



Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Project

Department of Automotive and Aeronautical Engineering

Life-Cycle Assessment of Commercial Aircraft – A Review of Methods and Tools

Author: Hoa Ly

Examiner: Prof. Dr. – Ing. Dieter Scholz, MSME

Supervisor: Dipl.-Ing. Andreas Johanning

Delivery date: 13 July 2012

Abstract

This project shows an efficient way of performing a cradle to grave Life Cycle Assessment of an aircraft because of the scarcity of the studies on this topic. Life Cycle Assessment (LCA) is defined as the analysis of all the inputs and outputs of a product throughout its entire life cycle stages on the environment; it is only existing method that gives the total environmental effects of a product. The first LCA could be traced back in 1960s and since then, it has been used for many different products. Sadly, there has been hardly any LCAs done for aviation, and the already done studies are not detailed LCA. This should be not taken lightly as aviation with the fastest growth in transportation has very huge impacts on environment. Before showing the LCA of an aircraft, an example of LCA of coffee machine using SimaPro, the world's leading LCA tool, was done to familiarize the audience with the tool and better grasp of LCA's methodology. The coffee machine LCA was performed following the guidelines of International Organization for Standardization (ISO) 14040 series, which specifies 4 steps in performing a LCA: Goal and Definition, Inventory Analysis, Impact Assessment, and Interpretation. Using the knowledge from the LCA of coffee machine, the suggested way of performing a LCA of an aircraft for all the life cycles stages is explained in detail.

© This work is protected by copyright

The work is licensed under a
Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License:
CC BY-NC-SA
<http://creativecommons.org/licenses/by-nc-sa/4.0>



Any further request may be directed to:
Prof. Dr.-Ing. Dieter Scholz, MSME
E-Mail see: <http://www.ProfScholz.de>
Download this file from:
<http://library.ProfScholz.de>



DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING ENGINEERING

Life-Cycle Assessment of Commercial Aircraft – A Review of Methods and Tools

Task for the *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

How are LCAs created today? What software tools are used? What methods (general and specific) are used for the creation of LCAs? What databases exist for the specific creation? How can we apply the existing knowledge about LCAs (for instance about deposit bottles, one-way towels) to commercial aircrafts?

- Do a literature review and summarize your results in the report
- Transfer the knowledge of existing methods, software tools and databases into the creation of LCAs for commercial aircrafts
- Your proposal for a method to create LCAs for aircraft should follow these steps:
 1. Aircraft manufacturing
 2. Aircraft operations
 3. Aircraft disposal

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

Declaration

Herewith I affirm that this project is entirely my own work. Where use has been made of the work of others, it has been totally acknowledged and referenced.

2012-06-15

.....

Date Signature

Table of Contents

	Page
List of Figures.....	7
List of Tables.....	8
List of Abbreviation.....	9
1 Introduction.....	10
1.1 Motivation.....	10
1.2 Objectives.....	10
1.3 Structure of This Project.....	10
2 Life Cycle Assessment (ISO 14040 Series).....	12
2.1 Definition.....	12
2.2 Methology.....	14
2.2.1 Definition of Goal and Scope.....	15
2.2.1.1 Goal and Scope.....	15
2.2.1.2 Functional Unit and Reference Flow.....	15
2.2.1.3 System Boundaries.....	16
2.2.1.4 Data Quality Requirements.....	17
2.2.2 Life Cycle Inventory Analysis.....	18
2.2.3 Life Cycle Impact Assessment.....	19
2.2.4 Interpretation.....	20
2.3 Brief History of Life Cycle Assessment.....	20
2.4 Benefits and Limitations of Performing a Life Cycle Assessment.....	21
3 Different Types of Life Cycle Assessment and Its Derivatives.....	23
3.1 Standardized Life Cycle Assessment.....	24
3.1.1 Conceptual Life Cycle Assessment.....	24
3.1.2 Simplified Life Cycle Assessment.....	24
3.1.3 Comprehensive Life Cycle Assessment.....	24
3.1.4 Streamlined Life Cycle Assessment.....	25
3.2 Life Cycle Costing.....	25
3.2.1 Economical Inputs and Outputs Life Cycle Assessment.....	26
3.3 Working Environmental Life Cycle Assessment.....	26
3.4 Social and Socio-Economic Life Cycle Assessment.....	26
4 Life Cycle Assessment's Tools.....	28
4.1 List of Currently Active Life Cycle Assessment's Tools.....	28
4.2 List of Free and currently active Life Cycle Assessment's Tools.....	30
4.3 List of Decommissioned Life Cycle Assessment's Tools.....	32
4.4 Life Cycle Inventory Databases.....	34
4.5 Life Cycle Impact Assessment Methology.....	35
4.6 Recommendation.....	36
5 Example of Life Cycle Assessment of Coffee Machine Using SimaPro.....	37
5.1 Goal and Scope.....	37
5.1.1 Process System.....	37
5.1.2 Functional Unit.....	38
5.2 Life Cycle Inventory.....	39

5.3	Life Cycle Impact Assessment and Interpretation.....	40
5.4	Recycling.....	43
6	How to perform the Life Cycle Assessment of an Aircraft.....	44
6.1	Goal and Scope.....	44
6.2	Inventory.....	45
6.3	Life Cycle Impact Assessment.....	46
6.4	Interpretation.....	47
7	Summary.....	48
	References.....	49
	Acknowledgements.....	52

List of Figures

	Page
Figure 2.1 Structure of Life Cycle Assessment.....	12
Figure 2.2 All Phases of Life Cycle Assessment.....	14
Figure 2.3 Example of Functional Units.....	16
Figure 2.4 Structure of System Boundary.....	17
Figure 2.5 Steps for Life Cycle Inventory.....	19
Figure 3.1 Three types of Life Cycle Assessment and its derivatives....	23
Figure 5.1 Process System of Model Sima.....	38
Figure 5.2 Partial Inventory of Model Sima During Manufacture and Production Phase..	39
Figure 5.3 Chracterization of Model Sima..	40
Figure 5.4 Normalization of Model Sima.....	41
Figure 5.5 Weighting of Model Sima.....	42
Figure 5.6 Single Scores of each subassembly.....	42
Figure 6.1 Components of an Aircraft.....	45
Figure 6.2 Subcomponents of an aircraft wing from Structural Repair Manual.....	46

List of Tables

	Page
Table 2.1 History of Life Cycle Assessment.....	20
Table 4.1 List of Currently Active Life Cycle Assessment's Tools.....	28
Table 4.2 List of Currently Free and Active Life Cycle Assessment's Tools.....	31
Table 4.3 List of Currently Decommissioned Life Cycle Assessment's Tools.....	33

List of Abbreviations

AOPA	Aircraft Owners and Pilots Association
DEAT	Department of Environmental Affairs and Tourism
EIO-LCA	Economical Inputs and Outputs Life Cycle Assessment
FAA	Federal Aviation Administration
ISO	International Organisation for Standardisation
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social and Socioeconomic Life Cycle Assessment
UNEP	United Nations Environment Programme
WE-LCA	Working Environmental Life Cycle Assessment

1 Introduction

1.1 Motivation

According to Aircrafts Owners and Pilots Association (AOPA), at the Thirty-Seventh Annual FAA Forecast Conference, FAA predicts that the air traffic will increase double compared to the previous year (**Moore 2012**). Such prediction stirs up the main concerns of aircraft's impacts on the environment. As stated in an aviation and climate report from U.S. Government Accountability Office(GAO), aviation produces about 2 percent of human-generated global carbon dioxide emissions, and about 3 percent of the potential warming effect of global emissions (**GAO 2009**). With the fast growth of aviation industry and increase in demands of air transport each year, a method of optimizing the aircraft design to protect the environment is needed. Life Cycle Assessment (LCA), a method of assessing the environment impacts from all the stages of a life cycle of a product, is a great tool to aid the eco design of the aircraft.

The result of this project could be used as a guide for all the future works regarding the creation of LCA of an aircraft. This work will contribute to the reduce of environmental impacts and better design for aircraft.

1.2 Objectives

Even though LCA has been conducted for numerous types of products, it is still foreign to the aviation. This report's main objective is to studying how to conduct a LCA of an aircraft and thus is served as the catalyst for developing an ideal model of LCA of an aircraft. The other smaller goals are to raise more awareness about Life Cycle Assessment and impacts of aviation on environment.

1.3 Structure of the work

Chapter 2 to 4 gives a theoretical background of LCA and LCA tools. Then, chapter 5 to 6 shows an example of LCA, which is used to deduce the possible way to perform LCA of an aircraft. In detail the distribution of the chapter is as follows:

Chapter 2 gives the definition, methodology, brief history of Life Cycle Assessment along with its benefits and disadvantages.

- Chapter 3** defines three types of Life Cycle Assessment and its derivatives.
- Chapter 4** presents the overview of Life Cycle Assessment's tools, Life Cycle Inventory databases, and Life Cycle Impact Assessment methods with a recommendation of good Life Cycle Assessment tools.
- Chapter 5** shows a Life Cycle Assessment example by performing a Life Cycle Assessment of coffee machine using SimaPro 7.3.1.
- Chapter 6** applies the knowledge from previous chapter to show a possible way of performing a detailed Life Cycle Assessment of an aircraft.

2 Life Cycle Assessment (ISO 14040 Series)

2.1 Definition

Life Cycle Assessment (LCA), also known as Cradle to Grave analysis, is an analytical method that evaluates all the inputs and outputs, and potential impacts of a product throughout its entire life cycle stages on environment by:

- Gathering all the inputs and outputs of a product system,
- Analysing the environmental impacts from these inputs and outputs,
- Interpreting the results from inventory analysis. (ISO, 1997)

A comprehensive LCA entails all life cycle stages of a product which consists of raw materials, manufacturing, transportation, installation, use, maintenance, disposal, and reuse. The Figure 2.1 depicts a detailed structure of how an LCA should look like.

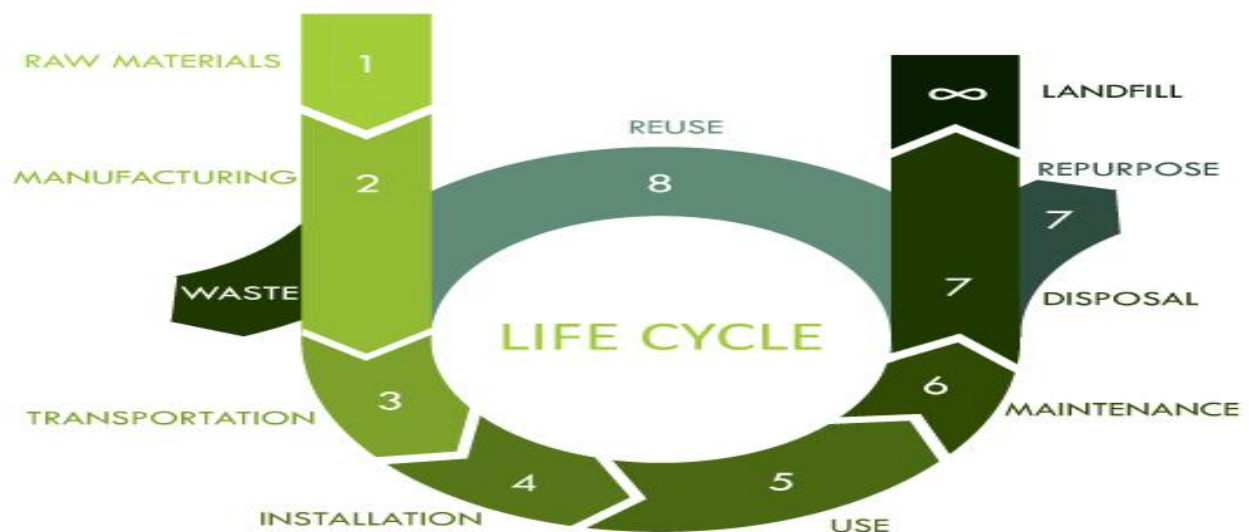


Figure 2.1 Structure of Life Cycle Assessment (Verdoorn 2010)

The term 'Cradle to Grave' refers to these eight life cycle stages. A report of cradle to grave LCA is expected to have detailed impacts of all these stages. Each stage is defined as follows:

- Raw materials- the methods of how materials are extracted from nature such as mining or excavating. The energy consumption and exhaust output of extraction materials and materials processing facilities are of main interests,
- Manufacturing- Process of converting raw materials into usable product. The energy consumption, exhaust output of the process, and fuel needed for the facility are of main interests,

- Transportation- distribution of the finished product. Fuel consumption of transporting vehicles and green house gas emissions are of main interests,
- Installation- the required set up of a product, like television, before operating it. This process is unnecessary for products that could be used immediately out of the packaging like ipods, headphones, or cameras,
- Use- the stage where the product is actually used by consumers. Energy consumption of the products, like batteries, and toxic emissions due to the use are of main interests,
- Maintenance- the product is in the supporting state for prolong of its duration and efficiency or restore to the original state. Energy consumption and exhaust output of maintaining equipment are of main interests,
- Disposal-the end of a product's life. It could be incinerated or buried in a landfill. Landfill pollutants and fuel for landfill equipments and garbage trucks are of main interests,
- Reuse- product is recycled and can be used again. Energy consumption and exhaust output of recycling equipments are of main interests. **(Verdoorn 2010) (Dictionary 2012)**

Each life cycle stage is assessed and grouped to different kinds of environment impacts such as global warming, acidification and so on. Some of the products ends at disposal stage if they cannot be recycled. According to ISO 14040, there are four phases in conducting a LCA:

- Definition of goal and scope,
- Inventory analysis,
- Impact assessment,
- Interpretation of results. **(ISO, 1997)**

These four phases are supposed to be done orderly, and they are interdependent of each other. If there are any mistakes in any of the phases, the subsequent phase will suffer and give incorrect results. The Figure 2.2 shows the links between these phases:

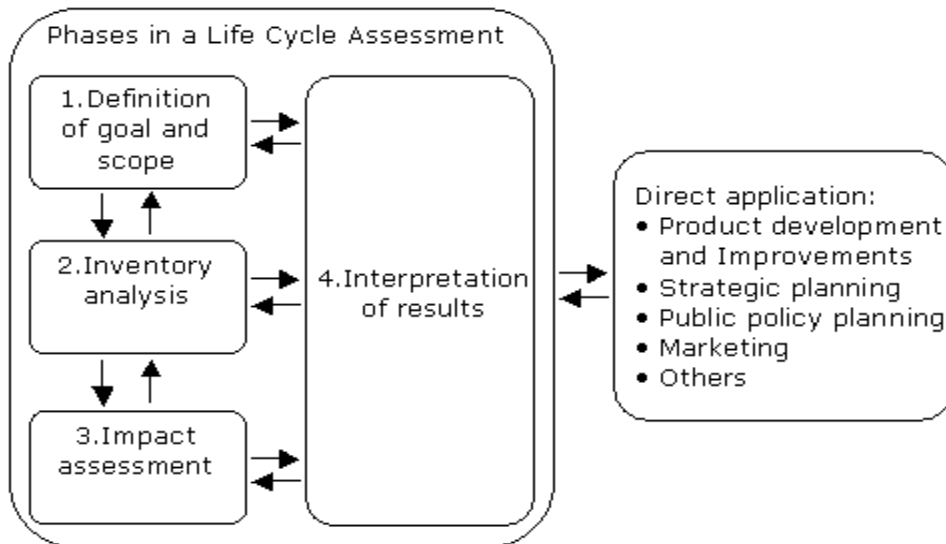


Figure 2.2 All Phases of Life Cycle Assessment (ISO, 1997)

A LCA could be performed for the following reasons:

- Improvement for study of environmental impacts from all life cycle of a product,
 - Decision making for strategic plan, priority setting, etc.,
 - More environmental friendly products(Greener/Eco products),
 - Selection of environmental performance indicators and measurement techniques.
- (ISO, 1997)

2.2 Methology

The four phases of LCA, mentioned above, are requirements of International Standards Organization (ISO) 14040 series. It is recommended to know the ISO standards before starting to conduct any LCA studies.

In general, the first phase, definition of goal and scope defines the framework of study with any assumptions, limitations and system boundaries. Then, the second phase, inventory analysis lists all the inputs and outputs at each stage of the product. The third step, Impact assessment, gives the relevant environmental effects. The final phase, interpretation of the result based on the last two steps is used for recommendations or suggestions in decision making (Steel 2012).

2.2.1 Definition of Goal and Scope

2.2.1.1 Goal and Scope

The first step of LCA is to define the goal and scope of the study. This step is important because it determines the choices to be made in the latter steps, and therefore, it is recommended to spend adequate time on this step to avoid wasting time later. In the middle or any point of the work, as the more knowledge is acquired, it may be necessary to redefine the goal and scope neither because the original goal and scope is not possible to be done or because some issues have not been taken into account in the beginning (**Pålsson 2011**).

The goal of a LCA should define clearly the intended application, reason for carrying out the study, intended audience, and comparative assertions disclosed to public (**ISO, 1998**).

The scope of a LCA, showing how the goal can be met, considers the following aspects:

- The functions of the product system, or, in case of comparative studies, the systems,
- The functional unit,
- The product system to be studied,
- Allocation procedures,
- Types of impacts and methodology, impact assessment and interpretation to be used,
- Data Requirements,
- Assumptions,
- Limitations,
- Initial Data Quality Requirements,
- Type of critical review,
- Type and format of the report required for study. (**ISO, 1997**)

2.2.1.2 Functional Unit and Reference Flow

Functions delivered by product systems must be clearly defined. Functional unit is the quantitative measure of these functions. It provides reference that shows the relation of inputs and outputs. Examples of some common functional units are shown in Figure 2.3(**Pålsson 2011**).

Examples of Functional Units

Class of products, process and services	System function	Functional unit
Goods use	Light generation	kWh/day
	Laundry washing	5 kg washed clothes
Process	Gasoline production	m ³ produced/h
	Liquid effluents treatment	t of removed COD/day
Transportation	Goods transport	tkm*
	Passengers transferring	Person km

Figure 2.3 Example of Functional Units (Sonnemann 2004)

The functional unit can be expressed by reference flow, the physical flow of energy or materials (Pålsson 2011).

2.2.1.3 System Boundaries

System boundaries determine all the processes and activities that should be included. It specifies what inputs and outputs from and to environment will be used, e.g. Elementary Flow. Even though system boundaries usually set in the first step- definition of goal and scope- it can be subjective to performance of Impact Assessments (Pålsson 2011). Figure 2.4 shows how to set boundaries for a product system.

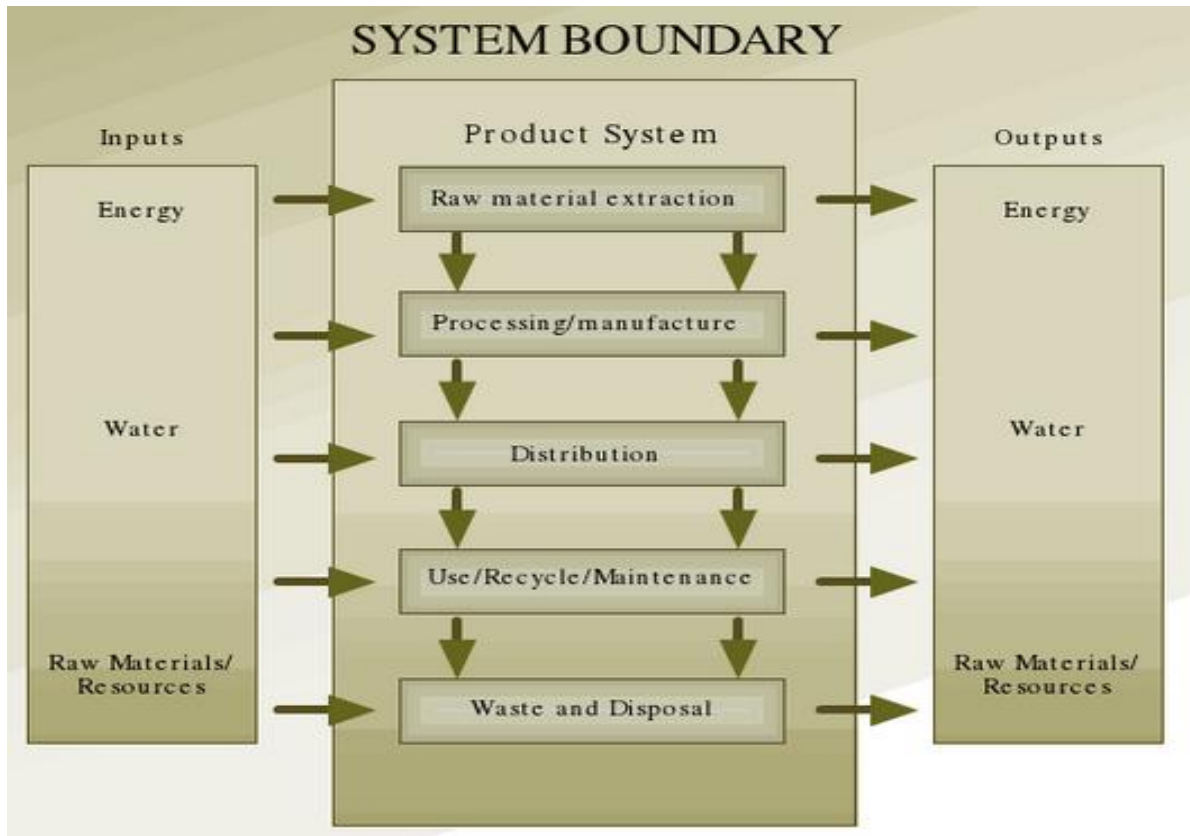


Figure 2.4 Structure of System Boundary (DEAT 2004)

2.2.1.4 Data Quality Requirements

Data quality requirements generally answer three questions of what, where, and how the data should be collected. How well these questions are answered will show the audience how reliable and useful the results of LCA are. Data quality requirements should be clearly stated in the Inventory analysis.

According to ISO 14040, the following parameters should be considered for data quality requirements:

- Time-related coverage,
- Geographical coverage,
- Technology coverage,
- Data precision,
- Completeness,
- Representativeness,
- Consistency,

- Reproducibility. **(ISO, 1998)**

2.2.2 Life Cycle Inventory Analysis

Life Cycle Inventory (LCI) contains all the defined inputs and outputs of the product system and explains how they should be allocated to different products. The two important parts in LCI are Collection (and Validation) of the data and Aggregation into Inventory Result. This is the most time consuming phase of LCA.

Collection of the data consists of:

- Preparation,
- Data Collection,
- Validation,
- Allocation. **(ISO, 1998)**

Among these four parts of data collection, allocation is a sensitive one to deal with. For the system with more than one product, the flow and releases should be properly divided between the products. The following procedures for allocation are recommended:

- Whenever possible, allocation should be avoided,
- Where allocation is not avoidable, inputs and outputs should be partitioned between the different functions or products in a way that reflects the underlying physical relationship between them,
- If the latter is not possible, allocation should be carried out based on other existing relationships. **(ISO, 1998)**

Aggregation into inventory result consists of

- Relating data to unit process and functional unit,
- Data aggregation,
- Redefining system boundaries (if necessary). **(ISO, 1998)**

Figure 2.5 summarizes all the steps in LCI:

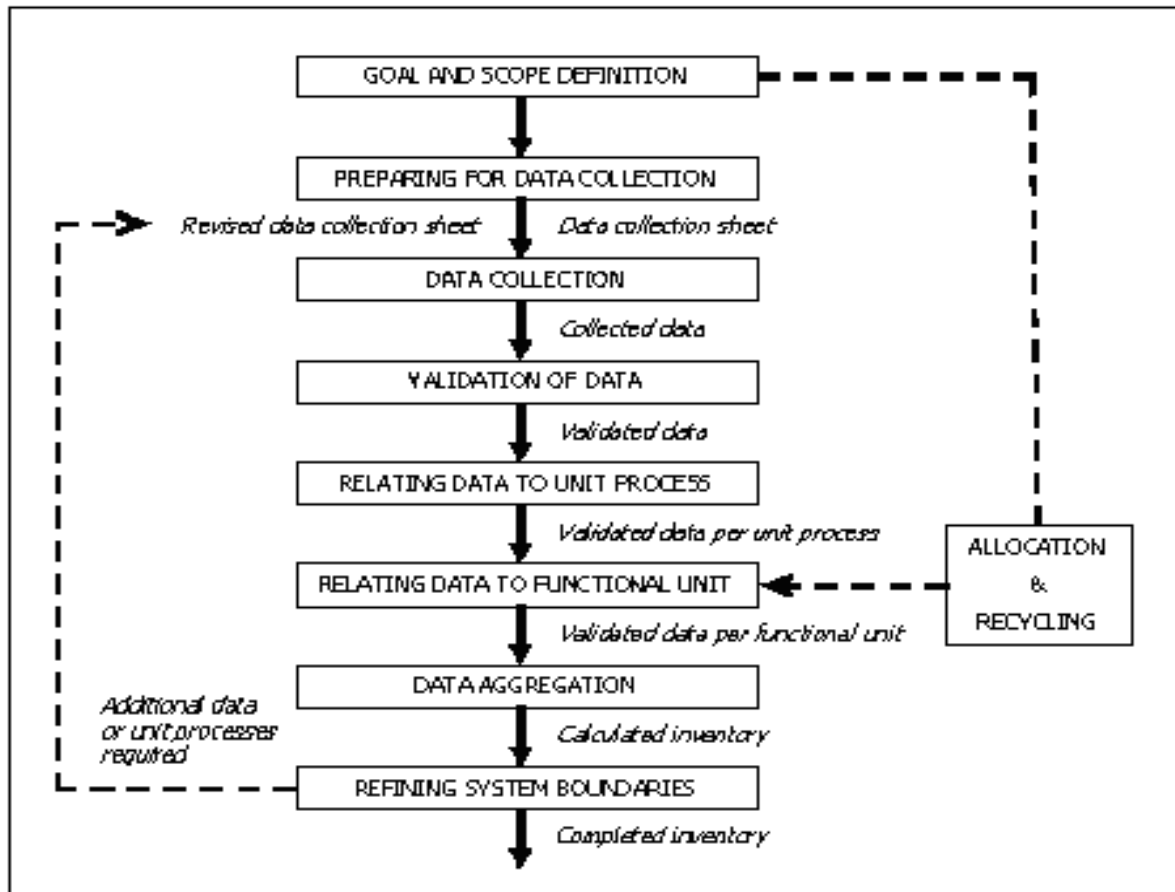


Figure 2.5 Steps for Life Cycle Inventory (ISO, 1998)

2.2.3 Life Cycle Impact Assessment

Life cycle impact assessment(LCIA) is the third phase of a LCA, and its purpose is to evaluate the environmental impacts from the results of life cycle inventory (LCI). According to ISO 1997 and ISO 2000a, this phase can be divided into two parts:

Mandatory elements:

- Selection of impact categories, category indicators and characterization models.
- Classification- assignments of inventory results to the selected impact categories.
- Characterization- result of category indicators is calculated by converting the result from inventory into common units.

Optional elements:

- Normalization- using a relative reference information(i.e different but similar product)

to calculate for the magnitude of category indicator results.

- Grouping- impact categories are divided into selected groups such as geographic relevance or company priority.
- Weighting- Conversion of indicator results from different impact categories using factors based on value choice.
- Data quality analysis- evaluate the results of impact assessment based on the credibility and reliability of the sources.

2.2.4 Interpretation

Interpretation, the last step in LCA's performance, aims to give conclusions and recommendations according to the goal and scope specified in the first step. The results of LCI and LCIA are summarized and interpreted iteratively to provide a complete and unbiased report of the study. The interpretation phase consists of three steps:

- Identification of significant issues,
- Evaluations of results,
- Conclusions, limitations and recommendations. (ISO, 2000b)

2.3 Brief History of Life Cycle Assessment

Green Council, a Non-Profit Organization(NGO) established in 2000 from Hong Kong, summarizes the highlights of LCA's history in their 2011 LCA seminar to raise the awareness of LCA, which is shown in the following Table 2.1.

Table 2.1 History of LCA (Ho 2011)

Time	Incidents
Early 1960's	Concerns about the rapid depletion of fossil fuels, which sparked interest in finding ways to account energy use and to project future resource supplies and use
1963	Harold Smith published the one of the first LCA report on energy requirements for the production of chemical intermediates at World Energy Conference
Late 1960's	The studies in <i>The Limits to Growth</i> and <i>A Blueprint for Survival</i> initiated the trend on predicting finite resources in the world

1969	The Coca-Cola Company conducted LCA study on different beverage Containers
1970-1975	USEPA refined The Coca-Cola LCA methodology and created the <i>Resource and Environmental Profile Analysis</i> .
Late 1970's-1980's	Environmental concerns shifted to issues of hazardous waste management and solid waste. The life cycle logic was incorporated into emerging method of risk assessment and analyzing the environmental problems.
Late 1980's	A broad base of consultants and researchers across the globe has been further refining and expanding the LCA methodology
1991	11 State Attorneys General in the USA denouncing the use of LCA results to promote products until uniform methodology and consensus reached on how environmental comparison can be advertised non-deceptively
1992	ISO 14000 family grew out of ISO's commitment to support the objective of sustainable development discussed at the <i>United Nations Conference on Environment and Development, in Rio de Janeiro</i>
1993	ISO launched the new technical committee, <i>ISO/TC 207, Environmental Management</i>
1997-2006	ISO developed the LCA standards 10 Environmental Protection Agency. 2006. <i>Life Cycle Assessment: Principles and Practice</i> .

Nowadays, LCA are used in many companies to answer market demands, legislative pressure, and to improve product design. The significance of LCA becomes more and more recognized as the concerns for environment are growing. Companies compete with each other by keeping the information secret. Certainly, the involvement of the stakeholders is needed for further development of LCA (DEAT 2004).

2.4 Benefits And Limitations of Performing a Life Cycle Assessment

Performing a Life Cycle Assessment can give the following benefits to the researchers:

- Systematically evaluate and analyze the environmental consequences related to examined product or process,
- Quantify the environmental releases, eg emissions into air or water, of a given product in every phase,
- Identify the differences in environmental impacts between every life cycle phase,
- Estimate the human and ecological effects of materials consumptions and environmental emissions,
- Compare the health and ecological consequences of two rival products,
- Categorize the environmental impacts of examined product to one or more areas of environmental concerns (**Stone 2012**).

Despite its benefits, like other environmental techniques, there are present of limitations in a LCA's performance as well:

- A LCA performance is prohibited economically for most of interested organization because it is very data intensive and time consuming procedures. The more time consumes, the more money needs to spend,
- None of LCA methodology is imperfect and generally not acceptable,
- As there are many different derivatives coming from LCA(see Chapter 3), the study is not always about the environmental impacts because it has another aims like economy or society, and so the results about environment may not be reliable,
- Many of the studies select only some phases of the examined product. In other words, there are very few cradle to grave LCA reports,
- An obvious disadvantages are the limitations and assumptions that need to be stated in the Goal and Step as they can be subjective,
- The results of LCA can hardly apply in the local level. They are more suited for national and regional levels,
- The accuracy of these results are depened on the reliability and quality of the resources and relevant data (**Stone 2012**).

3 Different Types of Life Cycle Assessment and Its Derivatives

In this chapter, three types of LCA will be discussed to help identifying a LCA study and give more options of the choosing the right LCA to perform.

Following the three types of the LCA, derivatives of LCA will be discussed. The reason why it is called “derivatives“ is that their methods are derived from methods of LCA, but they answer to non-environment issues such as economy, human health, and society. The Figure 3.1 sums up the main points of this chapter.

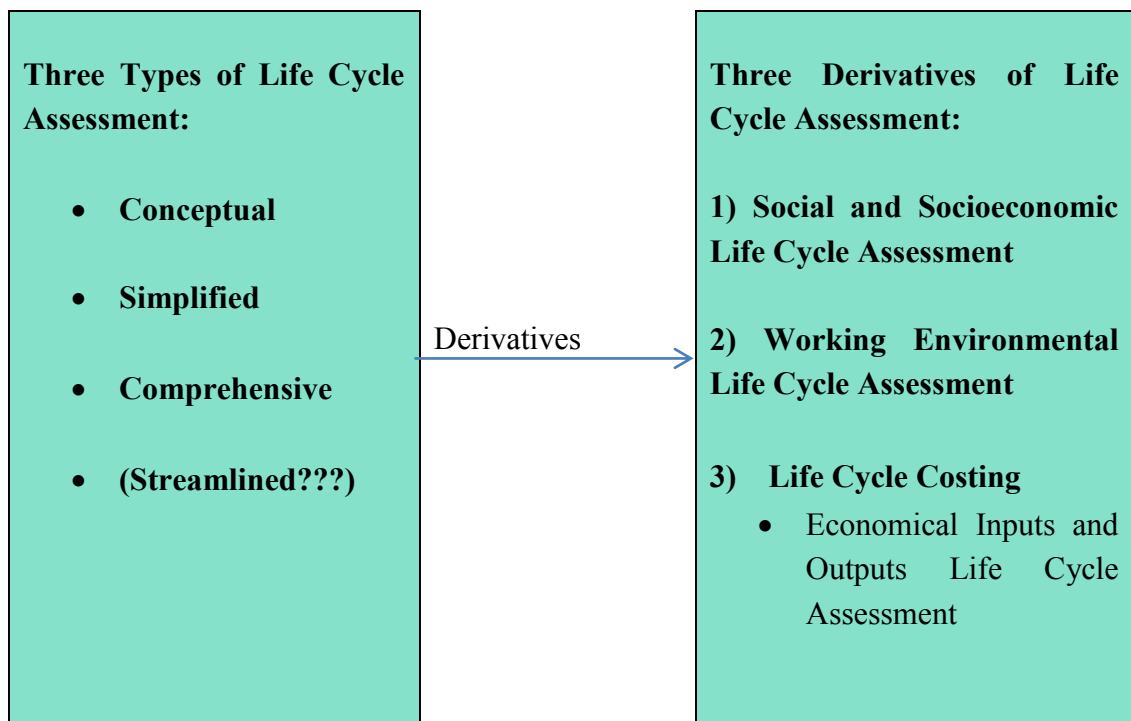


Figure 3.1 Three types of Life Cycle Assessment and its derivatives

The derivatives could be combined with standard LCA for more than just environmental issues report. The three dominant ones are Life Cycle Costing (LCC), Working Environmental Life Cycle Assessment (WE-LCA), and Social and Socio-Economic Life Cycle Assessment (S-LCA).

For the purpose of this project, only tutorial of a detailed standardized LCA will be given at later chapter. The derivatives of LCA, discussed in this chapter, are mainly for knowledge and the interest of further knowledge in LCA’s developments.

3.1 Standardized LCA

The detail of definition and how to perform Standardized LCA is discussed in Chapter 2. In this section, three types of Standardized LCA will be discussed; they are Conceptual LCA, Simplified LCA, and Comprehensive LCA.

3.1.1 Conceptual LCA

Conceptual LCA, also known as Life Cycle Thinking (LCT), aims to lower the environmental impacts and reduce use of resources at every stage for any possible improvements. By doing so, it helps to prevent burden shifting from one stage to another. For sustainable development, LCT is essential tool and should be applied in product design, processes and decision making aids (**JRC 2012**).

3.1.2 Simplified LCA

Simplified LCA uses the generic data and standard modules for energy production to screen the product, i.e. identify the important parts of a product or elementary flows. After the screening stage, it will only focus on assessing these important parts and ignore the insignificant ones to save times. Finally, it will assess the reliability of the results from simplifying process (**DEAT 2004**).

3.1.3 Comprehensive LCA

Comprehensive LCA is the most time consuming and detailed form of LCA. It undertakes the four phases of ISO 14040 extensively, especially in the second phase, inventory analysis. If there are only generic data available, then the researchers need to collect data on the product under review. A report of a comprehensive LCA determines or affects to a large extent the decision making of choices between two products (**DEAT 2004**).

For the purpose of this project, the tutorial targets the comprehensive LCA, but depending on the desired outcomes of the studies, the researchers could also use the other two types of LCA.

3.1.4 Streamlined LCA

Streamlined Life Cycle Assessment (SLCA) is supposedly the separate shorter version of Life Cycle Assessment (LCA). However, during the development of SLCA, the SETAC Workgroup realized that streamlining is an inherent part of any LCA because Workgroup defined streamlining as follows, “streamlining is a routine element of defining the boundaries and data needs of a study and is not in itself a different approach or methodology for LCA.” In summary, originally SLCA is thought of as shortened method of LCA but later was realized that it was only the point in the LCA’s process (SETAC 1991).

Therefore, there should no confusion that SLCA and LCA are two different approaches. The key of SLCA and LCA is linked to the goal and scope of the study. Most of the time, the goal and scope of study are not well established and left open until the every end of a project. In that light, every LCA is actually streamlined (SETAC 1991).

3.2 Life Cycle Costing

Life Cycle Costing is cradle to grave assessment of all the costs of a product over its entire life cycle. It is much similar to LCA except for the fact that it focuses on cost rather than environment. Like LCA, LCC also started in late 1960s and was first initiated by U.S military to calculate the costs of long living equipments. Since its inception, LCC has been very active in the many different industry sectors such as transport and construction. However, unlike LCA, LCC has not been standardized and thus does not have ISO standard although several industry guidelines and references are available (UNEP 2009).

What important in LCC are cost categories, cost “measurement procedures,” system boundaries, and possible discount rate. LCC can be combined with LCA to become Environmental Life Cycle Costing (eLCC). Such attempt was made by SETAC Working Group in order to have both economic and environmental impacts. They define eLCC as follows, “An assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or End of Life actor) with complementary inclusion of externalities that are anticipated to be internalized in the decision-relevant future.” (UNEP 2009)

Even though much effort is put in, LCC and LCA cannot become one. The matter is that decisions relating cost and environment are not always parallel.

3.2.1 Economical Inputs and Outputs Life Cycle Assessment

Economist Wassily Leontief, the Nobel Prize recipient in 1930 for his inputs and outputs work in economics, developed and theorized EIO-LCA in the 1970s. Twenty years later, the researchers at Green Design Institute of Carnegie Mellon University transformed the this method into a convenient and free online tool which is available on their website. They define EIO-LCA as, “method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy.” EIO-LCA online tool not only examines the effects of final assembly of a product, but also the effects of every part of the product (no matter how small.) (**EIO-LCA 2012**)

Trusted by millions of users ranging from LCA practitioners to government researchers from many different countries, EIO-LCA is reliable tool for applying to national and state economies (**EIO-LCA 2012**).

More information regarding EIO-LCA can be found on Green Design Institute of Carnegie Mellon University website.

3.3 Working Environmental Life Cycle Assessment

Working Environmental Life Cycle Assessment focuses on human health that could be impacted by working environment of a product system throughout its entire life cycle. This aspect is usually ignored or not much emphasized in normal LCA. WE-LCA is, in general, the result of integration of working environment into LCA after fifteen years of research and development. It examines how bad the working environmental for the workers will be at the expense of environmental improvements (**UNEP 2009**).

3.4 Social and Socio-Economic Life Cycle Assessment

Social and Socio-Economic Life Cycle Assessment (S-LCA) is a tool that assess social and socio-economic aspects of the products (as the name suggests it) along the entire life cycle. It can also be applied to standardized LCA, but by itself, S-LCA is not sufficient to provide any solutions for environmental issues because it does not have a goal and does not give any recommendations as whether should a product be used or not. The stakeholders can be positively or negatively affected by the results of S-LCA (**UNEP 2009**).

Unlike other assessing tools, S-LCA can be used for harmful products like weapons; therefore, it is strongly suggested that it needs to be peer review and done ethically to prevent any inappropriate methodology used in the report. S-LCA ultimately aims to assess social and socio-economic aspects of production and consumption for the improvements of organizations and protection of stakeholders' well being (UNEP 2009).

4 Life Cycle Assessment's Tools

There are numerous LCA's tools on the market nowadays; each has different methods (i.e accounting, function based and screening LCA) of performing a LCA and is designed for different types of users (i.e LCA beginners, experts, environmental and design engineers). The cost of a LCA software could range anywhere from free to more than 10,000 Euro. Below are the referenced tables that list extensively the currently active, free and decommissioned LCA's tools. Then, in the next two sub sections, information of Life Cycle Inventory databases and Life Cycle Impact Assessment methods will be provided.

4.1 List of Currently Active Life Cycle Assessment's Tools

In this section, the list of the currently active LCA's tools are provided along with the information about their names, versions, vendors, cost(non-commercial purpose), the industrial sector, and country where the softwares (or tools) are from . This is not a comprehensive list because there are still hundreds and hundreds more of LCA tools out there in the market, but this table should be sufficient in referencing a software that suits for any studies' purposes. The softwares and tools are chosen based on the list provided in **Tools 2012 and Siegenthaler 2005**. The information is mostly collected at the respective developers' websites.

Table 4.1 List of Currently Active Life Cycle Assessment's Tools

#	Software +Version	Vendor	Cost(non commer- cial)	Industrial Sector	Country of Origin
1	AUDIT Pro V3.1	AUDIT Solutions Ges.m.b.H.	10,900 €	Paper, Steel, Envi- ronment	Austria
2	AIST-LCA 4.0	AIST	unknown	General Production	Japan
3	Boustead Model 5	Boustead Consulting Limited	1,500 £	Fuel, Metals, Glass, Polymers, Papers, Chemicals, etc..	UK
4	EcoDesgin X- Pro 1.0(web)	EcoMundo	unknown	Environment, man- ufacturing process	France

5	EIME V5.0	Bureau Veritas CODDE	unknown	Electrical, Electronic, Mechanic, Transportation	France
6	EMIS 5.0	Carbotech Inc.	3,200 €	General Production, Transportation, Construction, Agriculture, etc..	Switzerland
7	GaBi 5	PE Europe GmbH	~10,000 \$	All	Germany
8	IdeMat Pro	Defts University of Technology	640 € up to 5 users	Materials	Netherlands
9	JEMAI-LCA Pro	Jemai +AIST	750 €	Assembling, Materials, energy	Japan
10	LCA-Evaluator 2.0	GreenDelta TC	Unknown	All	Germany
11	LEGEP	LEGEB Software GmbH	2,000 €/module	Building, house, Construction	Germany
12	Quantis Suite 2.0	EPFL & CIRAIG	3,400 €	All	Switzerland, Canada
13	REGIS 4.0	Sinum AG	3,750 €	All	Switzerland
14	Sabento 1.1	ifu Hamburg GmbH	Unknown	Biotechnical processes	Germany
15	SimaPro (Education)	7.3 PRé Consultants	1,200 €	All	Netherlands
16	TEAM 4.0	Ecobilian S.A.	3,000 €	Energy, raw materials, transport, chemicals	France

17	TEAM Simulator 3.0	Web	Ecobilian S.A.	10,000 €	Energy, raw materials, transport, chemicals	France
18	Umberto Consult	4.3	Ifu Hamburg GmbH	12,200 €	All	Germany
19	WISARD 4.0		Ecobilian S.A.	3,000€/year	Waste	France
20	WRATE Standard	Stand-	UK Environment Agency	1500 £/year	Waste	UK

All twenty of these softwares have prices. In the next sub section 4.2, table of free LCA softwares will be provided. In this Table 4.1, there are five softwares with unknown costs because they are not published in their developers' websites. Their costs, however, can be achieved by requesting the quotes directly from the vendors. Besides that, there are two softwares that are below 1,000 euro, eight softwares that is in between 1,000 and 10,000 euro, and four softwares that are equal or more than 10,000 euros.

Due to great fluctuation of the prices, it may raise the questions of which softwares are better, are the more expensive softwares better, and so on. The more expansive softwares tend to be the primary LCA tools, which offers a full LCA package, whereas the less expansive ones tend to be the secondary LCA tools, which offers the LCA based results. Some of primary tools are SimaPro, Gabi, and Umberto; and secondary tools are Solidworks, and Eco Design.

4.2 List of Free and Currently Active Life Cycle Assessment's Tools

In attempt of increasing awareness about LCA and making it more accessible to the public, there are free LCA tools that are available on the internet. Some of these tools are advanced enough for the complexity of LCA processes if used correctly. Again, there are more free softwares out there, but this list should be sufficient to serve as a reference. The softwares here are also selected from **Tools 2012** and **Siegenthaler 2005**.

Table 4.2 List of Currently Free and Active Life Cycle Assessment's Tools

#	Software +Version	Vendor	Cost(non commercial)	Industrial Sector	Country of Origin
1	BEES online	NIST	Free	Building Products	US
2	CMLCA 5.2	CML, Leiden University	Free	All	Netherlands
3	EIME V5.0- Test License	Bureau Veritas CODDE	Free	Electrical, Electronic, Mechanic, Transportation	France
4	EIO-LCA	Green Design Institute	Free	Transportation,	US
5	EuPeco- Profiler(Web)	SIMPPL	Free	Energy Using Products(EuP)	Spain
6	eVerdEE	ENEA	Free	Industry, agriculture	German, UK, Italy, Spain, Greece
7	Gabi 4- Education	PE Europe GmbH	Free	All	Germany
8	REET 2.7	Argonne National Laboratory	Free	Energy, Transportation	US
9	OpenLCA Beta 1.1	GreenDelta TC	Free	All	Germany
10	Stan 1.1.3	Vienna University of Technology	Free	Materials flow analysis tool	Austria
11	TESPI	ENEA	Free	Quality analysis, environment	Italy

12	TRACI	US EPA	Free	All	US
13	USES-LCA 2.0	Radboud University Nijmegen	Free	Toxic	Netherlands
14	WAMPS	IVL Swedish Environmental Research Institute	Free	Waste	Sweden

Among these 14 softwares listed in Table 4.2, Open LCA is only one that is still under development, but looks to be the most promising LCA softwares because it is being developed by the top LCA organizations such as PE international, and PRé Consultants. It estimates that after one and half year, the OpenLCA first full version will be available, and the expectation for its performance is high.

Gabi 4 is best choice for college students who wants to conduct a LCA study for their projects but do not have much funding. It is free for all students from a recognized university with the proof of their enrollment and reference from their professor (who supervises their projects.) They can have the full license of Gabi 4 with nearly no restrictions. The only set back would be the limited database for this version, which is made for educational use.

In short, thanks to the abundance of free LCA softwares, LCA beginners and people who are interested in LCA can start perform a LCA immediately. Unless they want to do very complicated LCA, free softwares should be more than enough for the performances of common products.

4.3 List of Decommissioned Life Cycle Assessment's Tools

Here is the table of the LCA tools that had been decommissioned because their developers's websites do not exist anymore. The exact reason has not been researched; however, it seems that these softwares did not get enough funding or merged with other LCA companies. These softwares are selected from **Jönbrink 2000** a LCA survey done in 2000, and **Siegenthaler 2005**.

Table 4.3 List of Currently Decommissioned Life Cycle Assessment's Tools

#	Software +Version	Vendor	Cost(non commer- cial)	Industrial Sector	Country of Origin
1	Balance 3.0	IER, Univer-sity of Stuttgart	250 \$	Energy, materials, transport, heat, electricity, waste	Germany
2	CEDA 3.0	CML and EnviroIn- formatica, Co.	349 €	All	Netherlands
3	CUMPAN 1.44	Debis Sys-temhaus In-dustry GmbH	6000 \$	Metals, plastics, energy, fuel	Germany
4	EcoDesgin X-Pro 1.0(web)	EcoMundo	unknown	Environment, man- ufacturing process	France
5	EPS 2000	Assess Ecos-trategy Scan-dianvia AB	3,300 €	General Production	Sweden
6	Green-E 1.0	Ecointesys	unknown	All	Switzerland
7	KCL-ECO 4.0	Oy Keskuslab Oy Keskuslaboratorio- Centrallaboratorium Ab, KCL oratorio- Centrallaboratorium Ab, KCL	3,600 €	All industrial pro-cesses	Finland
8	LCAiT 4.1.7	CIT Ekologik AB	3,600 €	All	Sweden
9	NIRE-LCA 3.0	AIST	700 €	General production	Japan
10	OGIP 2.0	t.h.e Software GmbH	50-200 €	Building Construction	Germany

11	PEMS v3.1	PIRA	9,100 \$	Energy, waste, transport, materials	US
12	SIMBOX 3.1	EAWAG	1,000 €	Materials flow analysis tool	Switzerland
13	WWLCAW	IMI	Free	All	Sweden

Many of these softwares are mentioned in the LCA studies that were done at the late 19s and early 20s. If interested, further investigation is recommended to complete the gap of knowledge as of why they were decommissioned. This Table 4.3 is primarily to inform the disappearance of these LCA softwares.

4.4 Life Cycle Inventory Databases

Life Cycle Inventory(LCI) database is an integral part of any LCA tool. It provides the information about the parts of a product, and depending on how detail of information a LCI database has, the reliability of the result will be determined. The bigger database is the better for computing the complicated products. For quick reference, here are the names of some dominant LCI databases in North America and Europe:

- The UNEP/SETAC Database Registry- Life Cycle Initiative beta project for creating database registry,
- E3IOT- Database for Europe that covers production, consumption and waste management,
- Earthster- web-based, free, and open source for general production,
- The ecoinvent Centre-The Swiss Centre for Life Cycle Inventories central database of LCI data and life cycle impact assessment (LCIA) methods data. Also, the world's leading LCI and LCIA Databases,
- EIO-LCA CMU Database- Included in free EIO-LCA software,
- ELCD Core Database- Database for Europe covers key materials, energy carriers, transport, and waste management,
- GaBi 5 Database- Included in Gabi 5 software
- IVAM LCA Data 4.0- IVAM Environmental Research Database,

- Sourcemap- directory of product supply chains and carbon footprints,
- US Life-Cycle Inventory Database- made by National Renewable Energy Laboratory is publicly available and used for fuel production and combustion, electricity generation and transformation processes (**Gloria 2012**).

When purchasing a LCA tool, it is recommended to look at what LCI database does a LCA tool offer. Even if the tool does not include a large database, it may accept imports from other database in a suitable format. More importantly, the researchers should choose that LCI database fitted their field of application.

4.5 Life Cycle Impact Assessment Methodology

Another integral part of a LCA tool is the Life Cycle Impact Assessment (LCIA). After collecting the necessary data from the LCI, the users need to do LCIA for the analysis of impacts of the product on the environment. There are many different LCIA methodology for different kinds of needs. Here is the summarized list of the common used methods:

- BEES Methodology- Building for Environmental and Economic Sustainability method developed by US DOC, NIST,
- CML Method- Institute of Environmental Sciences (CML) at Leiden University,
- Eco-Indicator 99- a science based impact assessment method for LCA and a pragmatic ecodesign,
- Ecological Scarcity Method- Swiss Federal Office for the Environment FOEN for Integrated Product Policy,
- EDIP- Environmental Design of Industrial Products at Technical University of Denmark,
- EPS- Environmental Priority Strategies in Product Design
- IMPACT 2002 and 2002- Risk and Impact modeling at the University of Michigan,
- JEPIX- Japan Environmental Policy Index,
- LIME- Japan Environmental Management Association for Industry,
- ReCiPe- method developed by RIVM, CML, PRe Consultants, Radboud Universiteit Nijmegen, CE Delft,
- US EPA Methodology – TRACI- The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (**Gloria 2012**).

Every LCA tool has different set of LCIA methods. Before purchasing a LCA tool, the users should know what LCIA methods does that tool performs. By selecting the right LCIA method, the user of the LCA tool can have expected results. For example, some methods do not

have calculation for the percentage error, and if percentage error is needed, a different method, like Eco-Indicator 99, should be chosen.

4.6 Recommendation

The currently active and leading primary LCA softwares are SimaPro, Gabi, Umberto, Team, and Quantis Suite. Being the primary softwares, they all can perform a full life cycle LCA of a product effortlessly. They are well known for their reliability, large LCI databases, and variety of LCIA methods. In the market, they are all competitive in price. The main differences of all the softwares come down to functionality, user friendliness, and customer service.

SimaPro and Gabi are probably the most famous because of their leading sales and extensive use in the industry. They have the same database, EcoInvent, but SimaPro offers more LCIA methods, one of which could calculate the percentage of inaccuracy. They both offer training courses on site and online. Gabi could be more preferable in universities because it offers a free educational version for students.

All of the softwares have demo versions for trial, so it is strongly recommended to try out the softwares before purchasing it.

5 Example of Life Cycle Assessment of Coffee Machine Using SimaPro

This example of LCA is a tutorial on SimaPro Demo version 7.3.1. The tutorial is intended to show how a detailed LCA is conducted, and get the readers more familiar with SimaPro, which is quite user friendly. In the next chapter the knowledge will be translated to study how a LCA of an aircraft should be done.

5.1 Goal and Scope

To begin with, goal and scope need to be defined. The goals are to demonstrate how the complete life cycles LCA of a product are performed and also how SimaPro works. This example is fictitious, meaning that coffee machine is imaginative and not based after any real model. In SimaPro tutorial, the coffee machine is named model Sima.

For the scope of the coffee machine, please refer to section 2.2.1.1 for the things that need to be defined. The function of this machine is to make coffee. Assuming that a household with two people, each drinks at least one cup of coffee a day, and so when buying a coffee machine, they would buy one with larger capacity for anticipation of guests. Based on this assumption, a coffee machine with 10 cups capacity would be examined. Its life time is estimated to be 5 years.

Assuming that the coffee machine is used two times a day, the filters that are needed for its whole life time is $365 * 5 * 2 = 3650$. During the use phase, it is clear that the electricity is main factor. SimaPro has calculated that 350 kWh will be needed during this period.

Since model Sima is not a real coffee machine, its LCI is made up by SimaPro and readily available in the tutorial. SimaPro is equipped with many different LCIA methods, and during the tutorial, the user can change back and forth to other LCIA method. By default, Eco-Indicator 99 is used.

5.1.1 Process System

The following process system shows the stages of coffee machine. Before that, it is important to know the definition of SimaPro's LCA terms in this chart. An assembly (the light blue col-

or box) contains the list of materials, processes, transport processes and links them to environmental data. The assemblies within an assembly are called subassemblies.

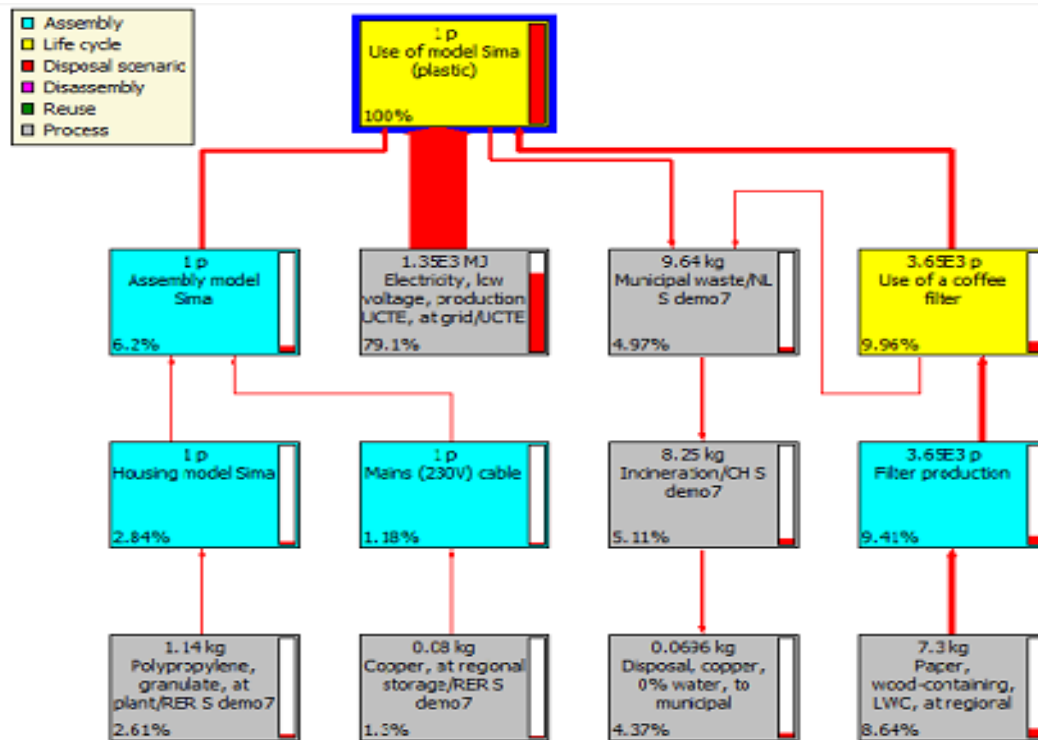


Figure 5.1 Process System of Model Sima

In Figure 5.1, the light blue boxes are the assemblies. The yellow boxes are the additional life cycles because they were not created initially. In SimaPro, the user can add the additional life cycles like packaging, production or filters at any time in the process. The gray boxes are the processes and materials in the subassemblies.

5.1.2 Functional Unit

The functional unit is totally subjective to the researchers. A product should have several possible functional units, whichever deems the most appropriate is used. In this case, the possible functional units of Model Sima could be:

- Watts per Hour (W/Hr),
- Coffee Cup per Day (CCD).

Since the main function of coffee machine is to make coffee, CCD is a better functional unit.

5.2 Life Cycle Inventory

After defining all the assemblies and put them into process system, SimaPro can immediately calculate the LCI results. The inventory contains the list of inputs and outputs throughout the production phase. The inputs are the raw materials extraction, while the outputs are emissions to the air and water. The “use of a coffee filter” was added during the use phase so it is not included in inventory, which is production phase.

The assemblies in the production phase are:

- Housing is made of Polypropylene(PP),
- About 15 smaller parts, mainly made of steel (hot plate), plastics and copper(wires),
- Main cable(copper and PVC),
- Glass coffee pot with handle made of Polypropylene (PP).

Because the whole inventory list is extensively long (over 500 lines), in Figure 5.2 only small of the list is presented to show the readers how the inventory list looks like.

No	Substance	/	Compartment	Unit	Total	Housing model Sima	Small parts for coffee machine	Mains (230V) cable	Coffee pot
1	Acenaphthene		Air	ng	2.98	1.83	0.559	0.0838	0.511
2	Acenaphthene		Water	ng	106	51.2	11.3	4.72	38.9
3	Acenaphthylene		Water	ng	6.64	3.2	0.704	0.295	2.43
4	Acetaldehyde		Air	mg	1.04	0.355	0.113	0.051	0.523
5	Acetic acid		Air	mg	14.5	7.48	2.23	0.524	4.24
6	Acetic acid		Water	µg	505	313	92.2	17.3	82.1
7	Acetone		Air	mg	1.16	0.429	0.142	0.0553	0.535
8	Acidity, unspecified		Water	mg	70.9	46.5	8.96	3.6	11.9
9	Adonifen		Soil	ng	634	318	98.4	29.3	189
10	Acrolein		Air	ng	302	151	62.4	19.3	68.5
11	Actinides, radioactive, unspecified		Air	mBq	542	342	96.6	14.7	88.5
12	Actinides, radioactive, unspecified		Water	mBq	69.8	43.3	12.8	1.95	11.7
13	Aerosols, radioactive, unspecified		Air	mBq	10.5	6.65	1.86	0.284	1.7
14	Aldehydes, unspecified		Air	µg	417	273	70.7	4.4	69.1
15	Aluminium		Air	mg	739	54	225	447	12.6
16	Aluminium		Water	g	4.28	3.49	0.379	0.128	0.285
17	Aluminium		Soil	mg	10.6	4.92	1.23	0.421	4.01
18	Aluminium, 24% in bauxite, 11% in crude ore, in ground		Raw	g	151	150	0.626	0.572	0.502
19	Ammonia		Air	mg	417	45.9	100	196	75.1
20	Ammonium carbonate		Air	µg	1.54	1.03	0.237	0.0262	0.245
21	Ammonium, ion		Water	mg	33	12.9	4.16	6.09	9.79
22	Anhydrite, in ground		Raw	mg	4.27	2.6	0.577	0.424	0.669
23	Antimony		Air	mg	1.85	0.0169	0.459	1.37	0.00399
24	Antimony		Water	mg	9.3	4.41	1.3	2.25	1.34
25	Antimony		Soil	µg	36.5	6.91E-5	9.79E-5	0.000139	36.5
26	Antimony-122		Water	µBq	18.7	10.2	3.99	0.729	3.78

Analyzing 1 p 'Assembly model Sima'; Method: Eco-indicator 99 (H) V2.08 / Europe EI 99 H/A

Figure 5.2 Partial Inventory of Model Sima During Manufacture and Production-Phase

SimaPro gives the option to show the results that includes all compartments (Air, water, soil, raw, etc...) in one table or can also be specified per compartment. The “total” column gives the accumulated amount, and the subsequent columns give the contributed amount from each subassembly.

To perform the cradle to grave LCA, the inventory should have assemblies from all the phases. Production phase only cover the materials extraction, manufacturing and transport. There are still other phases that needed to be added such as use, disposal, recycle, etc... Simply adding the wanted phase in the process system and defining its assemblies, then the inventory results will be calculated.

5.3 Life Cycle Impact Assessment (LCIA) and Interpretation

Once the detailed inventory is complete, the next step, LCIA, is required. The results in inventory will be converting into common unit of different impact category to see the environmental relevance. This procedure is called characterization.

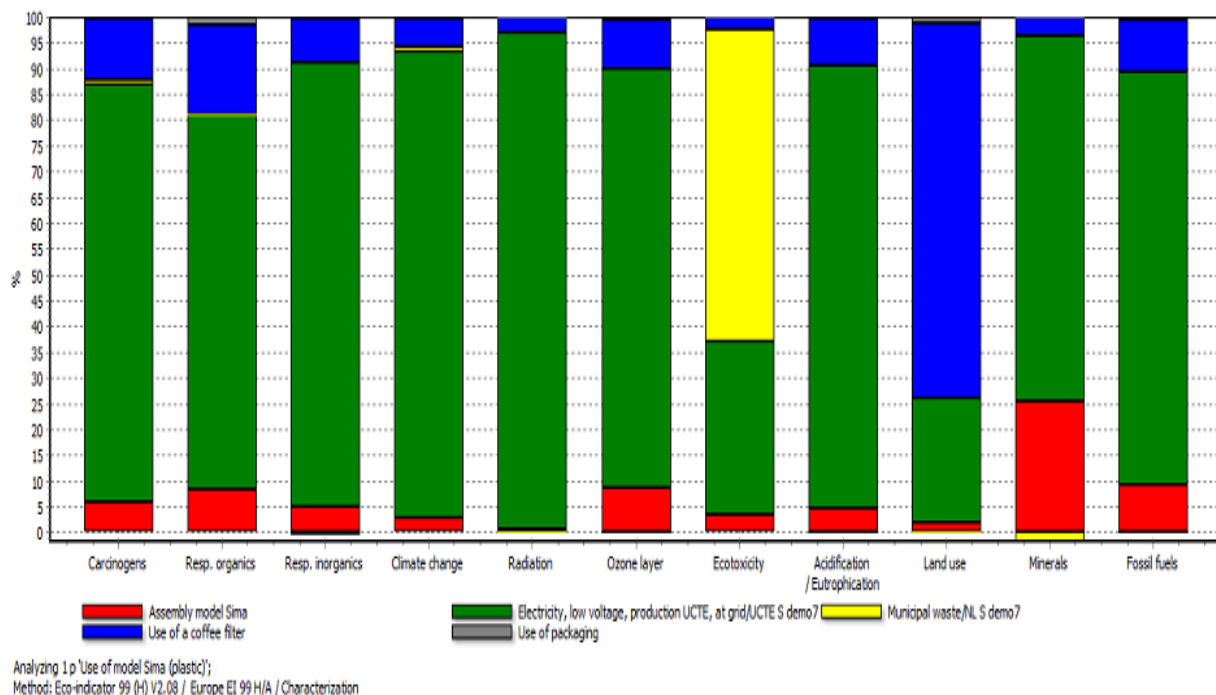


Figure 5.3 Chracterization of Model Sima

As shown in Figure 5.3, each impact category in characterization is scaled to 100%. This makes hard to tell which assembly has the highest overall impact because each bar on the graph could represent a very small or very large part of the impact.

An optional step, normalization of the results can be performed to see clearer environmental effects that are caused by an average European person per year is shown in Figure 5.4.

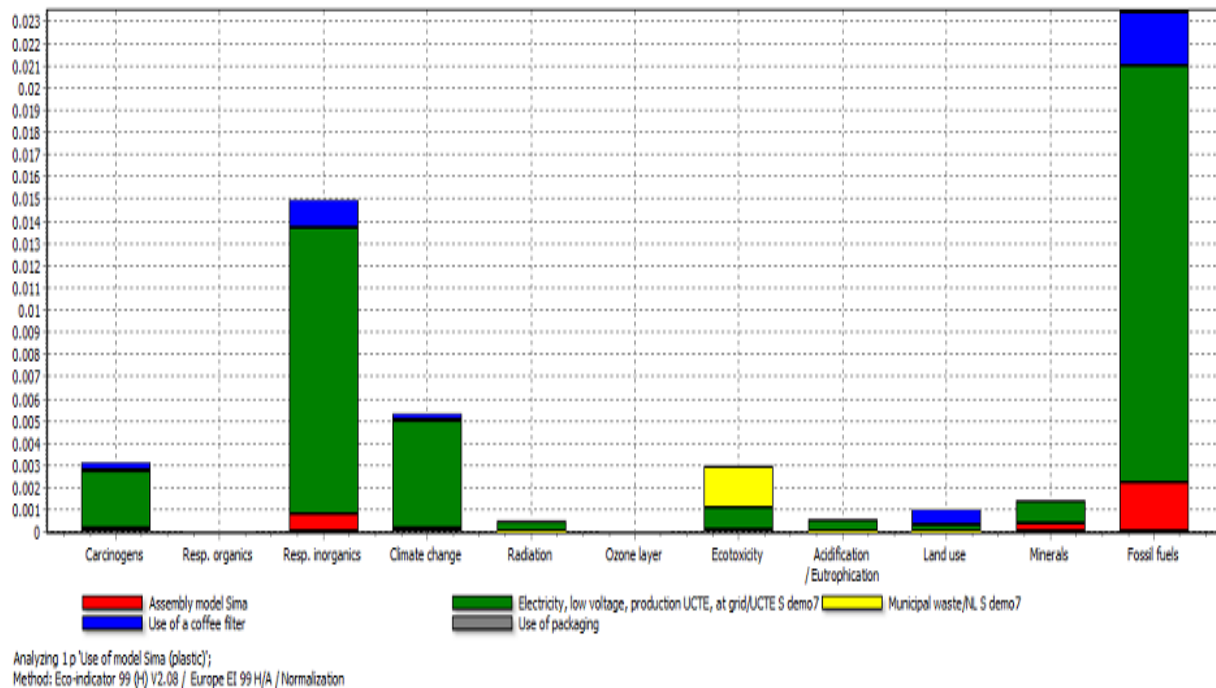


Figure 5.4 Normalization of Model Sima

Although normalization shows how big and small the effects are, it does not show anything about the relative importance of these effects. For example, how is climate change compared to acidification? Weighting raises the level of seriousness of normalization results by adding a weighting factor to each normalized result. By doing so, the relative importance of the environmental effects can be compared. The result is in Figure 5.5.

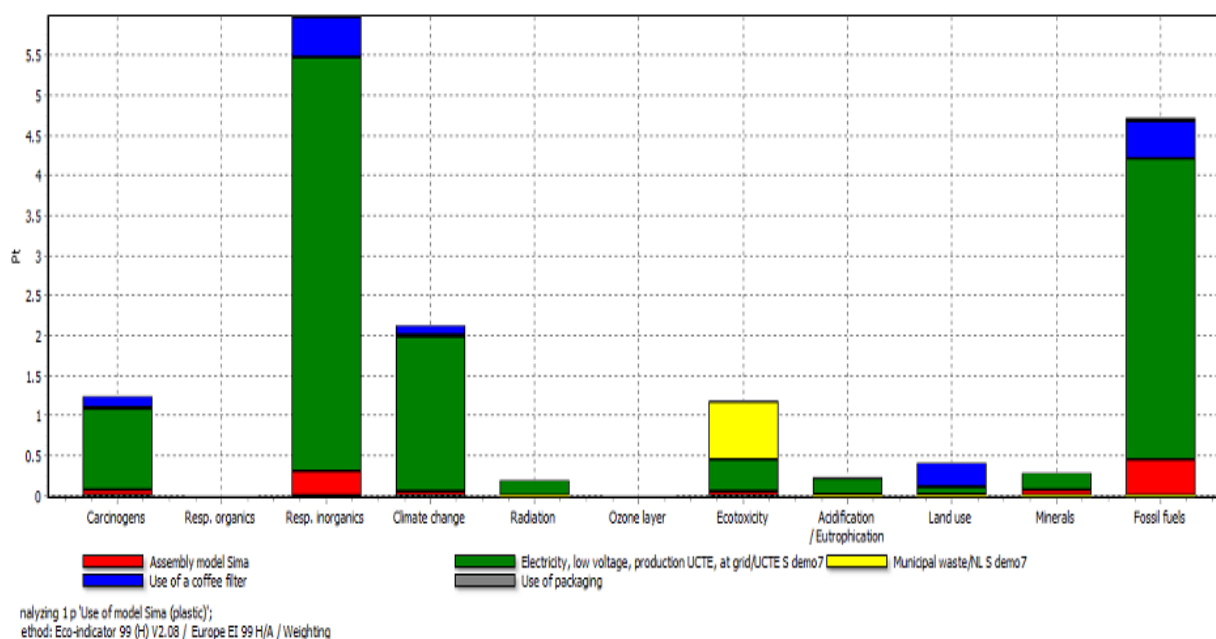


Figure 5.5 Weighting of Model Sima

Finally, in Figure 5.6 SimaPro sums up the all impact scores of each subassembly, materials, and processes of an assembly in the weighting graph and give the total single scores accordingly. The single score graph will make it easier to interpret the results. This is a nice feature of SimaPro.

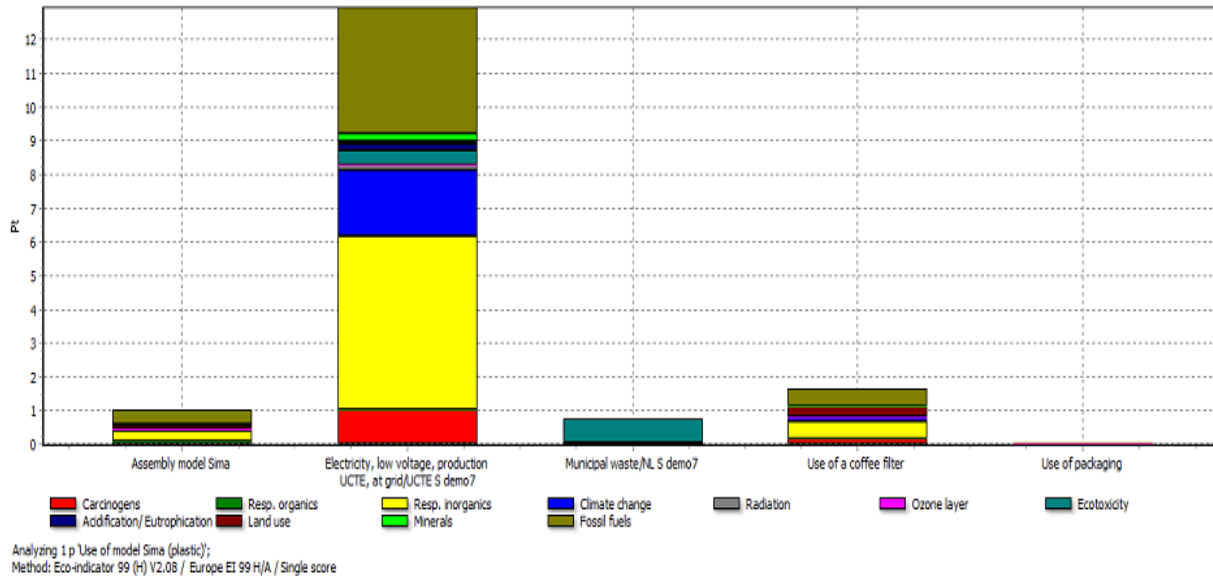


Figure 5.6 Single Scores of each subassembly

Clearly from the single scores graph, the electricity consumption (EC) in the use phase shows the highest effect on environment. The largest and second largest impacts in electricity consumption, which takes up about 70 % of the bar, are respiratory inorganics and fossil fuels respectively. In fact, the effects from other phases or assemblies, when compared to electricity consumption, are very small or nothing. Even if all the bars of other assemblies are added together, it barely reaches 40 % total height of EC.

The use of coffee filter is the second highest effect, following by assembly model Sima, Municipal Waste/NL S Demo 7, and use of packaging respectively. The use of packaging has almost no effect on environment.

Adding all the scores of the same impact category together, it is clear that respiratory inorganics and fossil fuels are the two largest issues of model Sima.

A new design that can reduce the usage of electricity during the use phase is encouraged. Moreover, for other assemblies, even though the contributions are small, the effect could still be lessened by choosing right materials. Since this is a fictitious example, everything is estimated. However, when doing a real LCA product, the limitations and assumptions should be justified to account for any possible errors.

5.4 Recycling

SimaPro tutorial for this example stops at the disposal phase. However, it could have been continued to recycle phase. Most of the materials of coffee machine are metals, which are could be easily recycled. It would be interesting to see further investigation into this phase.

6 How to Perform a LCA of a Commercial Aircraft

Since LCA is a standardized method, like any other products, LCA of an aircraft will go through same methodology according to ISO 14040 series, i.e. Goal and Scope, Inventory, Impact Assessment, and Interpretation. The main difference, however, is that aircraft is one of the largest man-made products, and its functions and specifications are not very familiar to many people. Moreover, top aircraft companies such as Boeing and Airbus usually hide their aircrafts' data due to competitiveness in the market or military reasons. Therefore, it is strongly advised that before doing LCA of an aircraft, the researcher should make sure that the information of that specific aircraft can be legally attained. Fortunately, most of the commercial aircraft information are publicly available. And this chapter's aim is to show how a LCA of a commercial aircraft can possibly be done.

It is important to note that most statements in this chapter are only logical assumptions based on the knowledge of performing the LCA of coffee machine.

6.1 Goal and Scope

In Goal and Scope, two questions need to be answered. What is the goal of the research? What is the scope? Goal defines the purpose or the reason for doing the research. For example, it could be something like improving the environment, making a better design, or planning a business strategy. Then, the scope defines the targeted audience, types of LCA(simplified or detailed), functions of the aircraft, functional unit, system boundaries, the limitations, assumptions, LCA software, LCIA, and type of research(comparative or non comparative).

The function of aircraft is to carry passengers, so it is reasonable to have the functional unit as passenger per kilometer.

Ideally, the system boundaries should be from cradle to grave, but since obtaining the data for an aircraft is not an easy task, some life cycles stages may be omitted. It may be not possible to clearly specify the system boundaries from the beginning, and it is okay to come back any-time to adjust the system boundaries that match with the research data

For students, it is recommended to use Gabi software because it is free and also one of leading softwares in the market with excellent tutorials (training). For non students, SimaPro would be very good choice because it is the most widely used software for many industries.

It is always a good idea to find the already literature of other LCA of aircrafts to see how they have been done.

6.2 Inventory

To begin with, the aircraft should be broken down into different parts such as tails, wings, landing gears, fuselage, cabin, and so on. Each part is a subassembly that when combines all together a complet aircraft assembly will formed. The Figure 6.1 is the picture of common components of an aircraft.

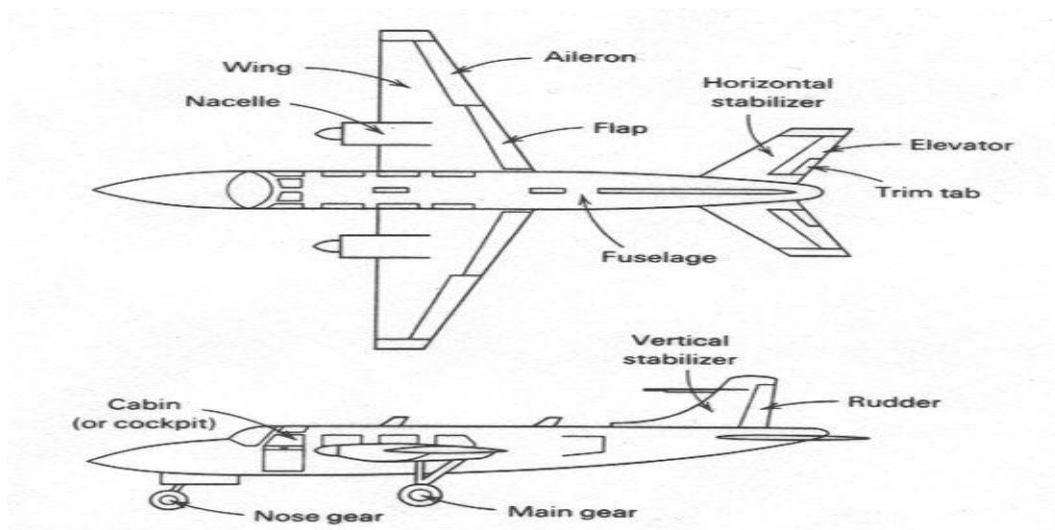


Figure 6.1 Components of an Aircraft (Scott 2002)

After each part is defined, the next task is to find the list of materials and possibly the processes of each component. This is where true efforts are needed. There are at least a few thousand materials that make up the whole aircraft. Although it is discouraging to list all the materials, the true challenge is how to collect the materials data. The first thing, anyone should do is to contact the place where aircraft is made and ask directly for the data. If that is too hard to get, looking at structural repair manuals or operational manuals for the examined aircraft, which can be found in large public libraries, is another option. The Figure 6.2 is the picture of subcomponents listed in a wing of an aircraft in structural repair manual.

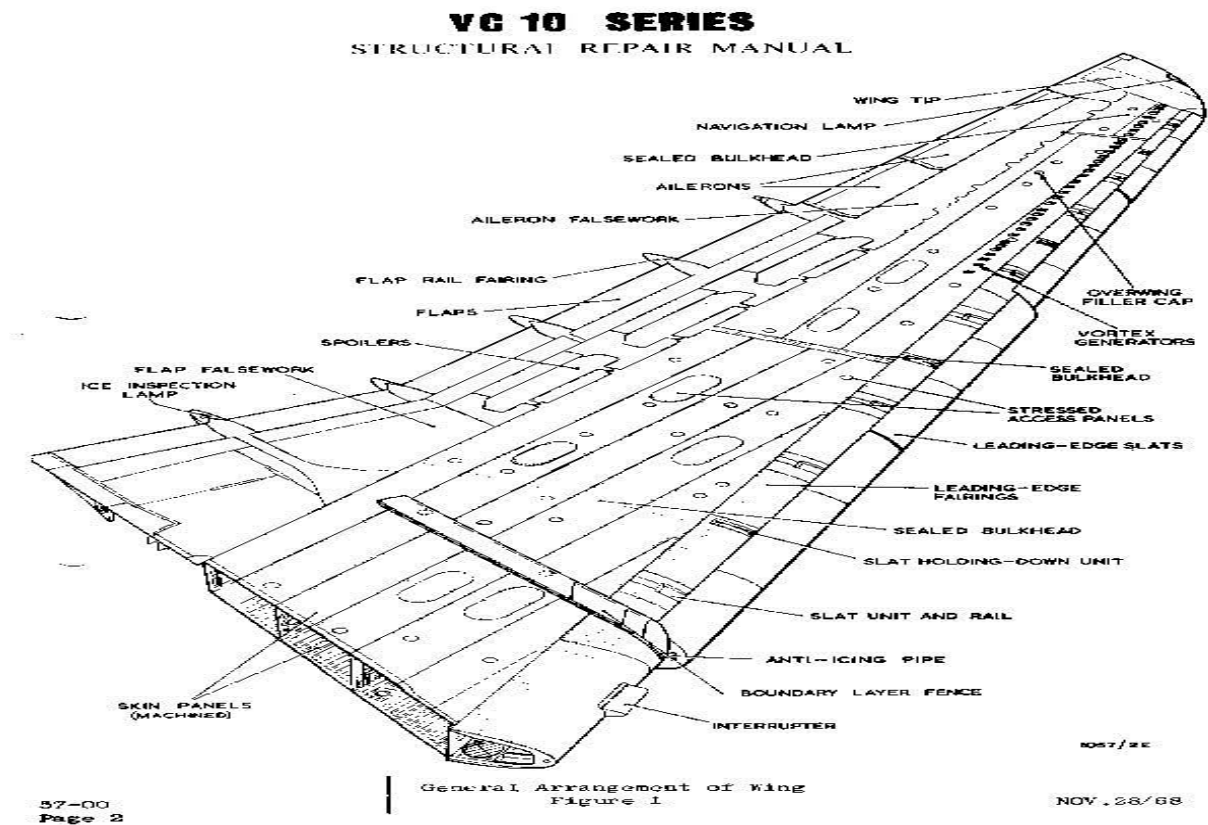


Figure 6.2 Subcomponents of an aircraft wing from Structural Repair Manual (Hie-minga 2012)

The LCI databases for aviation is not mentioned in most of LCA tools. Therefore, the researcher may need to import manually the collected data into whichever tool he uses.

6.3 Life Cycle Impact Assessment

Assuming that all the needed materials are collected, simply inputting all the data in a LCA tool will give the results of environmental effects for the production phase.

Similar to example of coffee machine, the use and disposal phase will also need to be added. For aircraft, the use phase should include four smaller phases, i.e. maintenance, taxiing, operation, and cruise. The researcher should have a good knowledge of how aircraft is functioned. How much fuel would it use during each phase? Aircraft consumes large amount of fuels during the use phase, and it would a logical guess to say that fuel consumption has the highest environmental effect just like electricity consumption in coffee machine example.

Lastly, the recycle phase will be added. Recycling an aircraft is not common term to say because most of airliners do not recycle the aircrafts. However, an end of life project for im-

provement of aircraft disposal called Pamela, by Airbus, has been going since 2005 and in 2007, the scope of the project had been finished. And now, the project is being undertaken at Tarmac Aerosave. The project's goal is to recycle about 85% of aircraft which would reduce significantly disposal phase effects on environment. Tarmac Aerosave has recycled a few dozen aircrafts, and its goal in the next 15 years, is to recycle 6000 more. If researcher chooses the aircraft that has been recycled by Tarmac Aerosave, he may be able to get recycle phase data from them and, thus, better his result.

6.4 Interpretation

The recommendation or suggestion for improvements should be given based on the interpreted results. The researcher should point out any errors or mistakes in his calculation due to the assumptions or whichever reasons. All assumptions that are made should be justified. Finally, he should give a general conclusion about his project.

Summary

Life Cycle Assessment is defined as the evaluation of environmental impacts of a product throughout its entire life cycles. LCA has been around for more than 40 years and become more and more recognized globally every day. Since its inception in 1960s, LCA has been spread quickly all over the world as people realized that it can address very well the environmental issues caused by man-made products. Nowadays, LCA is used extensively in almost every industry to aid better eco design products and any environmental making decision. The existence of LCA shows really good promise for the greener environment and optimal design in minizing the impacts on environment. Unfortunately, because not many studies of LCA for aircraft have been done, this project is a small contribution in encouraging more people to do LCA's aircraft by showing a good possible way to do it.

The project talked about the definition and methology of LCA in detail along with its brief history, advantages and disadvantages. This is to give the people with no or little knowledge of LCA a good foundation of LCA's basics before conducting a LCA. Near the end of this introduction, it was deemed necessary to do the brief history of LCA for motivation and better understanding about LCA's developments.

Three different types and derivatives of LCA were also discussed to prevent any confusions in classifying a LCA. After that, overview of LCA's tools is given in three tables- active, free and decommissioned LCA's tools respectively. LCI databases and LCIA methods were included and explained to help the readers in choosing the right LCA's tool. Lastly, SimaPro and Gabi were recommended to use.

A short example of LCA of coffee machine was used to illustrate not only in words but also visual charts for showing how a LCA is performed. By applying this knowledge, a possible way to perform a LCA of aircraft was suggested. Following this suggestion, hopefully a good performance of Aircraft's LCA can be achieved.

References

- DEAT 2004** Department of Environmental Affairs and Tourism: *Life Cycle Assessment, Integrated Environmental Management*. Information Series 9, Pretoria, South Africa, 2004.
- Dictionary 2012** URL: <http://dictionary.reference.com/> (2012-05-16)
- EIO-LCA 2012** ECONOMIC INPUT-OUTPUT LIFE CYCLE ASSESSMENT TOOL: US 2002 (428) model, Carnegie Mellon University, Green Design Institute, URL: <http://www.eiolca.net/> (2012-05-19)
- GAO 2009** U.S. Government Accountability Office: *Aircraft Emissions Expected to Grow, but Technological and Operational Improvements and Government Policies Can Help Control Emissions*, GAO-09-554, Jun 8, 2009.
- Gloria 2012** Gloria, T. PhD: *LCI Data Sources*. LCIA Methology. URL: http://www.life-cycle.org/?page_id=24 (2012-04-20)
- Hieminga 2012** Hieminga, J: *Structure*. Image of aircraft wing from Structural Repair Manual. URL: <http://www.vc10.net/Technical/structure.html> (2012-07-03)
- Ho 2011** Ho, L.: *Life Cycle Assessment (LCA) and Green Purchasing*. Green Council Non-Profit Organization Seminar, Hong Kong, March 25, 2011. URL: http://www.greencouncil.org/LCA_Seminar/doc/LCA_GreenCouncil.pdf (2012-05-02)
- ISO 1997** International Organisation for Standardisation: *Environmental Management – Life Cycle Assessment – Principles and Framework*. Ref. ISO 14040:1997(E). Geneva, 1997
- ISO 1998** International Organisation for Standardisation: *Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis*. Ref. ISO 14041:1998(E). Geneva, 1998

- ISO 2000a** International Organisation for Standardisation): *Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment*. Ref. ISO 14042:2000(E). Geneva, 2000
- ISO 2000b** International Organisation for Standardisation: *Environmental Management – Life Cycle Assessment – Life Cycle Interpretation*. Ref. ISO 14043:2000(E). Geneva, 2000
- Jönbrink 2000** Jönbrink, A.; Wolf-Wats, C.; Erixon, M.; Olsson, P.; Wallén, E.; *LCA Software Survey*. IVL report No B 1390(SIK research publication SR 672, IVF research publication 00824)Stockholm, september 2000
- JRC 2012** Joint Research Center: *Life Cycle Thinking and Assessment*. European Commission.
- Moore 2012** Moore, J.: *FAA forecasts air travel growth and piston decline*. Aircraft Owners and Pilots Association, March 15 2012. URL: <http://www.aopa.org/aircraft/articles/2012/120315faa-forecasts-travel-growth-piston-decline.html> (2012-04-14)
- Pålsson 2011** Pålsson, A.; Riise, E.: *Getting Started Guide for Life Cycle Assessment*. TOSCA Project, December 1, 2011. URL: <http://www.tosca-life.info/getting-started-guides/life-cycle-assessment/> (2012-04-15)
- SETAC 1999** Weitz, K.; Sharma, A.; Vigon, B.; Price, E.; Norris, G.; Eagan, P.; Owens, W.; Veroutis, A.: *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup*. Society of Environmental Toxicology and Chemistry Workgroup Re-port, July 1999.
- Siegenthaler 2005** Siegenthaler, C.; Braunschweg, A.; Oetterli, G.; Furter, S.: *LCA Market Software Guide 2005*. Market Overview – Software Portraits, published by Öbu, Zürich, 2005, ISBN: 3-908233-29-1
- Sonnemann 2004** Sonnemann, G.; Schuhmacher, M.; Castells, F.: *Integrated Life-Cycle and Risk Assessment for Industrial Processes*. Chapter 2, CRC Press 2004, ISBN: 978-1-56670-644-5.
- Scott 2002** Scott, J: *Parts of an Aircraft*. Question asked by Sandy O'Sullivan and Khalid. URL: <http://www.aerospaceweb.org/question/design/q0101.shtml> (2012-07-07)

- Steel 2012** Steel University: *Introduction to Life Cycle Assessment*. World Steel Association, 2002-2008. URL: <http://www.steeluniversity.org/content/html/eng/default.asp?catid=146&pageid=2081271422> (2012-04-18)
- Stone 2012** CEVALOR: *Life Cycle Analysis, Benefits and Disadvantages of the LCA Methodology*. EC Funded Project. URL: <http://www.stonecourses.net/environment/benelca.html> (2012-04-23)
- Tools 2012** European Commission- Joint Research Center: *LCA Tools, Services and Data*. List of LCA tools. URL: <http://lca.jrc.ec.europa.eu/lcainfohub/toolList.vm> (2012-06-17)
- UNEP 2009** United Nations Environment Programme: *Guidelines for Social Life Cycle Assessment of Products*. Published by UNEP, 2009, ISBN: 978-92-807-3021-0. (2012-05-13)
- Verdoorn 2010** Verdoorn, A.: *Conduct A Mini Life Cycle Assessment*. Apartment Therapy, August 16, 2010. URL: <http://www.apartmenttherapy.com/conduct-a-mini-life-cycle-asse-124497> (2012-04-01)

Acknowledgements

I would like to thank my parents' great support for my education that has put me at ease to focus on my learning, and my university, Wichita State University, in the U.S. for encouraging me to take up the Hamburg Exchange Program. It has been great experience to meet Erasmus students from all over the world, get to know German cultures and different teaching methods in Germany.

I would like to express my deep gratitude to Prof. Dr. -Ing. Dieter Scholz and Dipl.-Ing. Andreas Johanning who were my supervisors. I sincerely thank Dr.Scholz, my Aircraft Design Professor, to let me work on this project and Mr. Johanning for all the time and efforts that he had spent to proof read, correct my mistakes, and give me ideas for the project. He had been a very great help from the very start. I also like to thank AERO Group to let me work in the friendly office where the members were friendly and enthusiastic in their aeronautical works.

Thanks to other students on this Erasmus Program who supported me on this project, especially Jeroen Verstrate who worked on Life Cycle Assessment of Airbus A320 project had given me great ideas for my project and what needed to be improved.