are used to answer product sustainability questions. How can we design a sustainable aircraft that has a competitive advantage? They can give answers to (**GaBi 2012a**):

- Research and development,
- Sustainability/Environment Department,
- Marketing & communications,
- Supply Chain,
- Operations.

A comparison of LCA tools should be made to choose a suitable tool for LCA of an aircraft. A comprehensive list of tools can be found on the European commission LCA site (**Europe 2012**). **Primary tools** are dedicated packages for practitioners, **secondary tools** are for people who want LCA based results, but don't want to build large inventories. Solid Works, for example, is more a tool to be used on a single part or assembly to have LCA idea, and classified as a secondary tool. For the comparison only primary tools will be used. From literature (**Unger 2004**) and other LCA comparisons (**Sipilä 2012, Menke 2012**), 7 tools have been chosen, these are: GaBi, Simapro, Quantis SUITE, Umberto, LCAiT and KCL-ECO. No tools have been found with a mentioned database for aviation. Some properties of these tools are summed below:

- KCL-ECO, TEAM and LCAiT have highly detailed LCI and LCIA,
- GaBi and Simapro have a free tutorial and manual,
- GaBi, Simapro and TEAM are known to have a large database,
- Umberto has a smaller database,
- Simapro is extensively used within the industry,
- Many tools, including GaBi, Simapro and TEAM, offer Demo-versions.

Table 3.1 Implementation of tools (**Sipilä 2012, Menke 2012**)

LCA Software	GaBi	Simapro	Umberto	LCAiT
Implementation	moderate	Careful study is needed	Takes time	Very easy

Table 3.2 Comparison of tools (Developers websites, **Sipilä 2012, Menke 2012**)

	GaBi	**Simapro**	**Quantis SUITE 2.0**	**Umberto**	**LCAiT**	**TEAM**	**KCL-ECO**
origin	Germany	Nether-lands	Joint venture of Canada and Switzerland	Germany	Sweden	England	Finland
Price	Cost free student version	PhD: 1,2 K EUR	3,200 K EUR	6,6K EUR	3,5K $	10K $	3,6K $
Vendor	PE Europe GmbH	PRe' Consult-ing	Quantis International	IFU	LCAiT	Ecobilan (also Eco-balance)	Finnish Paper Inst.

No website has been found of LCAiT and KCL-ECO. These tools are probably sold to other companies. LCA references are quickly outdated; it is a rapid changing industry. **SimaPro** seems to be a good tool for LCA of aircraft because it has been used before on the A330-200 and on composite aircraft components. It can analyse complex products like aircrafts. **GaBi** is also a good tool. The determining factor is that it has a free educational version. Therefore GaBi is used.

3.3 Environmental and Energy Data

LCA tools rely on their databases. The following sources can provide environmental and energy data:

- World Resources Institute,
- United States Environmental Protection Agency,
- The United Kingdom department of Energy and Climate Change,
- Intergovernmental Panel on Climate Change,
- Inventory of Carbon & Energy, Bath University,
- European Environment Agency,
- EcoInvent,
- CO2 Benchmark,
- Centre for Agriculture and Environment,
- Carbon Disclosure Project.

3.4 Creating a LCA in GaBi

To familiarize with GaBi, a LCA of a paperclip will be made. After applying for GaBi education a link has been send to download and install the software. The database used in this example is education_DB.

In the Education_DB a new project can be made and activated. All plans, processes, etc. made when this project is activated are saved to the project. This makes it easier to find all data back. Then a plan can be made. The plan is named “Life Cycle Steel Paper Clip”. Process and flow information can be added to the plan as easy as dragging and dropping. After adding all the processes and flows the plan looks like Figure 3.5. The modelling of the life-cycle of a paperclip is now completed. A balance can be made by GaBi.

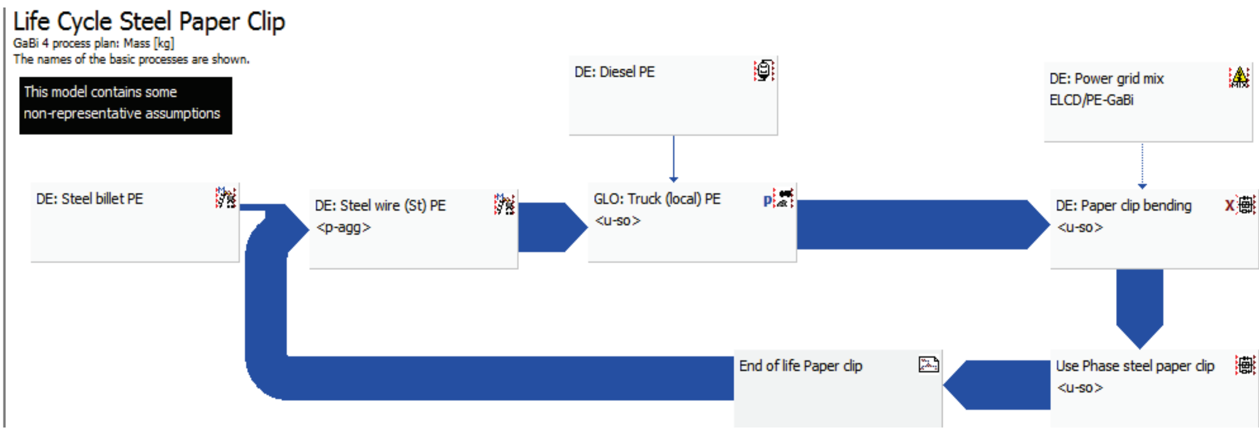


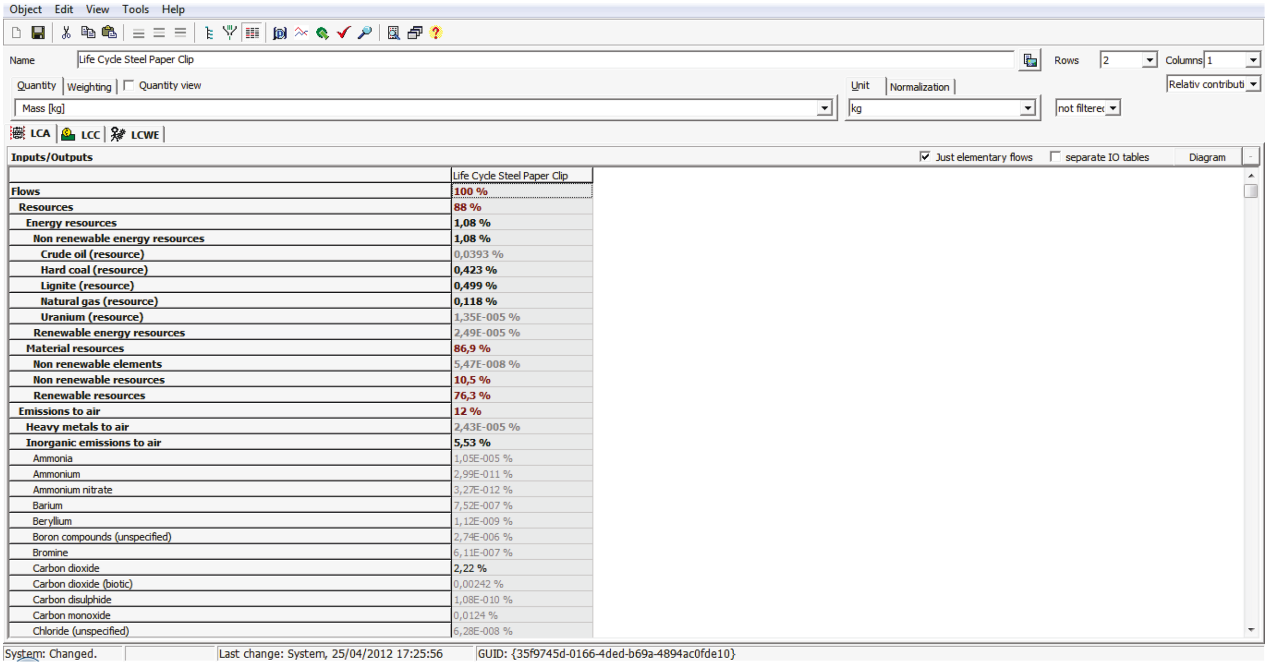
Figure 3.5 Plan of a steel paper clip

3.4.1 Creating a Balance

A balance is a file containing an overview of all LCI and LCIA results. The file can be found in the balances folder of the database. A balance is automatically generated when clicking on the respective button. When opening a balance in GaBi all the results are displayed in a Table. The way of viewing the results can be done in many ways:

- Table
  - Absolute values
  - Relative contribution
- Weak point’s analysis: display crucial contributors in red. This is very useful because there are many emissions that have no significant contribution.
- Quantities
  - Mass (kg)
  - Volume (m^3)

  - CML2001, Global Warming Potential 100 years (kg CO2 eq.)
  - ..
- Input/outputs
  - Aggregated
  - Separate
- Display only elementary flows
- …



	Life Cycle Steel Paper Clip
Flows	100 %
Resources	88 %
Energy resources	1,08 %
Non renewable energy resources	1,08 %
Crude oil (resource)	0,0393 %
Hard coal (resource)	0,423 %
Lignite (resource)	0,499 %
Natural gas (resource)	0,118 %
Uranium (resource)	1,35E-005 %
Renewable energy resources	2,49E-005 %
Material resources	86,9 %
Non renewable elements	5,47E-008 %
Non renewable resources	10,5 %
Renewable resources	76,3 %
Emissions to air	12 %
Heavy metals to air	2,43E-005 %
Inorganic emissions to air	5,53 %
Ammonia	1,05E-005 %
Ammonium	2,99E-011 %
Ammonium nitrate	3,27E-012 %
Barium	7,52E-007 %
Beryllium	1,12E-009 %
Boron compounds (unspecified)	2,74E-006 %
Bromine	6,11E-007 %
Carbon dioxide	2,22 %
Carbon dioxide (biotic)	0,00242 %
Carbon disulphide	1,08E-010 %
Carbon monoxide	0,0124 %
Chloride (unspecified)	6,28E-008 %

Figure 3.6 LCI of a steel paper clip

A desired number of rows can be selected to make a diagram. The numerous visual aspects of the diagram can be adjusted. Figure 3.7 gives us an idea of how much mass energy resources required to produce one steel paper clip.

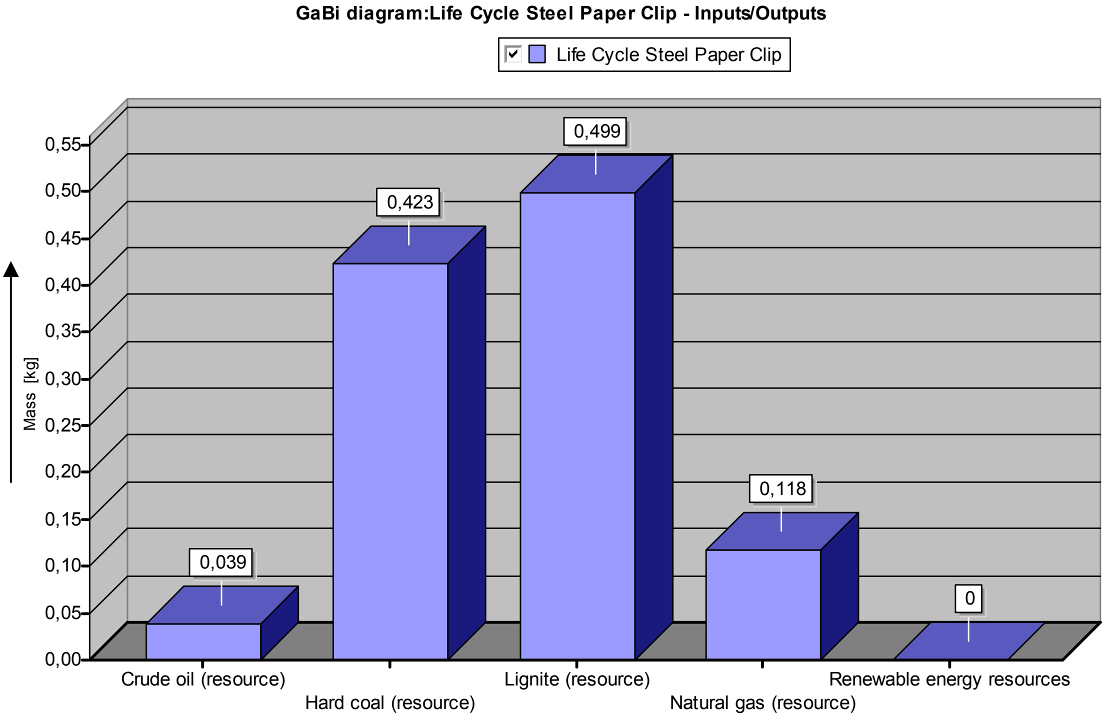


Figure 3.7 Diagram of the energy resources to produce one steel paper clip

4 Literature Research for already Existing Life-Cycle Assessments of Aircraft

12 search engines have been used to find existing life-cycle assessments of aircraft. The results are listed below:

University of Stuttgart (Germany):

- NICETRIP – Novel Innovative Competitive Effective Tilt Rotor Integrated Project. 2006-2011 (completed). WP6: Dissemination, sustainability and perspectives: Task 6.2: Sustainability assessment.
- SINTEG – Eco – Accounting of Manufacturing of Lining Elements. From 2009 to 2012 (still active).

Cleansky (EU):

Cleansky is a partnership involving industries and the European Union. It is an ambitious aeronautical research programme with a starting budget of 1,6 billion EUR in 2008. A large effort has been made on LCA. Benchmarking of existing tools has been conducted and LCA analyses have been performed on significant parts of aircraft. The documents are not yet published because it is still in progress.

Argonne national laboratory (US):

Development of a LCA module for aviation fuel / aircraft systems in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET). GREET is a fuel-cycle model which can be downloaded for free on the site.

University of Sheffield (United Kingdom, UK):

Potential emissions savings of lightweight composite aircraft components evaluated through life-cycle assessment.

Yale school of forestry & environmental studies (US):

Multiscale life-cycle assessment.

More:

Geldermann 2008, Horvath 2006, Enviroment 2009, Cooper 2003, Scelsi 2011, Koroneos 2005.

Table 4.1 Overview of methods used to create LCA of aircrafts

Project	**Scelsi 2011**	**Lopes 2010**	SINTEG 2009-2011	NICETRIP 2006-2011	**Chester 2008**
Software	Simapro 7.1	Simapro 7.2	GaBi 4	GaBi 4	See below
Database	Ecoinvent	Ecoinvent	GaBi databases		x
What	Composite aircraft components	Whole a/c	interior sidewall panel	Rotorcraft-system	Whole civil aviation
Who	**Scelsi 2011**	**Lopes 2010**	Diehl Aircabin & GaBi	GaBi	**Chester 2008**
LCI (data collection)	x	Matching SRM & W&B manuals	x	x	x
LCIA	x	ReCiPe 2008	x	x	x

Most environmental studies cover the cruise phase because aircraft have large fuel requirements. Also many LTO-cycle studies are done because population exposure rates could be higher around airports. Some components of aircraft have been assessed. The lack of studies could be due to lack of data availability (**Chester 2008**).

4.1 Methods and Results of Chester

A PhD thesis of the Life-cycle Environmental Inventory of Passenger Transportation in the United States has been made in 2008 (**Chester 2008**). It covers a literature research for LCI‘s of aircraft. The results are; one reference about the manufacturing and end-of-life scenario (1) and nine references that cover the operational aspect (2).

(1) **Facanha 2007**

(2) **Levinson 1998b**, **INFRAS 1994**, **Schipper 2003**, **FAA 2007**, **Greene 1992**, **EEA 2006**, **EPA 1999b**, **Lee 2001**, **Facanha 2007**

According to **Chester 2008**, his work is the first comprehensive LCI of the full passenger transportation system. Most LCI’s have a scope limited to the operation stage. Chester created his LCI with different methods. These are summarized in Table 4.2.

Table 4.2 Summary of the LCA methods of Chester

Phase	Data Sources	Tool
Manufacturing		
Airframe	Janes 2004, AIA 2007, Boeing 2007	EIO-LCA
Engine	Jenkinson 1999	EIO-LCA
At or Near-Airport Operations		
APU	FAA 2007	Process
Start-up	FAA 2007	Process
Taxi Out	FAA 2007	Process
Take-Off	FAA 2007	Process
Climb Out	FAA 2007	Process
Approach	FAA 2007	Process
Taxi in	FAA 2007	Process
Cruise Operations	EEA 2006, Romano 1999	Process, Literature
Maintenance		Disaggregated into
Aircraft Components	BTS 2007, fleet reports (EPA 1998)	EIO-LCA
Engine Components	BTS 2007, fleet reports (EPA 1998)	
Insurance		
Vehicle Incidents		EIO-LCA
Flight crew Health & Benefits		EIO-LCA

EIO-LCA (Economic Input-Output Life-cycle Assessment) is a tool that calculates the emission impacts according to the turnover of an industry process. The tool used to process at or near-Airport operations is Emission Data Modelling Software (EDMS) **(FAA 2007).**

The results of Chester are shown in Fig 4.1.

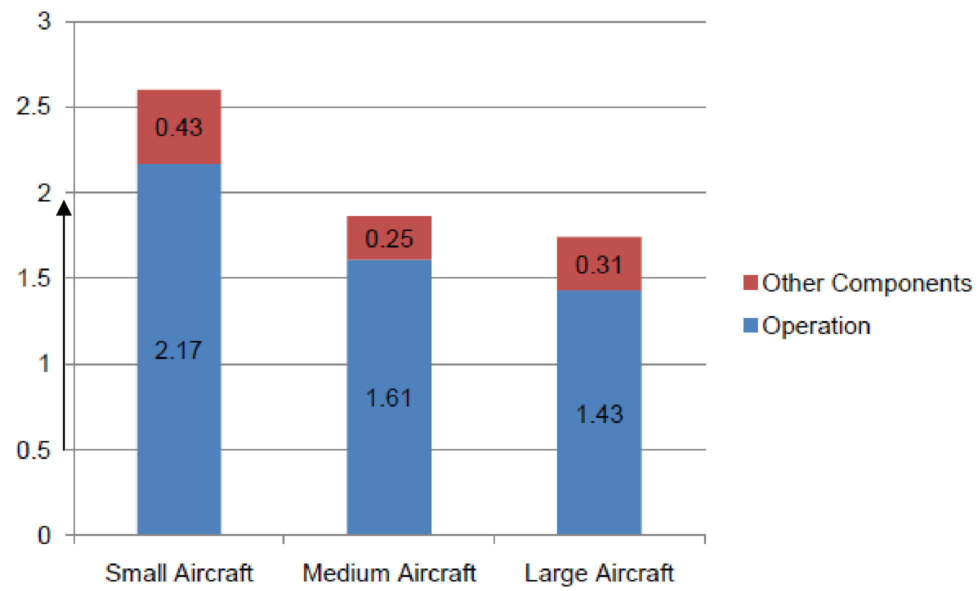


Figure 4.1 Emissions of air transport in the entire life-cycle in MJ/PKT

4.2 Method and Results of Lopes

Lopes used Simapro to create the LCA of an A330-200. The results of **Lopes 2010** are summarized in Table 4.3. Simapro offers the ability to perform an uncertainty analysis, which provided a reasonable uncertainty range regarding to the CO2 emission factor. Table 4.5 gives an overview of all the impact categories of the LCA. The conclusion of his work says that the environmental hot spot comes from fuel consumption. Further the manufacturing process modelled could be used for LCA practitioners in the future because it should be more realistic than the process from EconInvent database.

Table 4.3 The respective climate impact of every life phase of the A330-200 (**Lopes 2010)**

Phases of life-cycle A330-200	Impact on climate change (%)
Fuel burn	99,9
Airport construction	0,0591[a]
Aircraft maintenance	0,000158[a]
Manufacturing aircraft	0,00000468
End-of life scenario	Very small environmental benefit

[a]Assumptions and uncertainties of the adapted EcoInvent processes must be taken into account.

Table 4.4 Impact categories by **Lopes 2010**

Impact category	Unit	Total life-cycle A330-200
Climate change	kg CO2 eq.	1,26E-01
Ozone depletion	kg CFC-11 eq.	1,58E-08
Human toxicity	kg 1,4-DB eq.	2,64E-03
Photochemical oxidant formation	kg NMVOC	6,41E-04
Particulate matter formation	kg PM10 eq.	1,65E-04
Ionising radiation	kg U235 eq.	8,07E-04
Terrestrial acidification	kg SO2 eq.	4,87E-04
Freshwater eutrophication	kg P eq.	4,82E-07
Marine eutrophication	kg N eq.	2,12E-04
Terrestrial ecotoxicity	kg 1,4-DB eq.	1,17E-05
Freshwater ecotoxity	kg 1,4-DB eq.	5,57E-05
Marine ecotoxity	kg 1,4-DB eq.	9,07E-05
Agricultural land occupation	m2a	1,17E-04
Urban land occupation	m2a	1,92E-04
Natural land occupation	m2	6,33E-05
Water depletion	m3	1,50E-04
Metal depletion	kg fe eq	5,37E-04
Fossil depletion	kg oil eq	4,37E-02

Manufacturing phase components contribution to climate change:

- Wing 38,6 %,
- Engines 21,9 %,
- Fuselage 22 %,
- Other 17,5 %.

Material contribution to climate change:

- Largest contributor: Carbon fiber reinforced polymer (CFRP) 57,6 % (around 9 % of aircraft weight),
- 2nd contributor: Aluminium alloy 24 % (58 % of the total weight and most used material of the aircraft).

5 Comparison of EIO-LCA and Simapro

A method of Chester and Lopes will be compared in this chapter to see if those obtain the same results. Chester used EIO-LCA to model the manufacturing phase of the Boeing 737. Lopes used Simapro to model the manufacturing phase of the A330-200. With EIO-LCA the impact of manufacturing the A330-200 has to be assessed. This result can then be compared with Simapro. The impact category used for this comparison is Global Warming Potential (GWP). Because EIO-LCA has two different sectors for the engine and airframe, they will be separated.

5.1 Engine in EIO-LCA

The A330-200 can have different engines. The General Electric (GE) CF6-80E1 is used in this LCA. According to **IASG 2012** the engine cost is around \$ 12 million (2006 \$**)**. The A330-200 has two engines. To convert 2006 \$ to 2002 \$, a consumer price index tool of the US bureau of Labour statistics is used. This gives us 21 million 2002 \$ for two engines (**CPI 2012**). The price has to be reduced to production cost. According to an assumption of **Chester 2008** a 10% mark-up is used which results in \$ 19 million.

By entering this amount into the EIO-LCA tool the LCIA results are given. This tool uses a model to compute the results. Model US 2002 (last updated at 4 July 2010) is used because it is the most current version and it has a representative sector namely, „Aircraft and Engine Parts Manufacturing“. Even though the aircraft is not manufactured in the US, the model from Germany has no representative sector. Weighing factors are 100-year GWP values from the IPCC second assessment report. For example the 100-year GWP value for N2O is 310.

Table 5.1 GHG emissions from manufacturing the GE CF6-80E1 (**EIO-LCA 2012**)

Sector ↓	**Total t CO2e[a]**	**CO2 Fossil[d] t CO2e[a]**	**CO2 Proces[e] t CO2e[a]**	**CH4 t CO2e[a]**	**N2O t CO2e[a]**	**HFC[b]/PFC[c] t CO2e[a]**
Total for all sectors	*6690*	*5410*	*666*	*421*	*52,3*	*137*
Power generation and supply	2780	2730	0	7,52	17,0	17,6
Iron and steel mills	868,0	328,0	535,0	5,28	0	0
Aircraft engine and engine parts manufacturing	596,0	596,0	0	0	0	0
Truck transportation	283,0	283,0	0	0	0	0
Oil and gas extraction	234,0	65,9	42,9	12,0	0	0
Air transportation	123,0	123,0	0	0	0	0
Coal mining	117,0	13,2	0	104,0	0	0
Alumina refining and primary aluminium production	114,0	25,8	40,4	0	0	47,6
Petroleum refineries	114,0	113,0	0	0,352	0	0
Waste management and remediation services	88,4	3,23	0	84,2	0,957	0

a: Metric tons of CO2 eq.
b: Hydrofluorcarbons.
c: Perfluorcarbons.
d: Each sector from fossil fuel combustion.
e: Sector sources other than fossil fuel combustion.

5.2 Airframe in EIO-LCA

According to **Airbus 2012**, the average price list of the A330-200 is $ 208,6 million (2012 $). In a similar way as with the engine the assessment of the airframe can also be made. The results are in Table 5.2

Table 5.2 GHG emissions from manufacturing the A330-200 **(EIO-LCA 2012)**

Sector ↓	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFC t CO2e
Total for all sectors	*54400*	*41800*	*7340*	*3230*	*485,*	*1610*
Power generation and supply	20400	20100	0	55,4	125,0	129,0
Iron and steel mills	9850	3720	6070	60,0	0	0
Truck transportation	2780	2780	0	0	0	0
Oil and gas extraction	1890	533,0	347,0	1010	0	0
Aircraft manufacturing	1150	1150	0	0	0	0
Alumina refining and primary aluminium production	1090	246,0	385,0	0	0	454,0
Other aircraft parts and equipment	1040	1040	0	0	0	0
Petroleum refineries	1010	1010	0	3,13	0	0
Air transportation	1000	1000	0	0	0	0
Coal mining	995,0	112,0	0	882,0	0	0

5.3 Aircraft in Simapro

Figure 5.1 shows the manufacturing network made by Lopes in Simapro. The LCIA method used is ReCiPe Midpoint. This is an international methodology developed by Rijksinstituut voor Volksgezondheid en Milieu (RVIM), CML, PRe Consultants, Radboud Universiteit Nijmegen and CE Delft. The LCIA result of the complete aircraft (with engines) is 1,54 E06 kg CO2 eq. The LCIA result of the engines is 3,37 E055 kg CO2 eq.

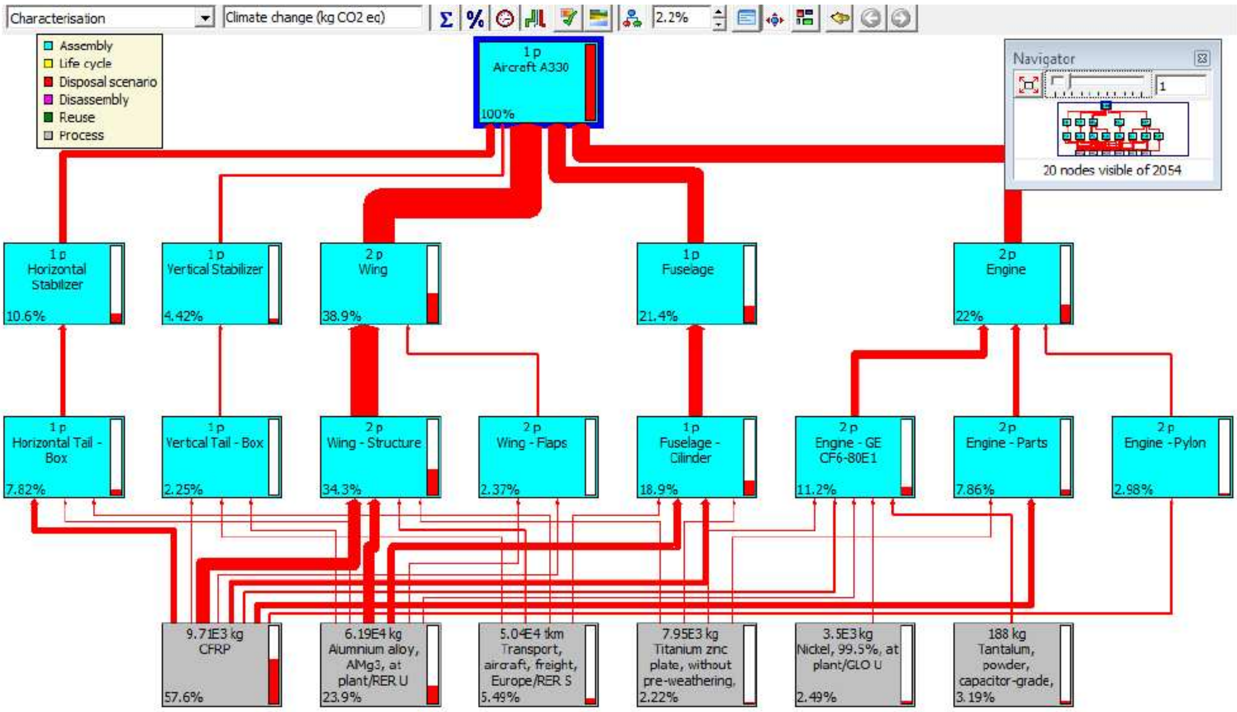


Figure 5.1 Manufacturing network model of the A330-200 aircraft, using Simapro through the ReCiPe Midpoint method.

Table 5.3 Life-cycle impact assessment results for the impact category 'Climate Change' using the ReCiPe Midpoint method.

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

5.4 Discussion

Engines:

Simapro: 337 000 Kg CO2 eq.

EIO-LCA: 6 690 000 Kg CO2 eq.

Full aircraft:

Simapro: 1 540 000 Kg CO2 eq.

EIO-LCA: 61 090 000 Kg CO2 eq.

The results of the EIO-LCA are much higher (The full aircraft is 40 times higher, the Engine is 20 times higher). The results of EIO-LCA might be more trustworthy. EIO-LCA has been used by Chester and many other LCA practitioners. The founder of EIO-LCA has won the Nobel-price in economics for his work.

EIO-LCA uses money to calculate the environmental impact. Money is therefore equivalent to emissions. In the case of gold, silver and other ores the purchase-price is very high. Mining of those materials produces a lot of toxic emissions. Also the melting of these products produces carcinogenic material. With the decision of Lopes to not include electronics, navigation, instruments, hydraulic fluids and expensive systems (only heavy structural components), possible important data might have been excluded. As mentioned in section 3.1.4 “missing or incomplete methods should be added”.

Assumptions have been made in order to simplify the work. For the material distribution of one component (for example a landing gear) a mass distribution of 90 %, 5 % and 5 % has been used for respectively steel, aluminium and titanium. This approach has been used because the aircraft manuals don’t give material distributions.

5.4.1 EIO-LCA

EIO-LCA has some **advantages** compared to the “bottom-up” approach of Simapro. No system boundaries have to be defined. The system boundary is the whole United Sates economy. No inventory has to be made because the data is already collected by the government. The “bottom-up” LCA probably took months to complete, EIO-LCA takes only a few hours. On this level accumulation, information is lost and a large accuracy cannot be guaranteed.

Not all the emissions that are of concern for the LCA have been found with EIO-LCA. Probably because EIO-LCA gives a LCIA result instead of an LCI result. CO2, CH4, N2O, HFC, PFC, sufur hexafluoride, energy, Resource Conservation and Recovery Act (RCRA) Hazardous waste and Toxic Releases are available. SOx, Pb, CO, PM and Pb might not be available. Nevertheless Chester stated all emissions in his results.

The **disadvantage** of EIO-LCA is price variability. E.g. The price of tip orange juice in the market might be twice as cheap as orange juice from another brand. Does this mean that tip orange juice has twice less the environmental impact? Another drawback (but not of concern for an aircraft) is that the use phase not is modelled. E.g. a computer can after his initial purchase cost consume electricity which is bad for the environment. Therefore also the electricity used has to be modelled in EIO-LCA (**MIT 2012)**.

5.4.2 Simapro

For the operational phase a simple copy of the "Operation, aircraft, passenger, intercontinental/RER" has been used. This process comes from EcoInvent database. The process does not use EI specific for the A330-200. For the construction and operation of the airport the processes "Airport=RER=I U" and "Operation; maintenance; airport=RERU" are used.

LCA tools have not yet been used extensively in aviation. Therefore, not many aviation data is available. Especially accurate specific data is not yet made for LCA tools. Other models have been used for aviation which are more accurate than the LCA databases. These are the Emissions Data Modelling Software (EDMS) and Aviation Environmental Design Tool (AEDT).

6 LCA of the A320-200

Figure 6.1 Airbus A320 (**Airbus 2012**)

The LCA of the A320-200 is a typical LCA with four aspects, namely goal and scope, inventory, assessment and interpretation.

6.1 Goal and Scope

The goal is to create a basic life-cycle assessment of the A320-200. For the scope, the manufacturing and operational phases will be included, because these have the largest impact on the environment (**Chester 2008**).

The environmental emissions of concern are stated chapter 2.5. These are; GHG, SOx, CO, NOx, VOC, PM and Pb. The same impact categories as in **Krieg 2010** will be used. These are**;** Eutrophication Potential (EP), Acidification Potential (AP), GWP, and Photochemical Ozone Creation Potential (POCP). Because LCA is an iterative process, the scope can be adjusted during the execution.

The LCA is not modelled completely in GaBi because the required EcoInvent database costs 1500 EUR and it is not very accurate for aircraft. More accurate EI from other data sources will be used. The free education database has limited EcoInvent data. This should be good enough to classificate the emissions to their impact categories. The results of the LCI should be comparable to the LCI of the Boeing 737 (**Chester 2008**).

6.1.1 Functional Units

The product description is quite simple: The product is the A330-200 which has to transport passengers over a certain distance. Sometimes cargo is transported. Therefore the most important functional unit could be Passenger Kilometres Travelled (PKT). It might be a good idea to include more than one functional unit to have a broader idea of the results. Therefore, also Vehicle Kilometres Travelled (VKT) and aircraft lifetime are incorporated.

6.1.2 Extensive LCA Flowchart

This project deals only with manufacturing and operation. But an extensive LCA flowchart has been drawn to be able to further expand the LCA.

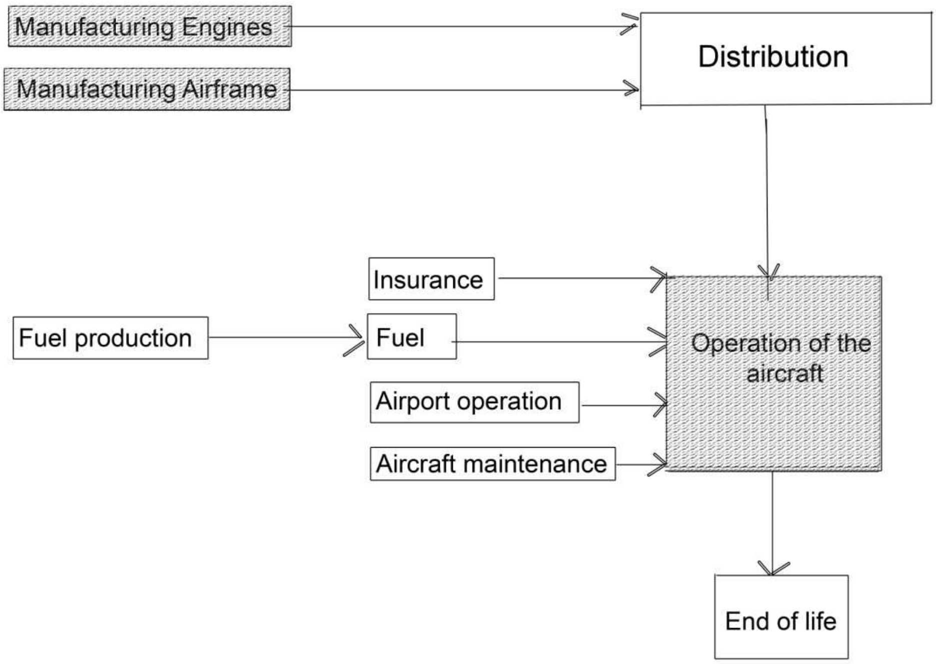


Figure 6.2 Extensive LCA flowchart

The elements included in this flowchart define the scope of a more extensive LCA, in other words: the elements that should be included in a more detailed LCA. This chart represents different life-cycle phases which are materials, energy, production, use, recycling and distribution of components. This chart gives the most relevant processes (boxes) and flows (arrows). The complexity of the flowchart can be increased and so does the accuracy of the LCA result. However, it is impossible to make a complete LCA. LCA databases help us to link our new processes to existing flows and increase the complexity. Because it is difficult to properly rank the processes, the iterative property of LCA appears.

6.2 Life-Cycle Inventory

The following life-cycle inventory consist out of the manufacturing phase and the operational phase. For the manufacturing, the engine and airframe is modelled separately. To find the emissions first the price of the engine and airframe has to be determined. For the operational phase, the flight is modelled and emissions for every flight phase are calculated.

6.2.1 Mass Method

It is possible to find the masses and materials of an aircraft by using the aircraft documentation. However this work is very time consuming and the accuracy of the distribution of masses to their respective material can be questioned. Therefore the EIO-LCA method is used.

For the mass method, the following manuals are required:
The IPC (Illustrated Parts Catalogue) contains a list of all parts of the airplane with their respective part number from the manufacturer and vendor code. Cross-reference with part-numbers and illustration is possible. The Pilot Operating Handbook (POH) contains a Weight and Balance (W&B) equipment list (ATA 21-79). Given in the list are the arm (m), moment (kg*m), and weight (kg) of every item. The SRM (Structural Repair Manual) has a list of the material types, temper condition and thickness of every component. There is also a list of consumable materials (LCM) which are required for operation and maintenance of the aircraft.

6.2.2 Estimating Manufacturing Costs

When designing an aircraft it might be difficult to define the manufacturing costs. Following graphs can help the estimation. Note that the engine is included in the aircraft purchasing price. Another method to estimate the costs is the **AEA 1989**, used in 8.1.3.

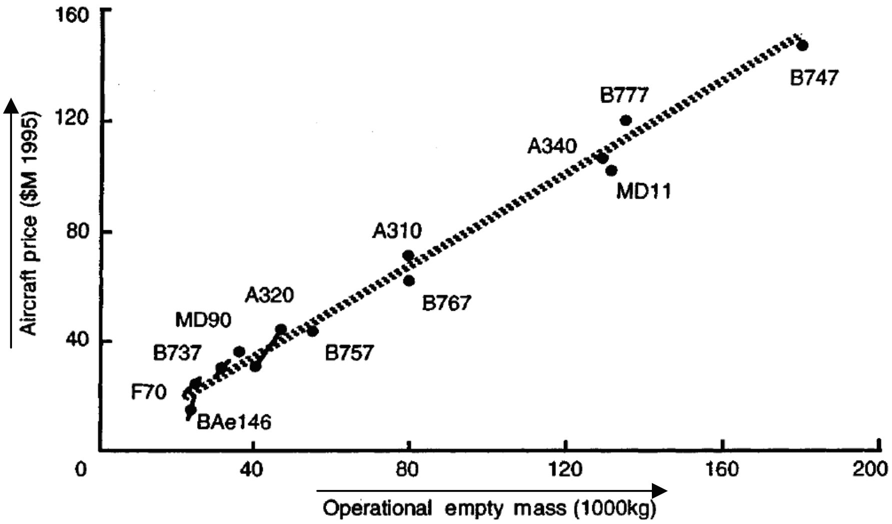


Figure 6.3 Aircraft purchase price against operating empty mass (data source **Avmark 2012**).

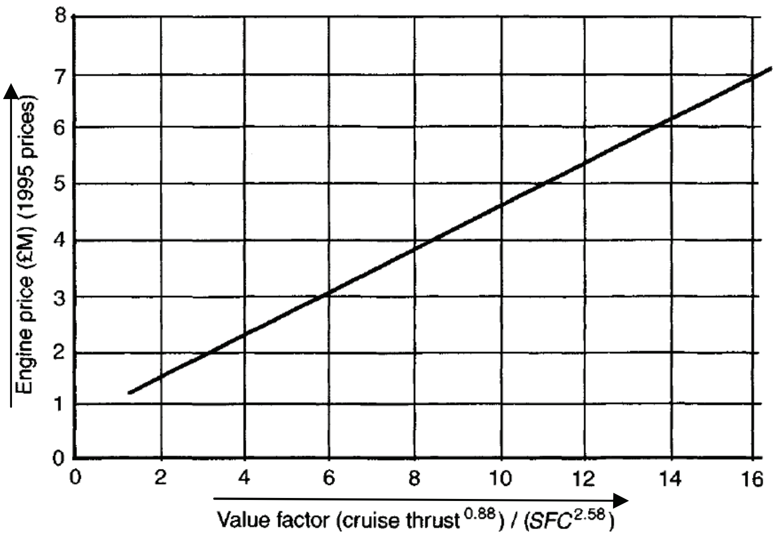


Figure 6.4 Engine price estimation (**Jenkinson 1999**).

An aircraft requires also spare parts. According to **Jenkinson 1999** we can estimate:

- The spare cost of the airframe as 10% of the aircraft price,
- The spare cost of the engine as 30 % of the engines price.

6.2.3 Estimation of Engine Price

The A320-200 can be equipped with different engines. The same engine as **NiȚĂ 2012** is chosen, namely the CFM56-5A1. The engine price can be estimated with the **AEA 1989:**

$$Engine\ price = 293 \times (take - off\ thrust)^{0,81} = \$3,63\ million \tag{6.1}$$

The take – off thrust [KN*1000] is also found in **NiȚĂ 2012**. The money has to be converted to 2002 $ ($ 2,83 million). A 10 % mark-up for engines which includes overhead, profit, distribution, and marketing and 30 % spares cost is assumed. This gives the final cost of one engine:

$ 3,32 million

Calculation

$$293 \times (113,2 \times 1000)^{0,81} = 3,63$$
$$3,63(2012\$) \cong 2,83(2002\$)$$
$$2,83 \times 0,9 = 2,55$$
$$2,83 \times 0,3 \times 0,9 = 0,76$$
$$2,55 + 0,76 = 3,32$$

According to **EIO-LCA 2012** the GWP is 2340 ton CO2 eq.

6.2.4 Estimation of Airframe Price

The average A320 price (including engines) can be found on the Airbus website (**Airbus 2012**). Converting this to 2002 $, gives $ 69,12 million. Also a 10 % mark-up and 10 % spares cost is assumed. The final aircraft price, without engines, is:

$ 62,82 million

Calculation:

$$88,3(2012\$) \cong 69,12(2002\$)$$
$$69,12 - 2 \times 2,83 = 63,46$$
$$63,46 \times 0,1 \times 0,9 = 5,71$$
$$63,46 \times 0,9 = 57,11$$
$$5,71 + 57,11 = 62,82$$

According to **EIO-LCA 2012** the GWP is 23300 ton CO2 eq.

6.2.5 LTO Cycle

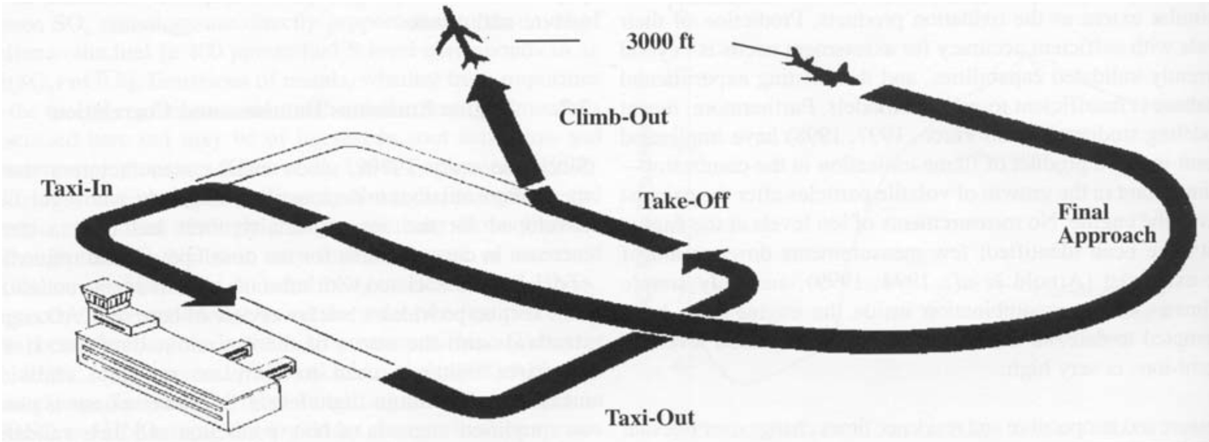


Figure 6.5 ICAO reference LTO-cycle

The conventional way of determining the LTO emissions is by using the International Civil Aviation Organisation (ICAO) emissions and the ICAO LTO cycle. With this quite simple method we use the proper aircraft/engine combination per LTO, and calculate the: sum of the four LTO mode products of: $time\_in\_mode \cdot fuel\_flow \cdot EI$

This result can be found on the website of the European Aviation Safety Agency (EASA). For 2 engines the LTO-cycle fuel (Jet A) and emissions are given in Table 6.1. Engine: CFM56-5-A1 (**NIȚĂ 2012**).

Table 6.1 LTO-cycle of the A320 (**ICAO 2012**)

	Fuel (kg)	HC (g)	CO (g)	NOx (g)
TOTAL LTO	770	570	6186	9012

6.2.6 Cruise Phase

The LTO cycle only assesses the emissions below 915 m (3 000 ft) and therefore it may be less accurate to use the same emission indices for cruise.

Table 6.2 Emission indices during cruise phase

	HC (g/kg)	CO (g/kg)	NOx (g/kg)	SOx (g/kg)	CO2 (kg/kg)	Particles (g/kg)
Emission indices	0,74026	8,03377	11,70390	0,8	3,16	0,02

SOx, CO2 and particulates EI come from **Schmitt 2009**. These are about the same for every engine.

Average operational data of the A320-200 is calculated by **NiŢĂ 2012**:

- Number of passengers: 180,
- 5663 kg Fuel mass per flight,
- 755 Nautical Miles (NM) per flight,
- 1511 flights per year,
- Average lifetime of A320 is estimated at 30 years (**Chester 2008**).

The fuel consumption can also be calculated by using Thrust Specific Fuel Consumption (TSFC). Then the thrust setting must be known through every flight phase. The thrust setting can be found in the Flight Management Computer (FMC) or Flight Data Recorder (FDR) of the aircraft. This can be measured in real-life or in a simulator.

Equations to normalize data to functional units:

$$I/O^{Operation}_{PKT} = \frac{Fuel \times EI}{NM \times n_{pax} \times 1{,}852} \tag{6.2}$$

$$I/O^{Operation}_{VKT} = \frac{Fuel \times EI}{NM \times 1{,}852} \tag{6.3}$$

$$I/O^{Operation}_{Lifetime} = Fuel \times flights \times lifetime \times EI \tag{6.4}$$

With:

- Flights (year^-1)
- Fuel (kg/flight)
- Emission Index EI (g/(kg fuel))
- Lifetime (year)
- I/O^{α}_{β} Input or Output for component (α) and functional unit (β).

This gives us emissions for the cruise phase:

Table 6.3 Operational emissions of the A320

	HC (g)	CO (g)	Nox (g)
PKT	0,01439	0,15618	0,22753
VKT	2,59042	28,11295	40,95602
a/c lifetime	284 260*10^3	3084 988*10^3	4494 326*10^3

Later, emissions data of the A320 has been found with the European Environment Agency (**EAA 2001).** Normalizing this data to the functional units gives following results:

Table 6.4 Operational emissions per phase of the A320-200

Life-cycle Component	I/O	per Aircraft-life	per VKT	per PKT
Taxi				
	Fuel (kg)	15166947	0,241	1,34E-03
	Nox (kg)	70252	0,001	6,20E-06
	HC (g)	25783810	0,410	2,28E-03
	CO (g)	515767201	8,192	4,55E-02
	Sox (g)	12133558	0,193	1,07E-03
	CO2 (kg)	47927553	0,761	4,23E-03
	Particles(g)	303339	0,005	2,68E-05
	lead	x	x	x
Take-off				
	Fuel (kg)	4074879	0,065	3,60E-04
	Nox (kg)	112912	0,002	9,96E-06
	HC (g)	403413	0,006	3,56E-05
	CO (g)	2444927	0,039	2,16E-04
	Sox (g)	3259903	0,052	2,88E-04
	CO2 (kg)	12876616	0,205	1,14E-03
	Particles(g)	81498	0,001	7,19E-06
	lead	x	x	x
Climb out				
	Fuel (kg)	10537710	0,167	9,30E-04
	Nox (kg)	247038	0,004	2,18E-05
	HC (g)	1053771	0,017	9,30E-05
	CO (g)	26344274	0,418	2,32E-03
	Sox (g)	8430168	0,134	7,44E-04
	CO2 (kg)	33299163	0,529	2,94E-03
	Particles(g)	210754	0,003	1,86E-05
	lead	x	x	x
Climb/cruise/descent				
	Fuel (kg)	178106974	2,829	1,57E-02
	Nox (kg)	2550710	0,041	2,25E-04
	HC (g)	31225808	0,496	2,76E-03
	CO (g)	162898889	2,587	1,44E-02
	Sox (g)	142485579	2,263	1,26E-02
	CO2 (kg)	562818038	8,939	4,97E-02
	Particles(g)	3562139	0,057	3,14E-04
	lead	x	x	x

Life-cycle Component	I/O	per Aircraft-life	per VKT	per PKT
Approach landing				
	Fuel (kg)	6590181	0,105	5,81E-04
	Nox (kg)	60904	0,001	5,37E-06
	HC (g)	59937700	0,952	5,29E-03
	CO (g)	252944341	4,017	2,23E-02
	Sox (g)	5272145	0,084	4,65E-04
	CO2 (kg)	20824973	0,331	1,84E-03
	Particles(g)	131804	0,002	1,16E-05
	lead	x	x	x
Flight total				
	Fuel (kg)	214476691	3,406	1,89E-02
	Nox (kg)	3041815	0,048	2,68E-04
	HC (g)	118404502	1,881	1,04E-02
	CO (g)	960399633	15,253	8,47E-02
	Sox (g)	171581353	2,725	1,51E-02
	CO2 (kg)	677746343	10,764	5,98E-02
	Particles(g)	4289534	0,068	3,78E-04
	lead	x	x	x

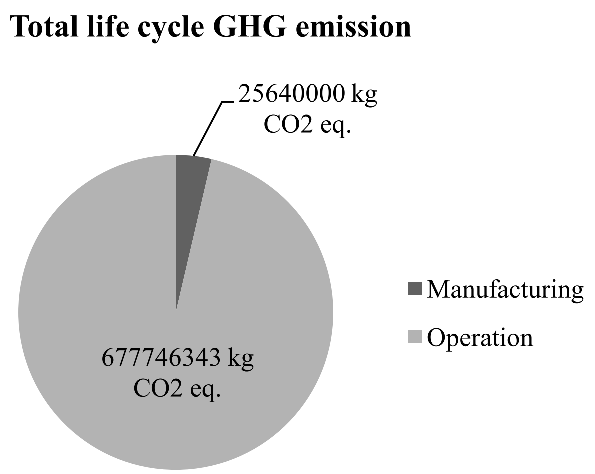


Figure 6.6 Total life-cycle GHG emissions

The GWP impact of the manufacturing phase is small compared to the operational phase but not negligible in the life-cycle assessment of the A320. The cruise phase is compared with Chester 2008's cruise phase of the Boeing 737. The results of Chester are average 1,5 times higher than the results in this work. Possibly the emissions of the 737 are higher.

6.2.7 Cargo

The primary purpose of an aircraft is to transport passengers. But often cargo is also transported. To have an idea of the environmental impact to transport mass a new functional unit is introduced.

$$I/O_{FKT}^{Operation} = \frac{VKT}{m_{PL}} = \frac{VKT}{m_{pax} + m_{baggage} + m_{cargo}} = \frac{VKT}{33548} \quad (6.5)$$

For a short to medium haul flight, the average masses are given by **Roskam 1989** and **NiȚĂ 2012**. For the A320, the percentage of cargo attribution to passenger weight is 85 %.

Table 6.5 Payload of the A320

Average passenger mass	79,4 kg
Mass of passengers	14 292 kg
Average passenger baggage mass	13,6 kg
Mass of passenger baggage	2 448 kg
Average A320 cargo mass	2 516 kg
Payload A320	33 548 kg
% cargo to passenger	85 %

6.3 Life-Cycle Impact Assessment

We have to make a process that represents the operational phase of the A320, if we would like to model this phase in GaBi. It will require an input flow of kerosene and emission output flows. These emission output flows should be to air. There have to be different flows for different altitudes because the impact of the emissions varies with altitude. Unfortunately GaBi Education database has not such flows. GaBi is a collection of data. Education_DB has a very small amount of data from aviation. The EcoInvent database has much more data and is widely used as database in LCA. The current price is 1500 EUR.

To specify the functional unit PKT the EcoInvent "RER: operation, aircraft, passenger [Air]" is used. EcoInvent is developed in Switzerland. RER means that the processes is valid for the situation in Europe. This is because Switzerland's economy is closely linked to the surrounding countries. After the process has been created, the LCI results can be displayed in graphs (Figure 6.11 and Figure 6.12).

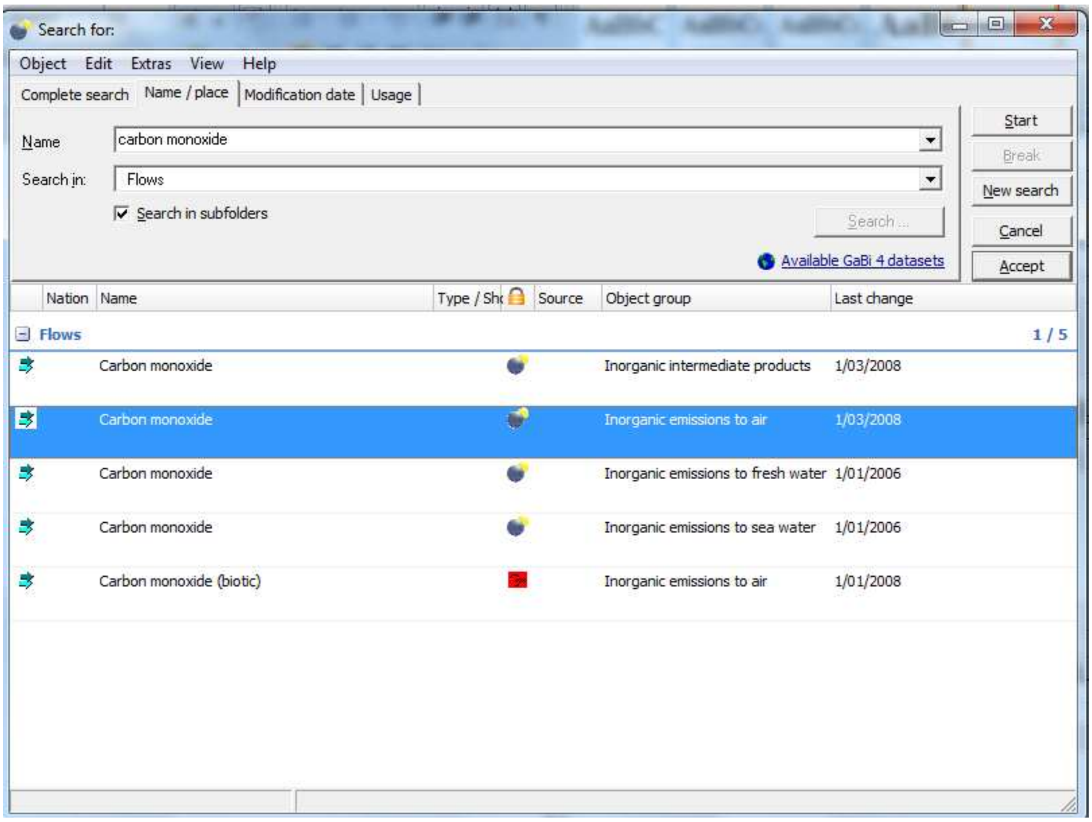


Figure 6.7 Search in Education_DB for CO-emissions to air at various altitudes

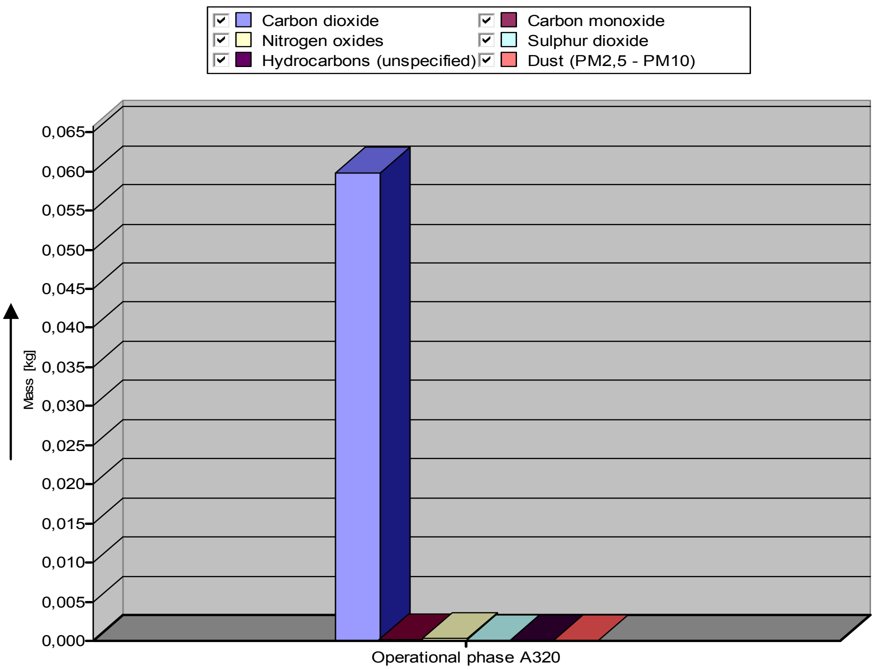


Figure 6.8 GaBi diagram: emissions life-cycle A320

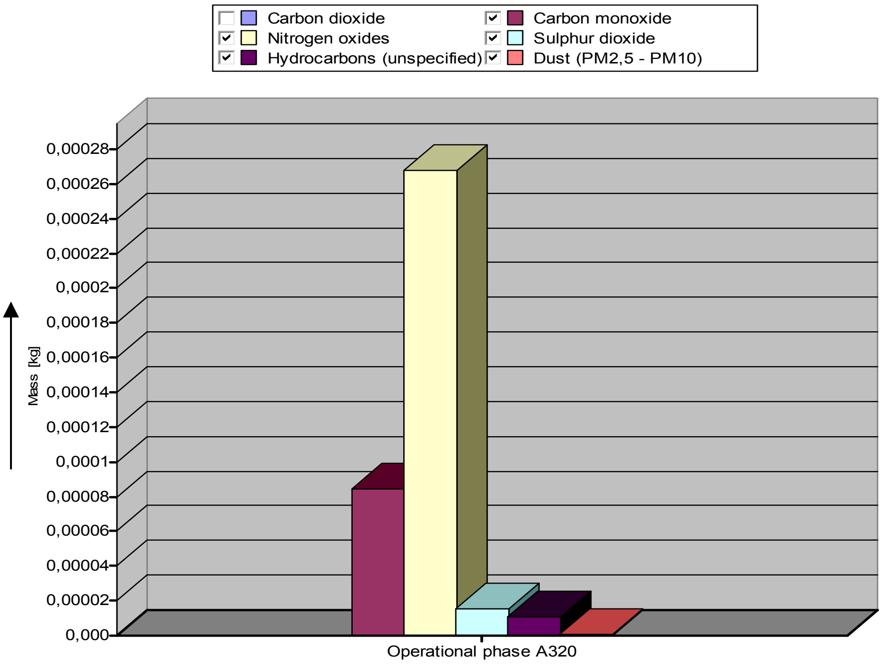


Figure 6.9 GaBi diagram: emissions life-cycle A320, excluded CO2

GaBi is used to classificate the emissions to their respective impact categories. The impact categories are already defined in the goal and scope.

CML2001 LCIA method is chosen to assess the results because, as said in section 3.1.3, this is the most widely used method in Europe. CML2001 – Dec. 07 is the most up-to-date version. The results are grouped in midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity).

CML2001 is developed in Leiden University, Netherlands. From the CML website, a spreadsheet with characterization factors of over 1700 flows can be downloaded. Normalisation factors are calculated via total substance emissions and characterization factors per substance. Characterisation factors can be found in **Leiden 2012**. Methodology principles can be found in **Guinée 2002**. The results are displayed in following 4 graphs:

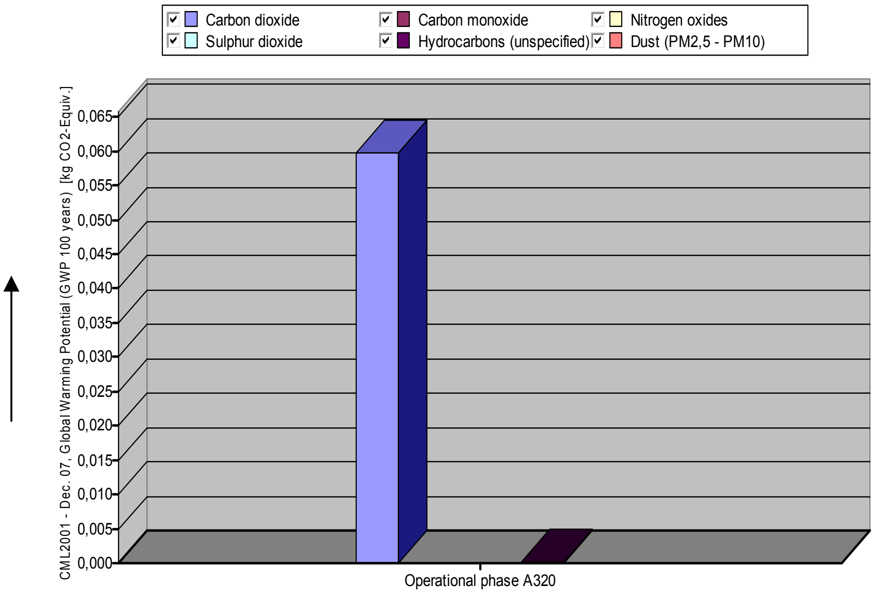


Figure 6.10 GWP [kg CO2-eq.], CML2001-Dec.07, (GWP 100 years)

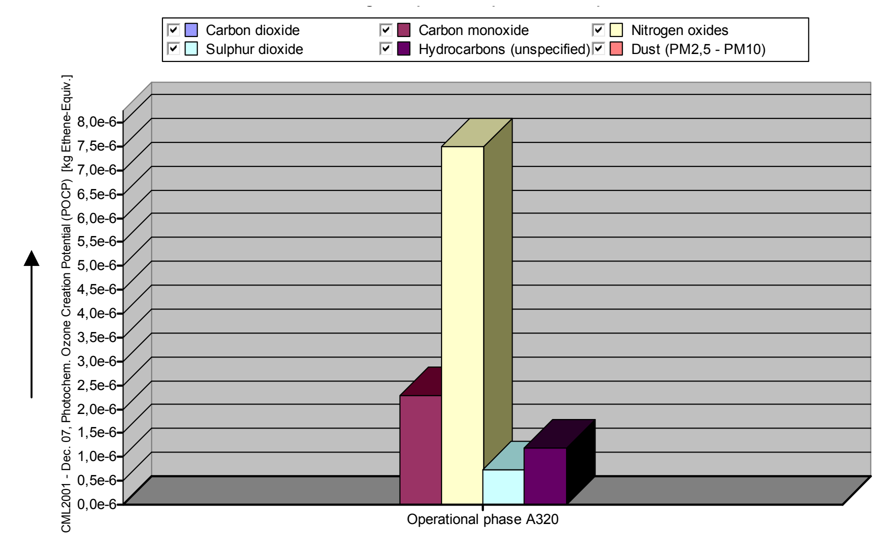


Figure 6.11 Photochemical Ozone Creation Potential (POCP) [kg C2H4-eq.], CML2001-Dec.07

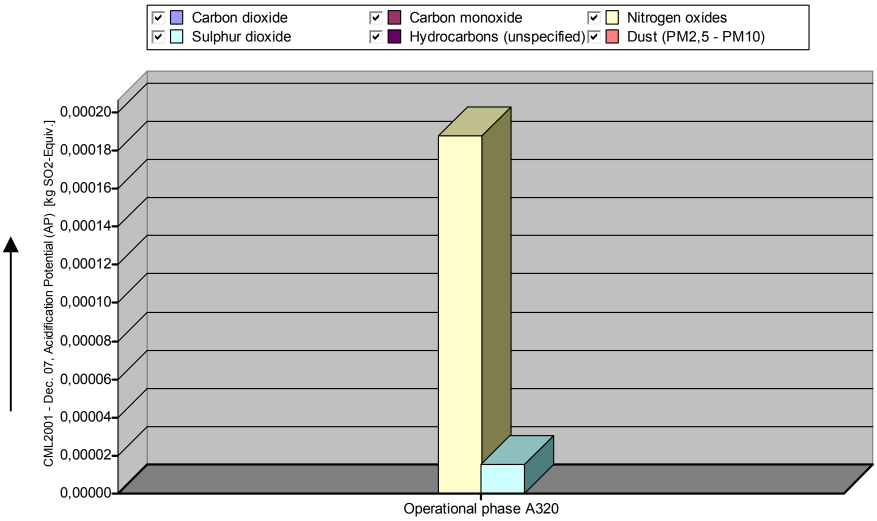


Figure 6.12 Acidification Potential (AP) [kg SO2-eq.], CML2001-Dec.07

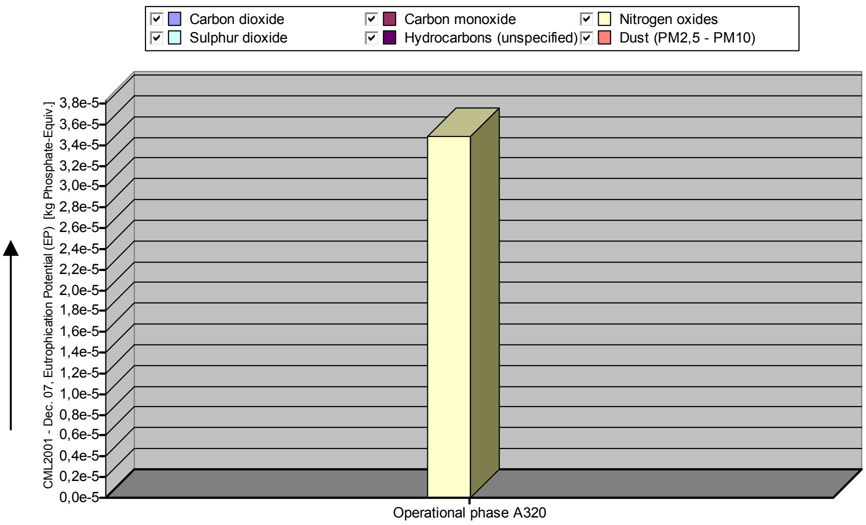


Figure 6.13 Eutrophication Potential (EP) [kg PO4-eq.], CML2001-Dec.07

In Figure 6.16 can be seen that only NOx has an effect on Eutrophication Potential. Figure 6.13 shows us that global warming is mainly caused by CO2. According to **EPA 2012b**, also CH4 and N2O should contribute to GWP. This is not seen in Figure 6.13.

6.4 End of Life

Airbus has developed a project named PAMELA which stands for Process for the Advanced Management of End-of-Life Aircraft. Airbus began this project in 2005 to improve the disposal of aircraft (**Airbus 2012**). Many aircraft are left in desserts, corroding even though materials could be recycled. This would reduce the waste and provide new materials to manufacture aircraft. The scope of the project was finished in 2007. It covered the entire process: disassembly, recycling and management of potentially hazardous waste.

Present-day the end of life process by airbus is operational in Tarmac Aerosave. This is the first company dedicated to end-of life saving aircraft. The aim is to recycle 85 % of the materials. On a pure environmental view this reduces the waste from 45 % to 15 %. Already a dozen of aircraft have been recycled including the A320 (**Europe 2012).**

The environmental benefit to the total life-cycle is very small according to Lopes 2010. Chester has not included an end of life scenario. This will also not be included in this project work.

6.5 Uncertainty

The uncertainty of the model depends from system boundary selection, process and hybrid flows, functional units, geographic variation of parameters attribution of inventory components to particular modes and component methodology (Huijbregts 1998). It is not possible to estimate the uncertainty of this LCA in a numeric way. To do a numeric uncertainty analysis Simapro can be used to create a monte-carlo analysis. A hybrid method between operation and manufacturing has been used in this project.

7 Conclusion

This project work has addressed the life-cycle assessment of an aircraft. A basic life-cycle assessment of an aircraft has been made. Research has been done regarding the environmental concerns of the aviation sector.

A literature research of already existing LCA's of aircraft has been done. Some LCA's of aircraft components have been found and some covering a part of the life-cycle. Only Chester and Lopes have performed a full life-cycle of an aircraft. The methods used have a large number of assumptions and a high degree of inaccuracy. The major problem in this work and those of Chester and Lopes was data availability. Most time has been spent in finding good data. For aircraft, much primary data has to be collected to make an LCI. Few secondary data is available. Information on aircraft material composition is protected.

The results of Chester and Lopes are very different. A completely other method was used. The results of Chester are more reliable and therefore his approach has been followed. Neither Chester, nor Lopes included spare parts of the aircraft in the LCA.

A life-cycle assessment of a paperclip has been made to gain knowledge of LCA's. Then a basic life-cycle assessment of an A320-200 has been performed. The manufacturing phase and the operational phase of the A320 have been modelled in this project work and a life-cycle inventory assessment is made in GaBi.

If aircraft should be designed for low environmental impact. They should consume less fuel because the operational phase is the hot spot in the life-cycle of the A330-200. The GWP impact of the manufacturing phase is small compared to the operational phase but not negligible in the life-cycle assessment of the A320. The results of Chester are average 1,5 times higher than the results in this work. Possibly the emissions of the 737 are higher.

Acknowledgements

First, I would like to thank my parents for their support, patience, help, advices, and economics efforts to let me study these years. Without your appreciation and words of encouragement I could never been writing this project work in Germany.

I would like to express my sincere gratitude to Prof. Dr.-Ing. Dieter Scholz for giving me this opportunity, to take up this project topic at Hamburg University of Applied Sciences. I also would like to thank Mr. Andreas Johanning for giving me ideas, advises and motivation. He has answered many questions and was guiding me in this work. He has corrected the flaws in this work until the final day.

I am also grateful to have had the opportunity to work in the office of Aircraft Design and Systems Group (AERO).

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Appendix: Compact Disk

The compact disk contains following documents:

- Comparison Chester-Jeroen-Operation.xlsx
- EmissionDataA320.xls
- Emissions Results.xlsx
- Ratio of functional units.xlsx
- Project work in Word 2007
- Project work in pdf