CRANFIELD UNIVERSITY

ZIQIAN LIU

LIFE CYCLE ASSESSMENT OF COMPOSITES AND ALUMINIUM USE IN AIRCRAFT SYSTEMS

SCHOOL OF ENGINEERING
MSc by Research

MSc Thesis
Academic Year: 2012 - 2013

Supervisor: Dr Nikolaos Asproulis & Dr Athanasios Kolios
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ABSTRACT

As a consequence of the gradually expanding aviation network, civil aircrafts are occupying an increasingly high proportion of the transport industry. Air transport now dominates the intercity rapid transit, long-distance passenger transport, international passenger and freight transport, and specific regional transport, advantaged as it is by fast, convenient, comfortable and safe options. Nevertheless, the potential adverse impact on the environment of air transport, specifically, in the case of this research, the pollutants generated during aircraft production remain a concern.

Using the A319 as the main research object, this thesis will conduct a life cycle assessment research about its environmental impact. Moreover, it will focus on the impact brought by the application of composite materials to the entire life cycle environmental influence of the aircraft, particularly the material production and disposal process. At the same time, a contrast with the B737-800 aircraft will be made due to their different composite material use rate.

Firstly, the inventory list is formed by collecting data about the weight and material of every component in the aircraft, the input and output information of the composite material manufacturing process, the disposal situation of the aircraft and the treatment of composite material. Secondly, the impact assessment of the aircraft is conducted to examine their environmental influence. During the assessment, each life stage and the whole life cycle of the aircrafts is assessed, and a comparison between these two aircraft types is made. Finally, according to the impact assessment result, the environment load increase brought by the manufacturing of composite material and the decrease of the environment impact due to the weight reduction character of composite material is calculated and compared.

From this research, the conclusion that the use of composite material has a positive effect on decreasing the environmental impact of the whole life cycle of the aircraft is obtained. This will enable aircraft manufacturers to target these areas for improvement, to produce more comfortable, environment friendly and market competitive aircraft.

Keywords:

Environment impact, produce process, disposal process, assembly, impact category

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

APU	Auxiliary power unit
CF	Caron fiber
CFRP	Carbon fibre reinforced polymer
GF	Glass fiber
GFRP	Glass fibre reinforced polymer
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
OEW	Operational Empty Weight
PAN	Polyacrylonitrile
PEMELA	Process for Advanced Management of End-of-Life of Aircraft
RAT	Ram air turbine

1 INTRODUCTION

At the end of 2002, there were approximately 10,789 aircrafts operating around the worldwide (Airbus, 2003). By 2011, in only nine years, this number had nearly doubled to 19,890 (Boeing Commercial Airplanes, 2012). This significant growth may be attributed to the comprehensive transportation system that allows people to reach the airport more conveniently, and also the price reduction caused by the appearance of low-cost flights that makes people more willing to choose the airplane as their long distance transportation option. At the same time, the development of commercial aircraft has also promoted the communication between people, allowing for more frequent business activities and improved the socio-economic environment.

On the other hand, from the manufacturing to operating stage, the airplane has demonstrated a substantial negative effect on the environment. For example, the product manufacturing and assembly processes will consume a lot of energy. The flight stage can burn a great deal of fuel and emit large quantities of harmful gases. In the process of taking off and landing, aircraft will also cause noise pollution. Thus the expansion of the aircraft market will bring greater pressure to the environment.

Many people believe that the most significant environmental impact of the airplane is the consumption of fuel, and some researchers have already studied this issue by replace the existing fossil fuels with biofuels (Howe, 2011). Moreover, aircraft manufacturing companies are reducing the fuel consumption by using composite materials to lower the weight of the aircraft. Composite materials can typically reduce weight by about 20% compared to aluminium and its maintenance cost is even lower (Sina, 2012). It is said that 25% of an A380 is produced by composite materials, and 50% of an A350 and B787 will also be composites (Sina, 2012; Boeing, 2013a; Airbus, 2008a). However, the production of composite materials is an energy-intensive process, especially when using autoclave technology. Therefore, whether the application of composites can reduce the pollution generated during the whole life cycle of an aircraft remains an important issue.

In response, a method called ‘Life cycle assessment (LCA)’ should be introduced. The life cycle means the processes from the acquisition of raw material, which is used to produce the product, to the manufacturing and assembling process, until the use phase and the disposal stage when it is disused. LCA is a technique that has already been widely used by researchers to examine environmental issues. It can discover the environmental impact of a product by assessing all the emissions released by a product during its whole life cycle.

To conduct an LCA research requires the collection of a large amount of information regarding emission type and category of environmental impact of a process. As a result, particular software and databases have been developed to help researchers conduct an LCA study.

This thesis will organise an LCA investigation on the A319 aircraft to assess whether the use of composite materials can improve its environmental performance. It will focus on the disposal stage, when the aircraft has retired from the airline routes, and specifically the composites manufacturing process. The research will also make a comparison of the environmental effect of different composites use rate. It is assumed that the aviation industry will be the main beneficiary of this research, and the quantified data will be used to manage and plan the utilization of composite aircraft in the future.

1.1 Aim and Objectives

1.1.1 Aim

The aim of this thesis is to undertake a life cycle assessment of composites and aluminium used in aircraft, and the potential emission savings of lightweight composite aircraft components will be evaluated through the LCA method.

1.1.2 Objectives

The objectives of the thesis are as follows:

- Collect data for the LCA study about A319 and B737-800.
- Conduct the impact assessment of the whole life cycle of these two aircraft types with the inventory data.
- Compare the impact assessment of A319 and B737-800 to analyse the environment influence caused by the utilization of composite material.
- Interpret the impact assessment result and obtain the conclusion of this research.

1.2 Thesis Structure

- **Chapter 1** is an introduction to this thesis. It includes the motivation of conducting this project and the objects of this research.
- **Chapter 2** contains a literature review about the Life Cycle Assessment to explain how to use this method to manage the environment research of the study object. It explains the four phases of an LCA study by reviewing previous researches.
- **Chapter 3** is a market research explaining the reason of making the A319 as the main observation object. It focuses on the Chinese aircraft market and completed a statistic of the aircraft utilization situation of Chinese airlines.
- **Chapter 4** presents the first two stages of the LCA study on the aircrafts, the goal and scope definition and the life cycle inventory data collection. This chapter firstly sets the goal and scope of the research and states the limitations. Secondly explains the resources of the inventory data and details the build-up process of the product model network.
- **Chapter 5** includes the last two stages of the LCA study: life cycle impact assessment and the results interpretation. At the beginning of this chapter, it explains the selection of the impact assessment method. Followed by the assessment of each life stage of the aircrafts. After that is the environment influence analysis about the whole life cycle. And finished with the outcome of this project. At the same time, the interpretation of the impact assessment result is included in each phase.
- **Chapter 6** includes the conclusion of this project and the suggestions for future work.

2 LITERATURE REVIEW OF LIFE CYCLE ASSESSMENT

2.1 Introduction

In this day and age, the advanced science and technology available improves people's living standards, but also has a significant negative impact on the environment. For example, the invention of cars allows for more convenient travel, but the burning of fossil fuels by them produces exhausts which pollute the air. Moreover, although chemical companies, such as paper mills have a positive impact on people’s daily lives, the sewage they discharge poison the rivers and oceans. Also, the usage of pesticides and fertilizers can lead to better harvests and agricultural products, but heavy use of them pollutes the soil.

The destroyed environment, in turn, will have an adverse effect on people's survival. The daily occurrence of haze in China is an example. It can significantly reduce the visibility and so traffic will be badly influenced. The haze also affects human health: accidental inhalation of tiny smoke particles may cause respiratory diseases. Another example is the melt of Arctic ice. The thick, floating ice cap which has covered the Arctic Ocean for at least 3 million years is disappearing due to the environmental change (Newscientist, 2012a). The ice extent contracted from above 7 million square km in 1979 to below 4 million square km in 2012, nearly half of that in 1980 (Newscientist, 2012b). If the ice cap disappears, arctic animals such as polar bears, arctic hares and arctic foxes will lose their habitats. Moreover, the melting of the Arctic ice will cause a rise in sea level, flooding coastal cities.

2.2 Life Cycle Assessment

Precisely because the environmental issue is so important, people are increasingly concerned about how to better understand and address these impacts. Life cycle assessment (LCA) is just one of the tools that helps people manage environmental problems.

LCA can systematically examine the whole life cycle of a product, from the phase of acquiring raw materials, production and manufacturing stage, product use period to the end-of-life disposal phase, looking for potential environmental impacts in those various stages and to avoid where possible (British Standards, 2006a). This article will introduce how LCA is used in different industries according to the four phases in an LCA study: the goal and scope definition, inventory analysis, impact assessment, and the interpretation phase (British Standards, 2006a) (Figure 2-1).

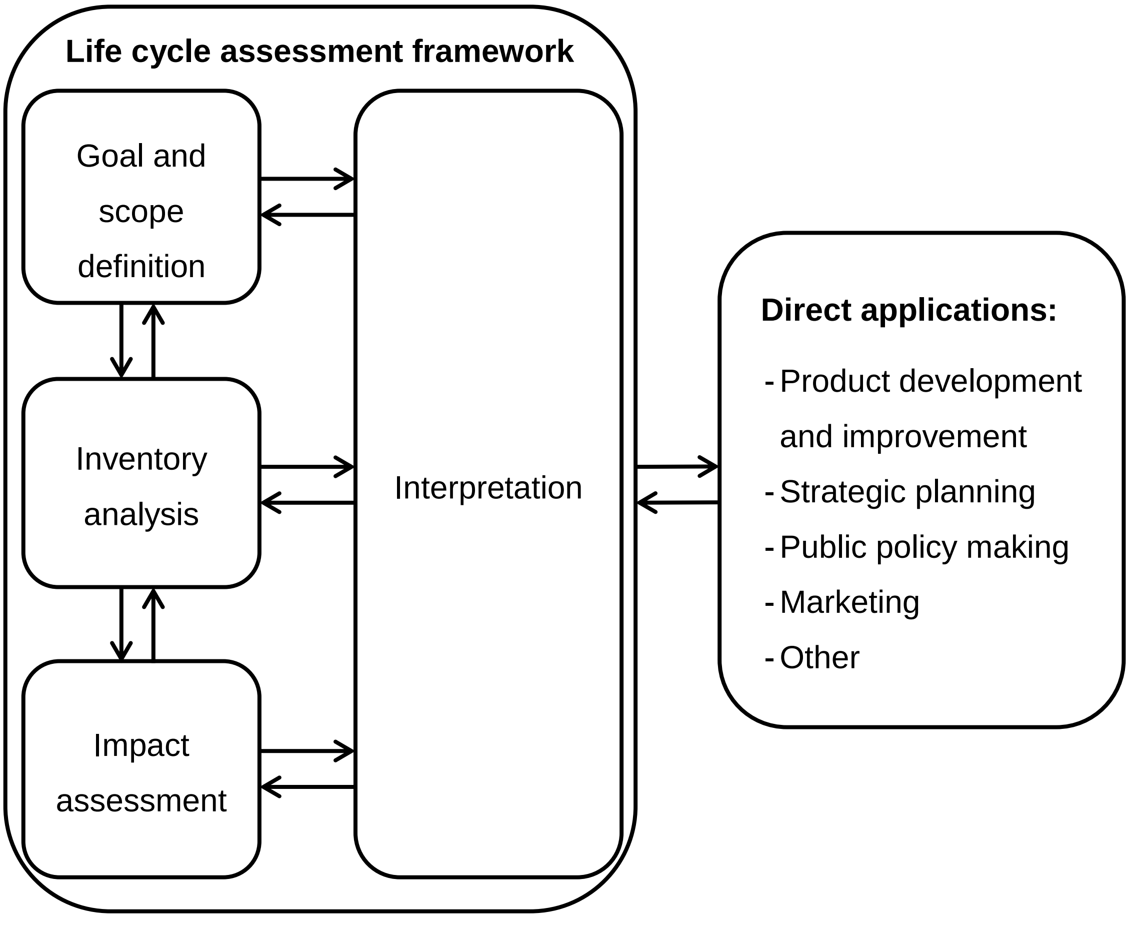


Figure 2-1 Phases in an LCA (British Standards, 2006a)

2.2.1 Goal and Scope Definition

The first is the goal and scope definition phase. The definition of a goal is to make a plan for the following phases by clearly expressing specific issues, which are:

- The purpose of the study - to specify whether the researcher want to compare different products, to improve a product or simply to find its strength and weakness;
- Intended audience - for academic exchange, companies, government or consumers;
- The subject of the study - to identify which product is to be studied, the amount of the product, during which time span and which function and the function unit;
- The scope of the study - to include the detail level, system boundary, announcement of assumptions and limitations which can limit the study range (United Nations Environment Programme & Industry and Environment (France), 1996).

For example, Liang et al. (2013) conducted a life cycle assessment on clean coal power generation technologies in China with up-to-date data (Liang et al., 2013). Its purpose was to compare four types of coal power generation technologies: (1) integrated gasification combined cycle (IGCC); (2) sub-critical coal power generation (Sub-C); (3) super-critical coal power generation (Super-C); and (4) ultra-super-critical coal power generation (USC) to judge China’s coal power industry (Liang et al., 2013). The audience for this study, which can serve as a powerful basis to formulate policies, was the government. Its subject was obviously the electricity generated from those four coal power generation technologies (Liang et al., 2013). Finally, the scope of this research was defined to include materials, transport and emissions during the mining process, power plant construction, power plant operation and decommissioning stage (Liang et al., 2013). It was assumed that the raw materials were produced in China and transported by rail or truck to the power plants. The limitation of the study was that the recycling of steel and aluminium was not included due to the lack of data (Liang et al., 2013).

On the other hand, the purpose of using an LCA of Unilever is to measure the environmental performance and provide a guide to improve their new products (Unilever, 2011). Its audience is therefore the company itself and the consumers.

Another example is the milk production life cycle assessment (Cederberg & Mattsson, 2000). Its subject was the conventional and organic milk production from September 1st 1996 to August 31st 1997 in two individual large dairy farms in the west of Sweden (Cederberg & Mattsson, 2000). Its "functional unit (FU) was 1000 kg energy corrected milk (ECM) leaving the farm gate." (Cederberg & Mattsson, 2000) When referring to the scope, it included the material, energy and transport in every phase of the life cycle of milk but the building and machinery was excluded for lack of data (Cederberg & Mattsson, 2000).

Furthermore, in order to identify a rigorous goal and scope, the exact purpose of the study and the width and depth of the research should be clarified and frequently revised during the subsequent research processes.

2.2.2 Life Cycle Inventory Analysis

The second stage is the life cycle inventory (LCI) analysis phase. This stage is used to collect, calculate and allocate data of inputs and outputs materials during different processes. It is proposed to establish a process flow chart (as shown in Figure 2-2, below) which consists of a series of processes (represented by boxes), linked by material flows (indicated by arrows). This chart can represent nearly all relevant processes involved in the life cycle of the system being studied (British Standards, 2006b). It will be beneficial for the researchers to have an overview of the system before collecting data. When it comes to collecting data, there are many methods such as using data bases, for example EcoInvent, or obtaining data directly from companies. Then, the quality of data should be checked to ensure completeness and consistency. Finally, the data should be arranged in a convenient form to calculate and be assigned to different processes.

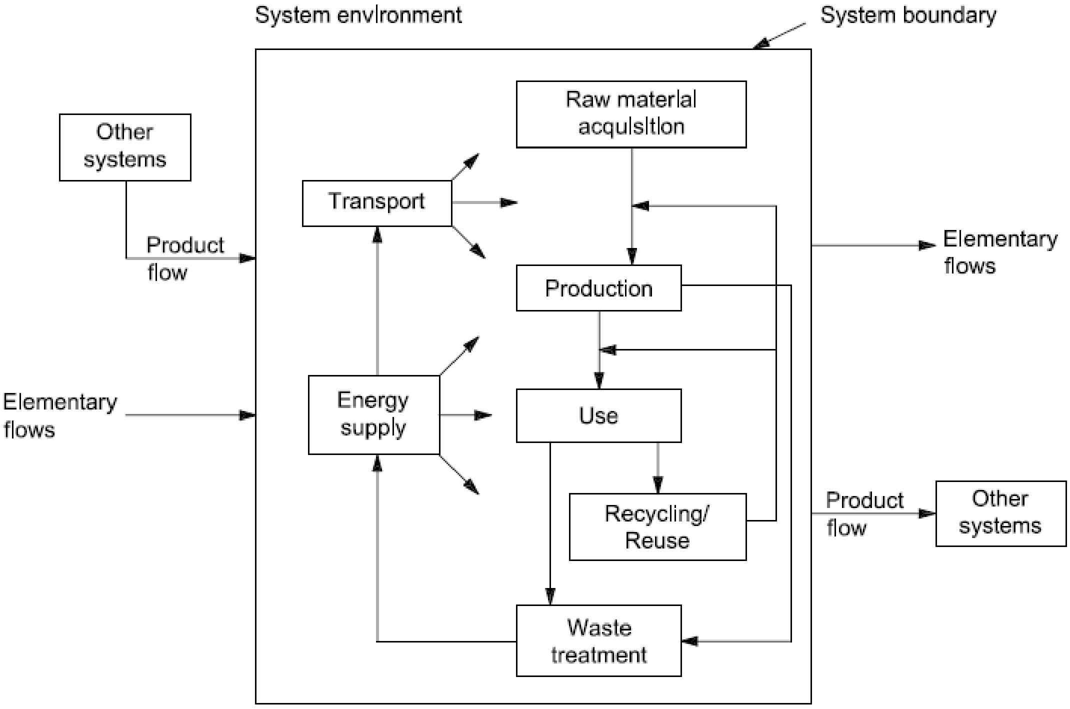


Figure 2-2 Example of process flow chart (British Standards, 2006b)

The study of clean coal power generation technologies in China should be noted as an example (Liang et al., 2013). The authors used different methods to collect a variety of data, utilizing commercial GaBi 4.0 software databases and the EcoInvent database to gain data about the fundamental industrial materials such as steel, aluminium, and concrete. The Mining Engineering Design Handbook was also used to obtain data about coal mining installation and construction. Coal mining operation data were gained from the China Coal Industry Yearbook. Coal transportation data were collected from China’s Traffic Yearbook. And the data for power plant construction were obtained from the Thermal Power Engineering Design Handbook (Liang et al., 2013). “Operation data, including net generating efficiency, emissions before flue gas cleaning systems, and the amounts of flue gas for a full load of the Sub-C, Super-C and USC power plants, are given by first-hand operation reports and feasibility study reports of the current operating power plants.” (Liang et al., 2013) The researchers then judged the data quality by correlation, concluding that the data collected from China was more suitable for this study (Liang et al., 2013). Finally, they allocated the data collected to each process of the system.

Another example is the LCA case study of composites and stainless steel I-beams (Ibbotson & Kara, 2013). Firstly, a process flow chart was designed (Figure 2-3). It clearly shows the relationship between various materials and processes. The data of this research were mainly “provided by the composite company and the two main LCI libraries are the EcoInvent 2.2 (EcoInvent Centre 2010) and the Australian data 2007 databases” (Ibbotson & Kara, 2013). These researchers evaluated the data quality by the consistency, such as contrasting the same data from different sources to evaluate their similarity (Ibbotson & Kara, 2013).

Sometimes, to simplify the data collection, a researcher can exclude some processes which have little effect on the result when using “generalized background dataset” such as “EcoInvent GaBi” or “environmentally extended input–output dataset” (Hawkins et al., 2012). It is because these datasets did not contain particular data. The author of environmental impacts of hybrid and electric vehicles similarly eliminated some overly complicated factors in their study and also provided a simplified flow chart (Figure 2-4) (Hawkins et al., 2012).

The life cycle inventory analysis phase can be regarded as the data preparation for the impact assessment phase. But it is also the core of the whole life cycle assessment, since the quality of data may impact the final result. Therefore it is also the most time-consuming phase for the reason that the researcher should conduct crosschecking.

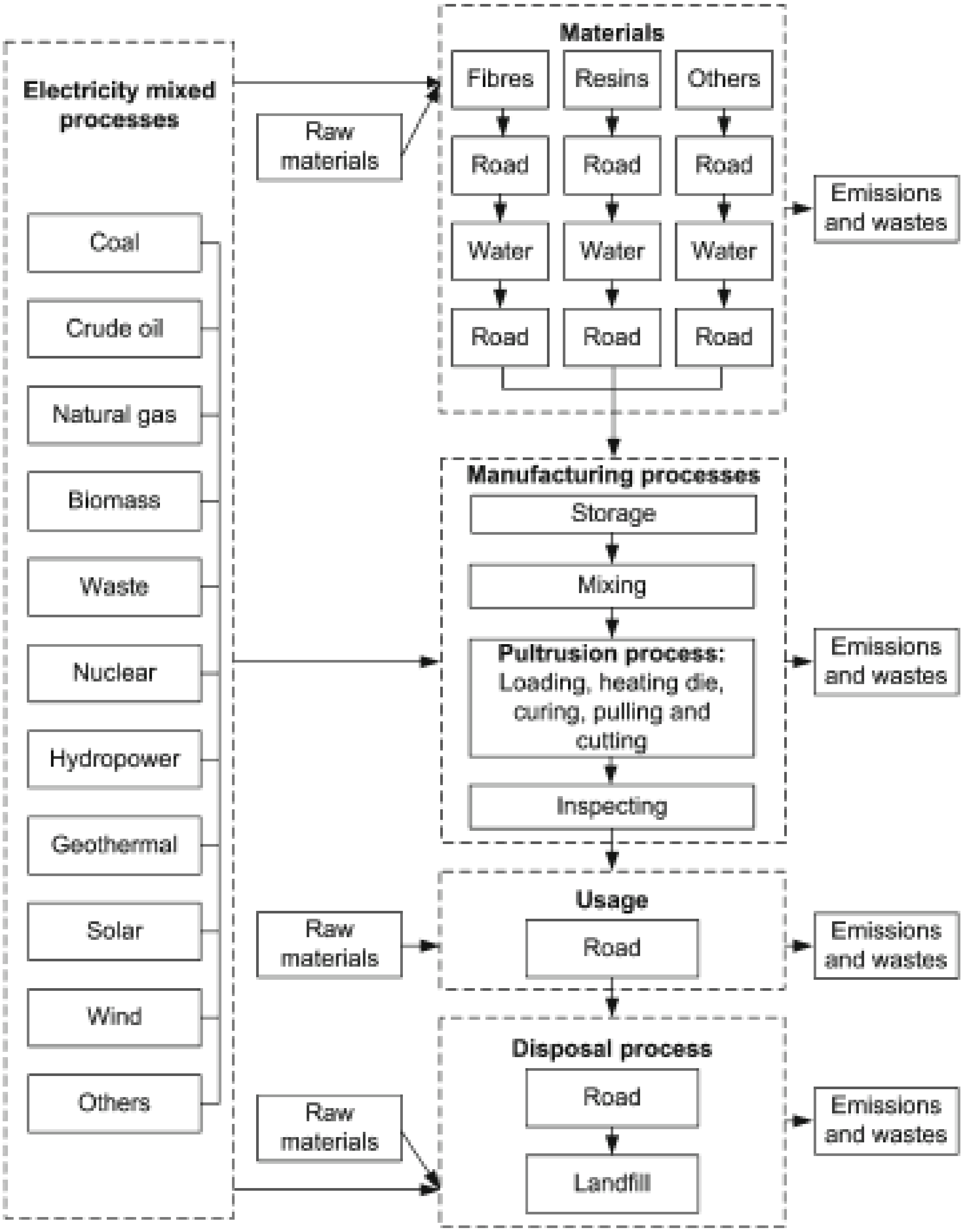


Figure 2-3 Process flow chart for a linear meter of the composite I-beam (Ibbotson & Kara, 2013)

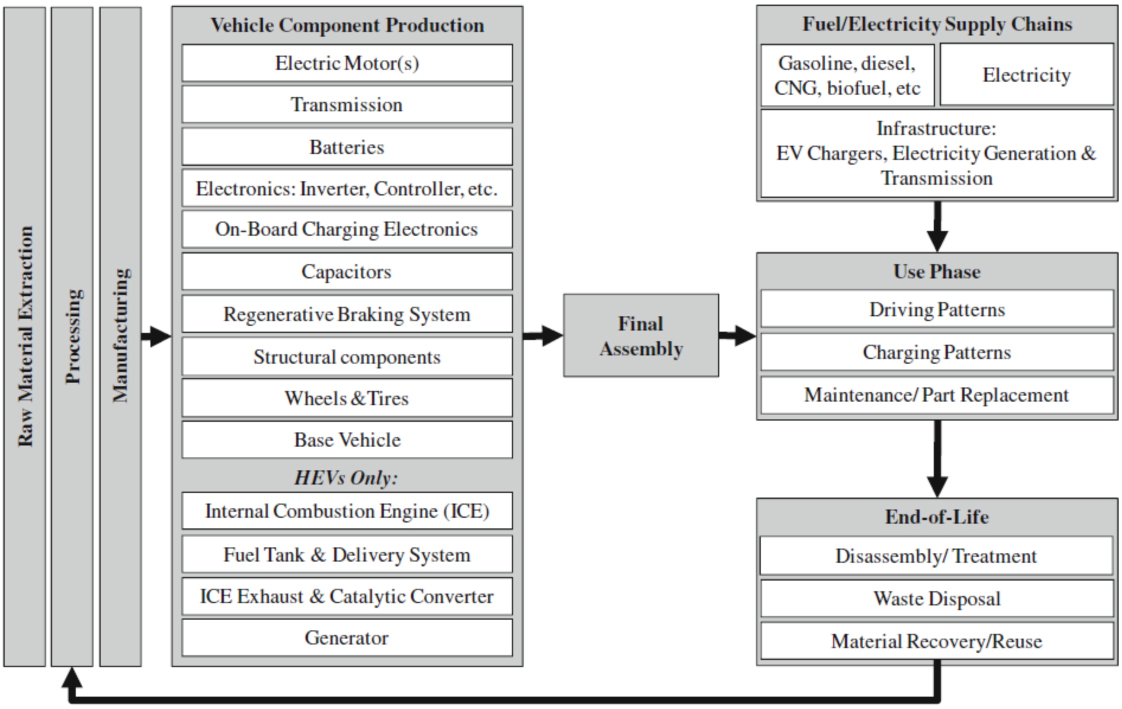


Figure 2-4 Simplified flow chart of the life cycle of a hybrid or electric vehicle (Hawkins et al., 2012)

2.2.3 Life Cycle Impact Assessment

The third stage is the life cycle impact assessment (LCIA) phase. This stage is used to link the result of inventory analysis to environmental impacts by assigning LCI results to impact categories and using category indicators to calculate (British Standards, 2006b). Its results provide information on the environmental issues associated with the research topic to achieve the established goal and scope.

For example, the life cycle assessment of milk production selected energy, material, land use, pesticide use, global warming, acidification, eutrophication, photo-oxidant formation and depletion of stratospheric ozone as the environmental impact categories were then calculated with the impact category indicators (Cederberg & Mattsson, 2000).

Usually this step is carried out by software such as Eco-Indicator 99 or SimaPro. In the study carried out by Liang et al., the researchers used the CML 2001 baseline impact categories, category indicators, and characterization methods to conduct Life cycle impact assessment (LCIA) (Liang et al., 2013). Its impact category “include the following: global warming potential (GWP), ozone layer depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photo-oxidant formation potential (POCP), ecotoxicity potential (EP), human toxicity potential (HTP), and abiotic resources depletion potential (ADP).” And the outcome was credible (Liang et al., 2013).

In the environmental impact analysis of composite use in car manufacturing, Eco-Indicator 99 quantification method, Egalitarian weighting scheme, and SimaPro 7 LCA software were used to operate the analysis (Duflou et al., 2009).

After obtaining a series of data relating to environmental damage, in order to facilitate the subsequent analysis, the results should be weighted to obtain one index about the most important environmental impact on the subject being studied.

2.2.4 Interpretation

Finally, the interpretation phase should explain the results of LCI and LCIA stage according to the goal and scope of the study, and ensure they are consistent (British Standards, 2006a). In order to prove the rigors of the study and to state the limitation, the explanation should include the assessment of main data and method selection. Also, conclusions and future recommendations need to be provided.

In the interpretation phase of the life cycle assessment on clean coal power generation technologies in China, the researchers firstly assessed the main input data - energy and the output data – emissions to air, and interpreted the result of each environment impact category (Liang et al., 2013). A conclusion about the environmental performance of those four coal power generation technologies was then ascertained and the future direction of coal power generation technology in China recommended (Liang et al., 2013).

In conducting their interpretation, Ibbotson et al. specifically listed the uncertainty and limitations after assessing and explaining the results of LCIA

(Ibbotson & Kara, 2013). The conclusion and recommendations identified the one linear meter composite I-beam as more environmental friendly (Ibbotson & Kara, 2013).

In the study of the life cycle assessment of milk production, the main inputs and outputs data and their environmental impacts were interpreted and the researchers also presented an improvement assessment of both milk production methods (Cederberg & Mattsson, 2000).

After conducting extensive research, the final important step is to write an effective report. The report should objectively and accurately elaborate the research objectives, methods, data and the analysis of results to provide a strong basis for the audience to make their decision. Charts are commonly used, being a more effective presentation of results than simply lists of data.

2.3 LCA in aviation industry

In light of the current concern in the aviation industry towards environmental efficiency of aircraft, the LCA research is also utilized in this domain. For example, Koroneos et al. have conducted an LCA case study on the aviation kerosene (Koroneos et al., 2005). Although the main pollution during the whole life cycle of kerosene comes from the burn process during the operation stage of the aircraft, this research focused on the kerosene refining process to find improvement space. Moreover, an LCA study about the environment benefit brought by the use of composite was conducted in 2010 (Scelsi et al., 2011). The researchers programed the study on the component scale (the plate and the tubular component) which may have limitation in analysing the environment influence caused by composite material in the aviation industry. Thus developing an LCA study about a complete aircraft to examine the environmental effect of composite in aviation industry is extremely necessary.

2.4 Summary

The life cycle assessment technology has made great progress. Currently it has its own ISO standard to guide researchers, and many databases and software programmes have been invented. It has been widely used by industries, governments, consumer organizations and environmental groups from various countries including China (Liang et al., 2013), Europe (Cederberg & Mattsson, 2000; Szczechowicz et al., 2012), and Canada (Rose et al., 2013). It can be used by industries when developing a new product or upgrading an original product to evaluate their investment in environmental protection and the benefits they obtain from an environmentally friendly product. The governments may use it to help policy making and decide the support direction. Consumer organizations can also use the LCA to help them decide which product to buy. And environmental organizations can use it to affect public opinions, and thus indirectly influence the decisions of the industries, governments and consumers.

To conclude, life cycle assessment is a highly effective environmental impact valuation technique. Although it cannot directly overcome environmental problems, it provides the decision makers a basic concept regarding the product with great enhancement value for environmental protection. Researchers are currently applying the LCA method to many studies in order to find greener products. The transportation industry in particular is conducting LCA studies: for example, in the review of environmental impacts of hybrid and electric vehicles, the author was able to reference more than 50 papers (Hawkins et al., 2012).

Evidently, the transportation industry not only refers to the automotive industry, it also includes the aviation industry (Scelsi et al., 2011; Koroneos et al., 2005), railway transportation (Chester & Horvath, 2010) and shipping industry (Okasha et al., 2010; Zuin et al., 2009). And since China is becoming increasingly concerned about environmental issues, LCA technology will certainly be able to play a positive role in the assessment of the environment impact of an aircraft throughout its whole life course for the Chinese aeronautical market. This study can help people improve the manufacturing ability and to promote the research and development of new products.

3 MARCET RESEARCH FOR THE OBJECT AIRCRAFT SELECTION

As this project aims at developing LCA research for the Chinese aircraft market, the finding of a proper aircraft to carry out this research is essential. Consequently, a market research is conducted as follows.

Firstly, a forecast by Airbus for the next 20 years indicates there will be 28200 new aircraft during this time period, and 19520 of them (69%) are single-aisle aircraft. For the Asia-Pacific region, these figures are 9618 in total and 6028 for single-aisle aircraft (63%) (Airbus S.A.S., 2012b). Boeing similarly claimed that over the next 20 years, the share scale of single-aisle aircraft in the fleet will rise from about 63% in 2011 to 70% in 2031. Moreover, the number of aircraft in the Asia-Pacific region will account for the largest share of the world aircraft market (35%) (Boeing Commercial Airplanes, 2012). These two companies occupy significant positions in the aviation industry, thus their forecast regarding the prominence of single-aisle aircraft for the Chinese market and their value as the main object of the study should be accepted.

Secondly, statistics about China’s airline fleet structure have been compiled (Xmyzl, 2013) (Table 3-1, Table 3-2, Table 3-3). There are approximately 24 airlines in China, with about 40 types of aircraft. According to the statistical data, there are roughly 2451 aircrafts operating in China. Almost 1146 are Boeing aircraft, 1003 from Airbus with the remaining from other companies such as Embraer, Bombardier and Dornier. From Table 3-1 it can be seen that the Boeing aircraft utilized in China are concentrated on the B737 series and the Airbus airplanes on the A320 series (Table 3-2). Regarding the market share scale of one single type of aircraft, the first is B737-800 (501 aircrafts), the second A320-200 (486 aircrafts) and the third A319 (165 aircrafts.)

Finally, since this project is being conducted in the UK, it is more convenient to obtain data from the European aircraft company. As the A320 has been studied by other researchers, the statistic figures shown above identify the A319 as extremely suitable for this study.

Airline	Aircraft number for each aircraft type																
	B737						B747			B757-200	B767		B777				Sum
	B737-300	B737-300F	B737-400	B737-700	B737-800	B737-900	B747-400	B747-400M	B747-400F		B767-300	B767-300ER	B777-200	B777-200ER	B777-300ER	B777F	
Air China	9			19	87		4	5	11	4			10		11		160
Shenzhen				3	48	5											56
Kunming				8	1												9
Dalian					4												4
China Eastern	16			37	23												76
Shanghai				7	40					10	4	3					64
China United				11	12												23
China Southern	21			37	71				2	13	4		4	4		6	162
Chongqing																	0
Xiamen				17	64					6							87
Hainan	4	13	4	9	96				3		3						132
Grand China					3												3
Capital																	0
Tianjin																	0
Lucky				6	4												10
West																	0
Sichuan																	0
Shandong	6			3	46												55
China Express																	0
Henan																	0
Hebei				2	2												4
Chengdu																	0
Joy																	0
Tibet																	0
Spring																	0
Juneyao																	0
sum	56	13	4	159	501	5	4	5	16	33	11	3	14	4	11	6	845
	738						25				14		35				

Table 3-1 The statistics for Boeing aircraft serving in all airlines (Xmyzl, 2013)

Airline	Aircraft number for each aircraft type											
	A300-600R	A319	A320-200	A321		A330			A340		A380-800	Sum
				A321-100	A321-200	A330-200	A330-200F	A330-300	A340-300	A340-600		
Air China		30	32		42	28		11	4			147
Shenzhen		5	59									64
Kunming												0
Dalian												0
China Eastern	7	22	143		33	16		15		5		241
Shanghai						2						2
China United												0
China Southern		40	102		62	16		11			5	236
Chongqing		4	7									11
Xiamen												0
Hainan		32	34			6	1	6		3		82
Grand China												0
Capital												0
Tianjin												0
Lucky												0
West												0
Sichuan		21	32	2	20	4		2				81
Shandong												0
China Express												0
Henan												0
Hebei												0
Chengdu		3	7									10
Joy												0
Tibet		8										8
Spring			38									38
Juneyao			32		1							33
Sum	7	165	486	2	158	72	1	45	4	8	5	953
				160		118			12			

Table 3-2 The statistics for Airbus aircraft serving in all airlines (Xmyzl, 2013)

Airline	Aircraft number for each aircraft type										
	ERJ					CRJ			Dornier328JET	MA60	Sum
	ERJ145	ERJ145LR	E190	ERJ190LR	E190/Lineage 1000	CRJ200	CRJ700	CRJ900			
Air China											0
Shenzhen											0
Kunming											0
Dalian											0
China Eastern	10					5					15
Shanghai						3					3
China United											0
China Southern	6		17		1						24
Chongqing											0
Xiamen											0
Hainan	23		50						28		101
Grand China											0
Capital											0
Tianjin		23		50					28		101
Lucky											0
West											0
Sichuan											0
Shandong						5	2				7
China Express						5		3			8
Henan			4								4
Hebei		5	4								9
Chengdu											0
Joy										6	6
Tibet											0
Spring											0
Juneyao											0
Sum	39	28	75	50	1	18	2	3	56	6	278
	192					23					

Table 3-3 The statistics for other company's aircraft serving in all airlines (Xmyzl, 2013)

4 LIFE CYCLE ASSESSMENT OF A319 AND B737-800

Following the clarification of the LCA theory, research exploring life cycle assessment of composites and aluminium using in aircraft can be carried out. This project will be performed follow the 4 stages of an LCA study. Firstly, the goal and scope definition and the inventory analysis phase will be observed. The impact assessment and interpretation phase is explained in Chapter 5.

4.1 Goal and scope definition

4.1.1 Goal definition

According to ISO 14040 (British Standards, 2006a), in order to define the research goal, the purpose of the study and the intended audience should be elucidated.

Regarding the purpose of this study, the environment influence of the whole life cycle for A319 and B737-800 will be assessed. As discussed in Chapter 1, the noticeable increase in civil aircraft places great pressure on the environment due to the pollutants generated during its production procedure. It is believed that by introducing composite material and thus saving fuels it is possible to reduce the environmental pollution. Nevertheless, the energy-intensive character of composite manufacture and its low recycle rate reduce the conclusiveness of this option. This project aims to address this issue by focussing on the following three aspects: 1) assess the energy consumption and harmful emissions during the composite manufacturing process; 2) compare the fuel consumption during the operation stage between aircrafts with various composite utilization rate to calculate the fuel savings, which may significantly reduce the pollution generation; and 3) identify the valid disposal methods to increase the potential recycle rate of composite materials..

Concerning the intended audience, the result of this project may be useful for the aviation industry. The research on composite manufacturing and fuel consumption may well be a valuable reference for the aircraft designers to select material. And the disposal method comparison could provide assistance to the composite manufacturing company and the material disposal agency to increase the recycle level of composite materials.

4.1.2 Scope definition

In the scope definition section, the product system, the functions of the product system, the functional unit (FU), the system boundary, methodology of impact assessment and the limitations will be outlined (British Standards, 2006a).

4.1.2.1 Product system

This project has two objects, one Airbus A319 aircraft, which is the main target, and one comparison reference aircraft: Boeing B737 - 800. The B737 - 800 is the reference subject mainly because it has the different composite use rate with the A319. Moreover, they are approximately at the same transport level. That is to say, both of them are single-aisle aircrafts, operating on extensive short- to medium routes worldwide and have a wide service, from short commuter sectors to trans-continental flights (Airbus, 2013b).

The A319 aircraft is “a shortened-fuselage version of Airbus A320 cornerstone single-aisle jetliner (Airbus, 2013b)”. It “has the same optimised cabin cross-section as the other A320 family members– which have the widest single-aisle fuselage on the market (Airbus, 2013b)”. Until 31st August 2013, there have been 1528 orders and 1378 deliveries of the A319. Furthermore, 1372 aircrafts are still in operation (Airbus, 2013b). Besides, the Airbus 330-200 can be operated with two different engines: the CFM International CFM56-5B and the IAE International Aero Engines V2500-A5 (Airbus, 2013b). In this project, the selected engines were the CFM International model CFM56-5B. The key dimensions, capacity and performance figures for the A319 are listed in Table 4-1.

On the other hand, “the Boeing 737-800 is the best-selling version of the successful Next-Generation 737 family (Boeing, 2013b).” “The 737-800 was launched on Sept. 5, 1994, with commitments from customers for more than 40 airplanes (Boeing, 2013b).” Until August 2013, there have been 4389 orders and 2995 deliveries (Boeing, 2013b). The engine utilized on this aircraft is the

CFM International CFM56-7BE (Boeing, 2013b). Its information is listed in Table 4-2.

Table 4-1 Key figures of A319 (Airbus, 2013a)

Dimensions	
Overall length	33.84 m
Cabin length	23.78 m
Fuselage width	3.95 m
Max cabin width	3.70 m
Wing span (geometric)	34.10 m
Height	11.76 m
Wheelbase	11.04 m
Capacity	
Typical seating	124 (2-class)
Max seating	156
Performance	
Range	6 850 km
Max ramp weight	64.4 tonnes
Max take-off weight	64.0 tonnes
Max landing weight	61 tonnes
Max zero fuel weight	57.0 tonnes
Max fuel capacity	24,210 litres

Table 4-2 Key figures of B737-800 (Boeing, 2013b)

Dimensions	
Wing Span (With Winglets)	35.8 m
Overall Length	39.5 m
Tail Height	12.5 m
Interior Cabin Width	3.53 m
Capacity	
Typical seating	162 (2-class)
Max seating	189
Performance	
Max taxi weight	79.244 tonnes
Max take-off weight	79.010
Max landing weight	66.362
Max zero fuel weight	62.733
Max fuel capacity	26,020 litres
Maximum Range	5,765 km [2-class with winglets]
Typical Cruise Speed	0.785 Mach

4.1.2.2 Function and function unit

The function of this product system is the civil aviation transportation. For example, the functional unit of the operation stage is: passenger.km. Namely the transportation of the aircraft will be assessed on one passenger through one kilometre travel distance.

4.1.2.3 System boundary and limitations

The system boundary of this study is the whole life cycle of the aircraft; that is, the material acquiring phase, the manufacturing and assembly stage of the aircraft, the operation period and the final disposal segment.

Firstly, due to the time limitation, the material obtaining phase will just detail to the semi-product stage. In other words, the composite material manufacturing process is started from the production of reinforced fibre. Moreover, the metal product is considered from the manufacturing of sheet metal. In this way, the mining process will not be introduced.

Secondly, the manufacturing and assembly stage will divide the aircraft into the sub-assembly components and exclude the aircraft systems and internal components. This is because that the aircraft has numerous parts; therefore, elucidation of all will be too huge a task. Moreover, the evidently sensitive character of the aviation industry makes the collection of detailed data extremely difficult. Additionally, most aircraft systems and internal components are provided by a third- party; this tends to increase the difficulty of obtaining such data. On the other hand, since the main components of the aircraft are manufactured in various places and transported to the final assembly line in Toulouse, France or Renton, Washington, the transportation process is included.

Thirdly, the operation duration of the aircraft is considered to be 24 years, which is calculated by the common aircraft movement limitation (Sina, 2013). It should be mentioned that the life of an aircraft is influenced by many factors and may not be just 24 years. However, for this project, the average limitation is adopted.

Finally, the disposal stage including the treatments to the components and materials after the aircraft gets to the end-of-life is detailed. Treatments might involve the cleaning and emptying process of the aircraft, the dismantling and classifying of the components and the re-use, recycle, incineration and landfill procedures of the materials and parts.

4.1.2.4 Methodology of impact assessment

The research process of an LCA study, especially the data collection phase, is a complicated procedure that requires the researchers to consult a great deal of reference materials and to record data in detail. To accomplish this complex process, LCA software is utilised.

The LCA software used in this project is the SimaPro software. It is the market-leading LCA software developed by PRé Consultants in the Netherlands, with an international network of LCA specialists (PRé Consultants, 2013). It has been utilized in more than 80 countries around the world (PRé Consultants, 2013).

Since the SimaPro software is used to help researchers conducting life cycle assessment, its main functions can similarly be divided into the four stages of an LCA study. For the inventory stage, the software involves about 13 libraries, including the Ecoinvent unit processes and the IDEMAT 2001. These libraries contain information about the most commonly used materials and processes. Hence the researchers can concentrate on collecting data on special materials and processes. In the impact assessment phase, the impact assessment methods can assist the classification of emissions of each process to their respective impact category, and the visual representation of the results of the analysis. SimaPro has a number of authoritative impact assessment methods. These methods assess the environmental influence with various impact categories and analyse procedures. An appropriate LCA method should be selected to assess the environmental impact of the research object according to the goal and the relevant impact categories of the LCA research. Consequently, the impact assessment method selected in this project is the Eco-indicator 99 (H) V2.07, the most widely utilized and complete method.

4.2 Life Cycle Inventory Analysis

The Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of the product system (British Standards, 2006a). It will involve every stage in the life cycle of the A319 and B737-800. Data of materials and processes utilized in these stages will be collected to generate an inventory list and the model of the product. As mentioned in Section 2.2.2, a process flow chart can help the researchers gain an overview of the system prior to collecting data. This chart is shown in Figure 4-1.

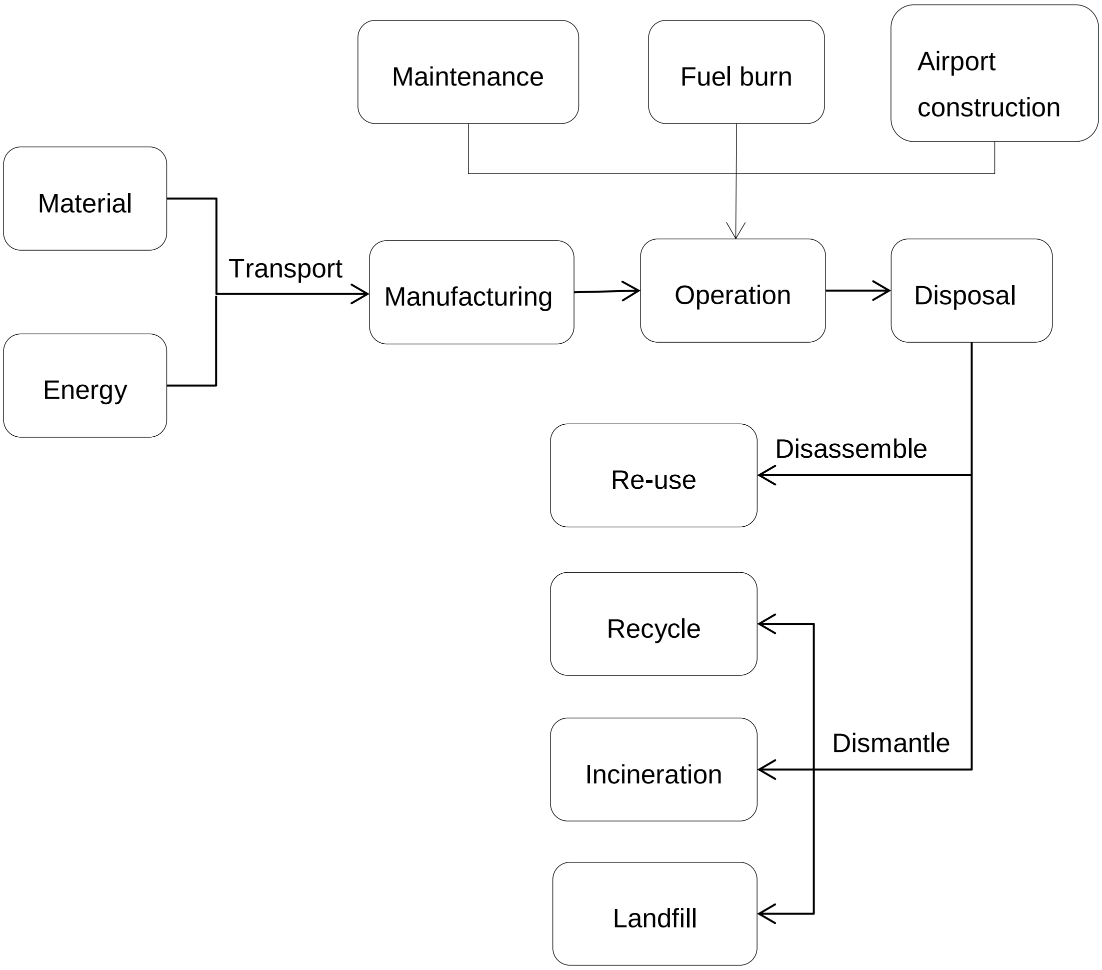


Figure 4-1 Process flow chart of A319/ B737-800

To develop the model of the aircrafts, the software primarily use two functions under the inventory function: the processes and the product stages. Normally, a product model is assembled with the structure shown in Figure 4-2. One life cycle contains an assembly and a disposal or waste scenario. The assembly indicates the manufacturing stage of the aircraft and is built up by the materials, manufacturing processes or some subassemblies. The disposal/waste scenario represents the disposal stage. It includes one disassembly and several treatments. Additionally, the operation stage includes specific aircraft operation processes which are linked directly to the life cycle. The life cycle, assembly and disposal/waste scenario belongs to the product stages and the others are processes.

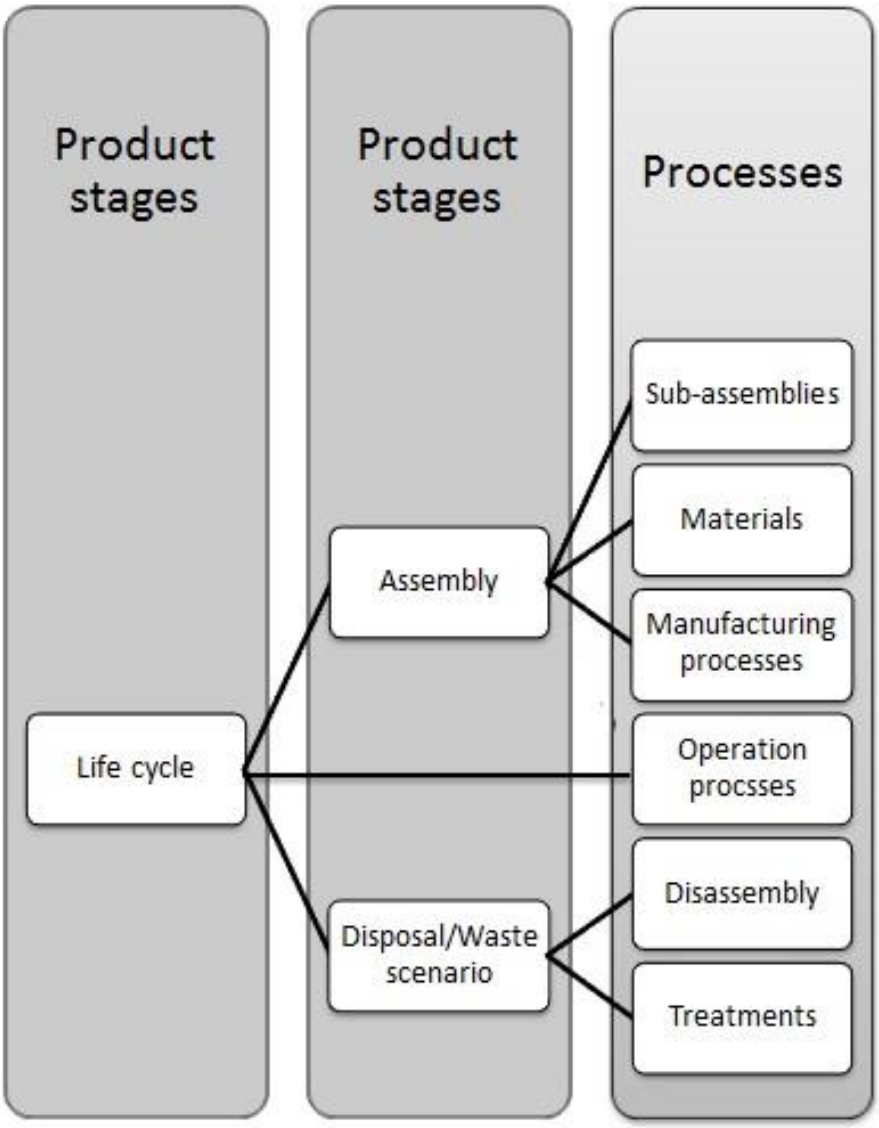


Figure 4-2 Structure of a product model

4.2.1 Manufacturing stage

The purpose of this stage is to form the assembly in the product model; therefore the information about the composition of the aircraft is required. Following this, the materials and weights of these components should be obtained to link the processes to the assembly. Furthermore, to create these processes, the data on the input and output products and emissions of those materials and manufacturing processes should be collected.

4.2.1.1 Components, materials and weights of A319

The A319 can be divided into six main structural components: the fuselage, wing, stabilizers, landing gears, nacelles/pylons and the power plant (Airbus, 2002b; Airbus, 2012). Each component is assembled by several secondary components and sub-assemblies. There are in total 25 secondary components and 107 sub-assemblies of this aircraft (Airbus, 2002a; Airbus, 2002b). Figure 4-3 shows the main components and sub-assemblies of A319. The detailed information is listed in Appendix A.

Most of the weight and material data is from the A320 Weight and Balance Manual (Airbus, 2002c) and previous research (Howe, 2011). Despite both referring to the A320, the weight of the A319 can be calculated by the ratio of the fuselage length. This is because, according to the dimension of these two type airplanes on the official web set of Airbus (Airbus, 2013a; Airbus, 2013b), the difference between the A320 and A319 is the length of fuselage (Table 4-3).

The total mass of the A320 aircraft structure and engines is 39.181 tons and the weight of fuselage is 11.755 tons (Howe, 2011). Therefore the mass of the A319 aircraft studied in this project could be calculated as:

$$\begin{aligned} Weight_{A319} &= Weight_{A320} - Weight_{Fus} + Weight_{Fus} \times \frac{Length_{A319}}{Length_{A320}} \\ &= 37.46\ tons \end{aligned} \tag{4-1}$$

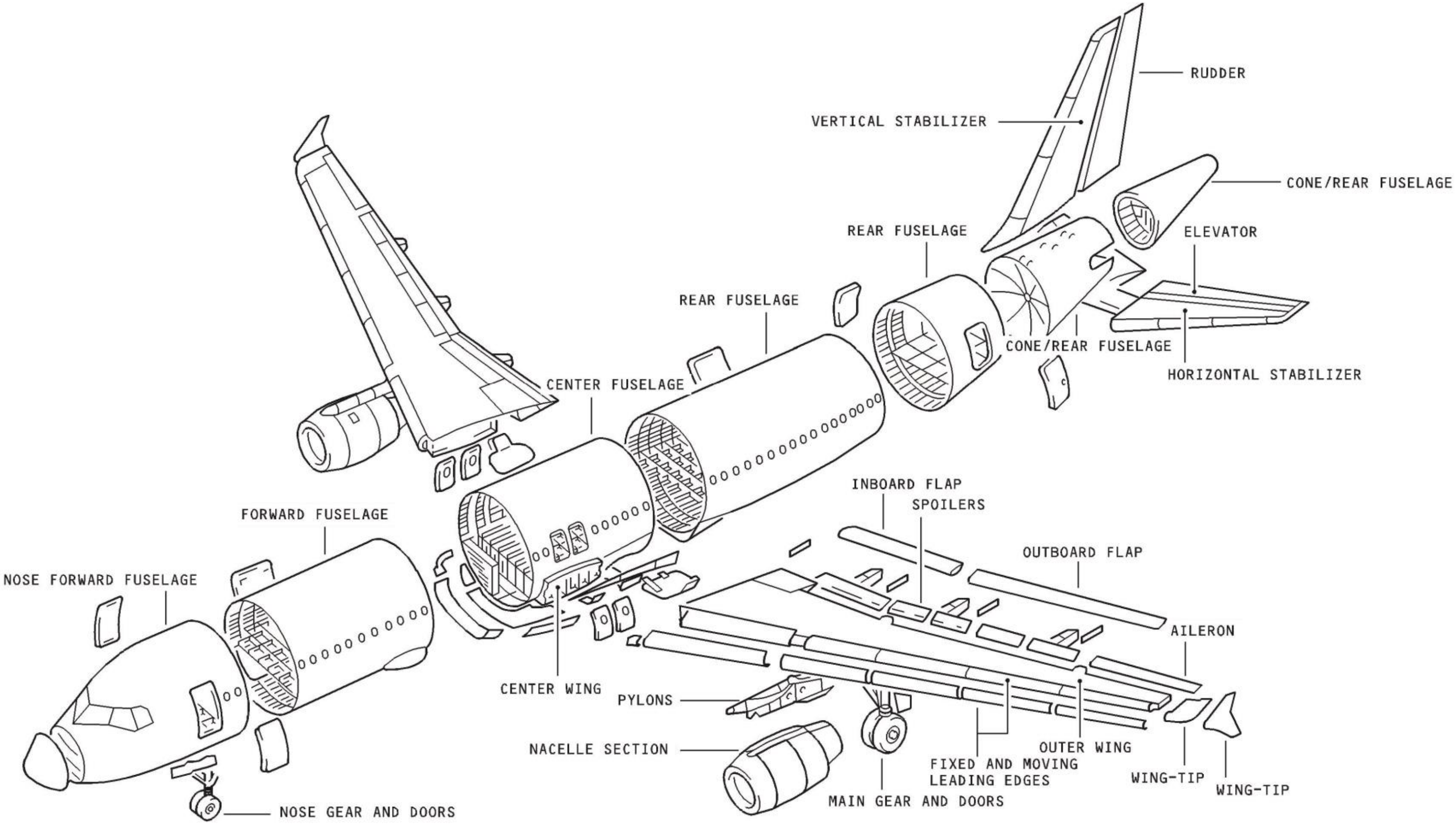


Figure 4-3 Main components of A319 (Airbus, 2002b)

Table 4-3 Dimension comparison of A319 and A320 (Airbus, 2013a; Airbus, 2013b)

Items	Dimensions of A319	Dimensions of A320
Overall length	*33.84 m*	*37.57m*
Fuselage width	3.95 m	3.95 m
Max cabin width	3.70 m	3.70 m
Wing span (geometric)	34.10 m	34.10 m
Height	11.76 m	11.76 m
Track	7.59 m	7.59 m

The total weight of the A319 was then broken down into the components, secondary components and sub-assemblies depending on the A320 Weight and Balance Manual (Airbus, 2002c) and the previous research (Howe, 2011). Because the detailed information of the aviation industry is extremely sensitive, the weight and material information of every sub-assembly of the aircraft is not always wholly available, thus about 30% of data requires estimation. Nonetheless, these less accurate data may not have a significant influence on the LCA result as the weight and material information about most components, important sub-assemblies and the composite parts are accurate. Figure 4-4 shows the weight of the primary components of the A319. Figure 4-5 indicates the weights of various materials used in this aircraft and their percentage of the total weight. The detailed data is listed in Appendix A.

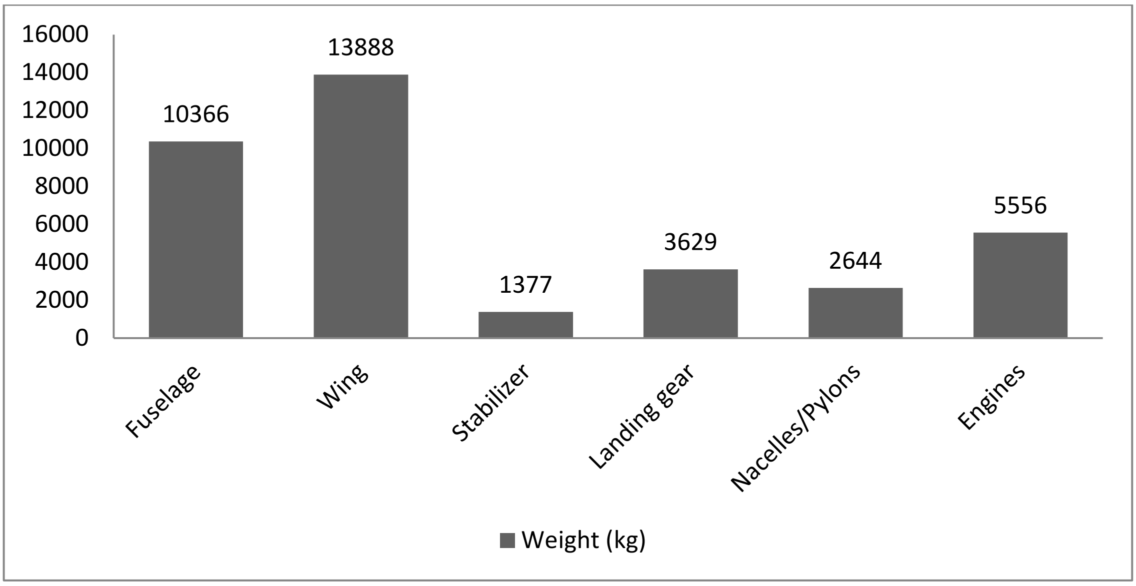


Figure 4-4 Primary components' weight of A319

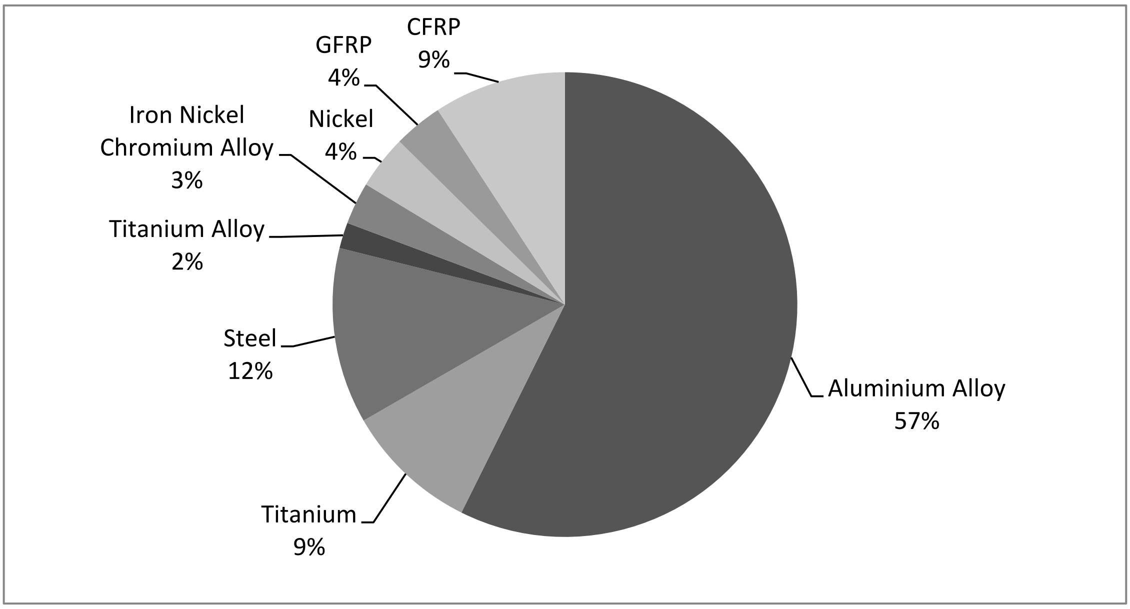


Figure 4-5 Material weight and percentage of A319

4.2.1.2 Components, materials and weights of B737-800

The B737-800 also can be divided into the six main structural components (Boeing, 2007; Boeing, 2005). There are in total 26 secondary components and 173 sub-assemblies of this aircraft (Boeing, 2007; Boeing, 2010). Figure 4-6 shows the main components and sub-assemblies of the B737-800. The detailed information is listed in Appendix B.

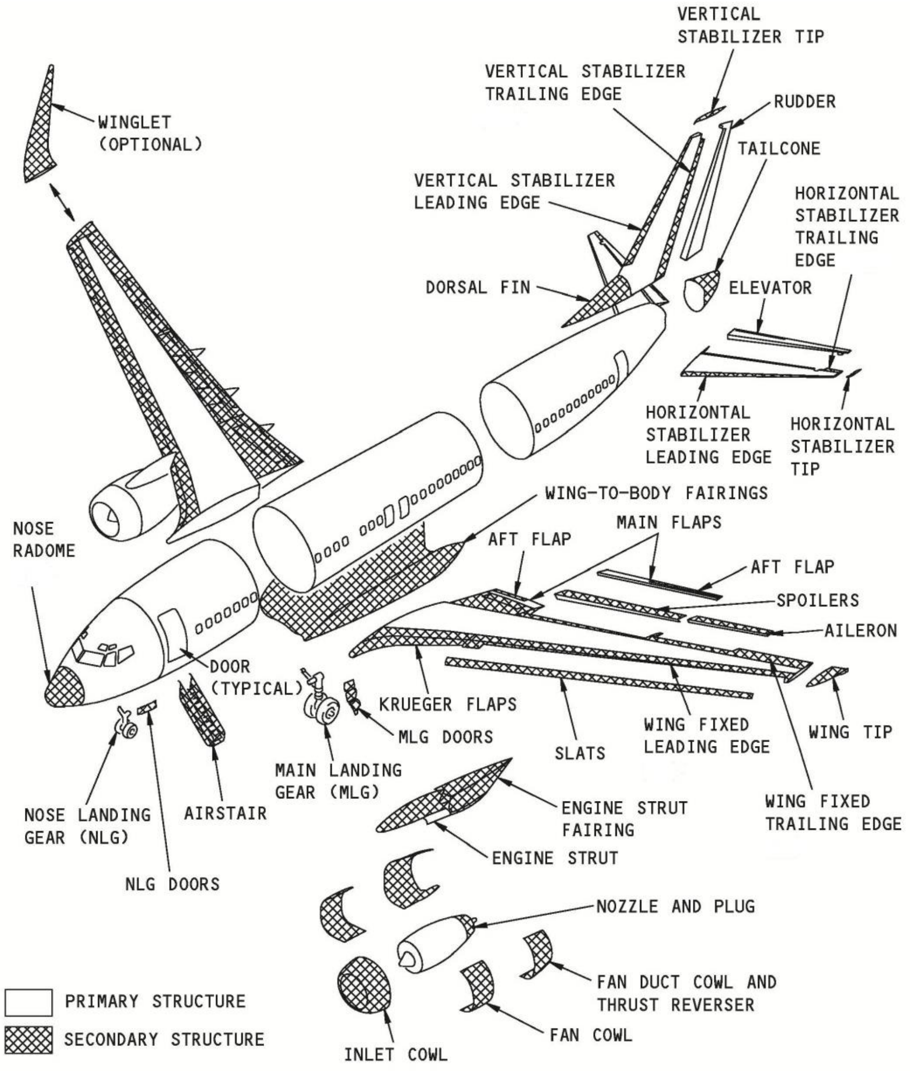


Figure 4-6 Main components of B737-800 (Boeing, 2007)

The data on the components and materials of the B737-800 is from the Boeing 737-800 Structural Repair Manual (Boeing, 2007) and Aircraft Maintenance Manual (Boeing, 2010). Most of these data are accurate. Majority weight information comes from the B737-800 Weight and Balance Control and Loading Manual (Boeing, 2002). Assumptions are made accordingly. The Operational Empty Weight (OEW) of the B737-800 is 41.145 tons which includes the structure, power plant, furnishings, systems and the operational items (Boeing, 2002). Since the system boundary of this project has excluded the systems, furnishings and operational items, the weight of these items should be subtracted. Assuming these objects will occupy about 10% of the OEW, the weight of the A737-800 analysed in this research will be 38.295 tons.

There is no information in the manuals regarding the material of the engine utilized on this aircraft; nevertheless, the engine of the B737-800 is CFM56-7B and the engine of the A319 is CFM56-5B. Both are manufactured from the same company and both are the primary series of aircraft engine (CFM International, 2013). Therefore, their material might be similar. For this reason, an assumption was made to break down the total weight of CFM56-7B to different materials with the same material weight ratio of CFM56-5B. Figure 4-7 shows the primary component weight of B737-800. Figure 4-8 indicates the weight of various materials used in this aircraft and their percentage of the total weight. The detailed data is listed in Appendix B.

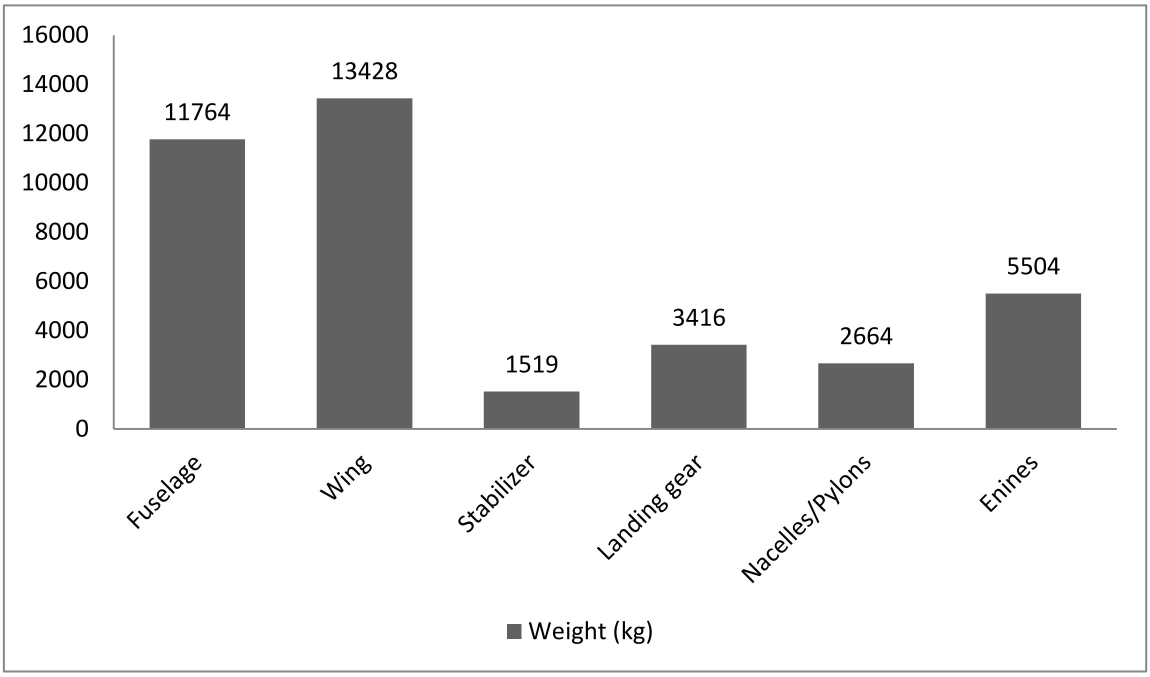


Figure 4-7 Primary components' weight of B737-800

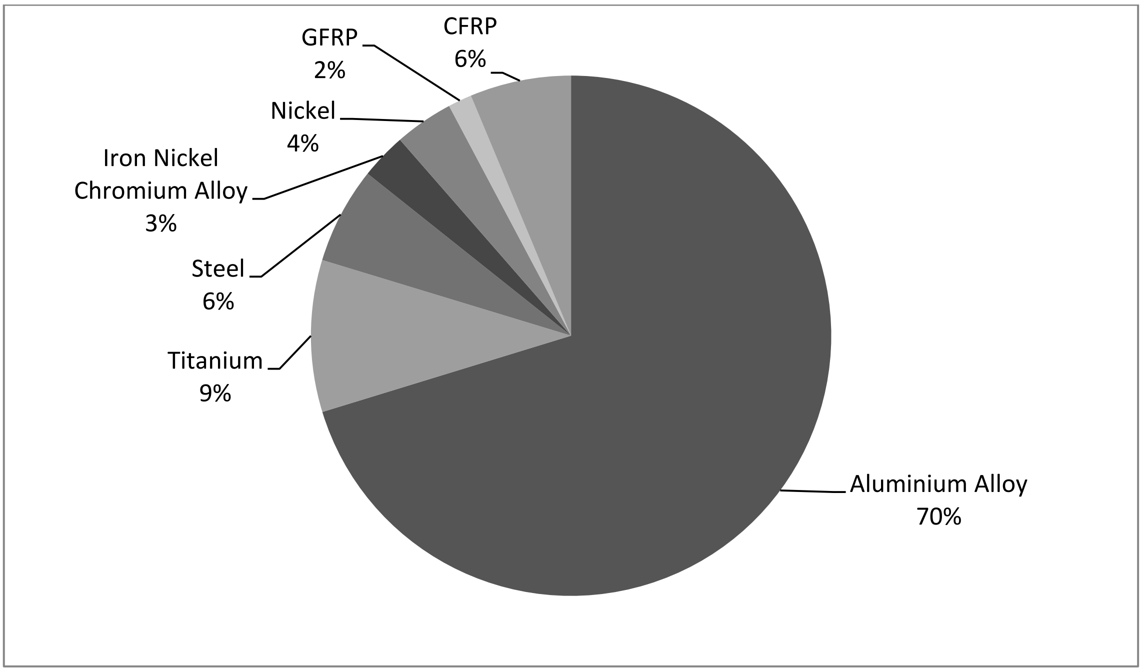


Figure 4-8 Material weight and percentage of B737-800

As can be seen from Figure 4-5 and Figure 4-8, aluminium alloy is the main material of both these two aircraft types. Moreover, the composite utilization rate of the B737-800 (8%) is less than that of the A319 (13%).

4.2.1.3 Material manufacturing process

From Figure 4-5 and Figure 4-8, it can be indicated that the material used in these two aircraft types are aluminium alloy, steel, titanium, nickel, iron nickel chromium alloy, titanium alloy, carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP). Except the composite material CFRP and GFRP, the manufacturing processes of all the other materials are included in the LCA libraries. The data to be collected in this stage regards the composite material.

The system boundary has defined the manufacturing process of the composite product from the obtaining of reinforced fibre. According to the experience of producing composite product for aircrafts, the commonly composite product manufacturing processes are: (1) produce the fibres, (2) combine the fibre and polymer together to make prepregs, (3) lay the prepregs on the model, (4) send the laid prepregs and model to cure in the autoclave and obtain the composite product. Since the process of producing glass fibre has already been included in the LCA library, the data requiring research is the manufacturing process of carbon fibre and the other composite material forming processes.

Firstly, the most commonly used manufacturing process of carbon fibre is based on the carbonization of polyacrylonitrile (PAN) fibre (Das, 2011; Duflou et al., 2009). During subsequent carbonization of the stabilized fibres in a nitrogen atmosphere at temperatures between 1000 and 1700 °C, hydrogen, nitrogen and oxygen atoms are removed from the fibre and are emitted as NH_3, H_2O, H_2, CO, CO_2, HCN and CH_4 (Corbière-Nicollier et al., 2001; Duflou et al., 2009). With a further heating, those harmful air HCN, CO CH_4 and NH_3 are converted to CO_2, H_2O, N_2 and NO_2. The overall processes result in approximately 50-55% of the original PAN precursor mass converted to carbon fibres (De Vegt & Haije, 1997). The energy consumed in this process is about 7.56 MJ/kg (De Vegt & Haije, 1997; Shen & Patel, 2008). Thus the input information of this process are: PAN, hydrogen, nitrogen, oxygen and energy, the output materials are carbon fibre, H_2O, H_2, CO_2, N_2 and NO_2

For the prepreg making stage, the average fibre and resin ratio of the composites utilized in these aircrafts is 6:4 (Airbus, 2002b; Basbagill et al., 2012). The energy exhausted in this stage is roughly 40MJ/kg (Suzuki & Takahashi, 2005a; Song et al., 2009).

Finally, during the manufacturing process of composite product, the usual model material is steel, and the average model weight for 1 kg composite product is 200kg (Talked with the engineer in Commercial Aircraft Corporation of China (COMAC), (Wang, 2013)). Moreover, the energy consumption of this process is around 21.9 MJ/kg (Song et al., 2009; Suzuki & Takahashi, 2005b).

4.2.1.4 Transportation process

As mentioned in Section 4.1.2.3, the transportation of the components from the manufacturing location to the Final Assembly Line factory will be included in this project. The A319 is mainly manufactured in the European, while the B737-800 is manufactured worldwide, including the USA, Europe and Asia. Table 4-4 indicates the transportation of main components for the A319 (Howe, 2011) while Table 4-5 shows this information for the A737-800 (Chris, 2013).

Table 4-4 Transportation of main components for A319 (Howe, 2011)

Components	Assembly location	Transport method	Distance (km)
Fuselage	Toulouse, France	-	-
Wing	Broughton, UK	Aircraft	966
Vertical Stabilizer	Stade, Germany	Aircraft	1288
Horizontal Stabilizer	Getafe, Spain	Road	805
Main Landing Gears	Bidos, France	Road	233
Nose Landing Gear	Bidos, France	Road	233

Table 4-5 Transportation of main components for B737-800 (Chris, 2013)

Components	Assembly location	Transport method	Distance (km)
Fuselage	Wichita, USA	-	-
Horizontal Stabiliser	Korea Aerospace Industries	Sea	13000
Ailerons	Asian Composites Manufacturing, Malaysia	Sea	13000
Rudder	Belfast, UK	Sea	8000
Elevator	Fuji, Japan	Sea	13000
Tail section	China	Sea	13000

4.2.1.5 Modelling the assembly of the aircrafts

To set up the models, the processes should be created prior to the assembly product stage. As has been noted in Section 4.2.1.3, the processes requiring customization are the manufacturing of carbon fiber, prepregs with carbon fiber (CF), prepregs with glass fiber (GF), CFRP product and GFRP product. For example, the data for the CFRP producing processes are listed in Table 4-6.

Table 4-6 Data of CFRP producing processes

Output products		Inputs				Outputs	
Item	Quantity	Materials/fuels		Electricity/heat		Emissions to air	
		Item	Quantity	Item	Quantity	Item	Quantity
Carbon fiber	1kg	Polyacrylonitrile fibres (PAN)	2kg	Heat, natural gas	7.56MJ	Nitrogen	0.6kg
		Nitrogen	12kg			Water	5.2kg
						Carbon dioxide	2.8kg
						Nitrogen dioxide	2.4kg

Output products		Inputs				Outputs	
Item	Quantity	Materials/fuels		Electricity/heat		Emissions to air	
		Item	Quantity	Item	Quantity	Item	Quantity
Prepreg	1kg	Carbon fiber	0.6kg	Heat, natural gas	40MJ	-	-
		Epoxy resin	0.4kg				

Output products		Inputs				Outputs	
Item	Quantity	Materials/fuels		Electricity/heat		Emissions to air	
		Item	Quantity	Item	Quantity	Item	Quantity
CFRP product	1kg	Prepreg	1kg	Heat, natural gas	21.9MJ	-	-
		Steel	200kg				

Enter the output product and link the input and output items from the database to create the processes. Then, the connections between different process units can be built up to configure the network of the product model as Figure 4-9. This network contains all the raw materials, produce processes, emissions and wastes information.

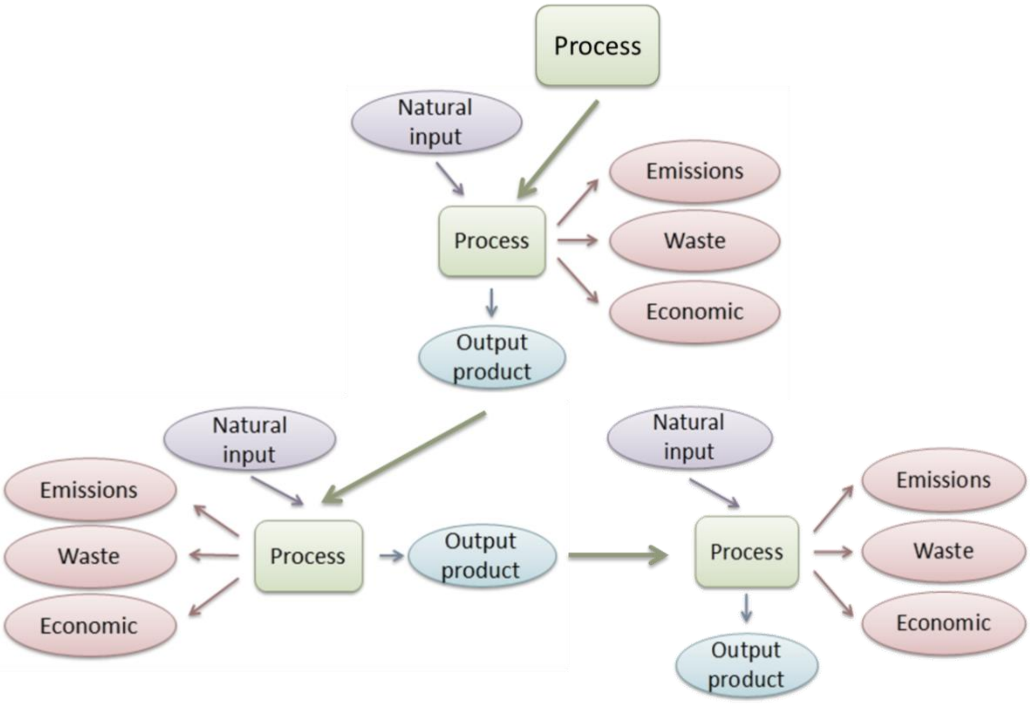


Figure 4-9 Use process unit to form network of product model

Subsequently, the assembly product stage is accomplished. This stage contains the materials, sub-assemblies and transport processes based on the data in Appendix A and Appendix B. It does not include environmental issues since these have already been included in the processes. Finally, the network of the assembly model of the aircrafts can be obtained as Appendix C.

4.2.2 Operation stage

The operation stage consists of three parts: the estimate of fuel consumption during the whole operation period of the aircraft, the construction of the airport and its maintenance. As the processes of the airport construction and maintenance are included in the libraries, the required calculation work relates only to fuel consumption.

Calculating total fuel consumption involves two steps: obtaining the fuel consumption rate of each aircraft, and multiplying the fuel consumption rates with the total passenger number and the travel distance during their whole life span.

Firstly, the fuel consumption rate calculation process will be explained. The fuel consumption rate is defined as the fuel consumed per passenger per kilometre. The equation of this factor is shown below:

$$Fuel\ consumption_{Per\ passeger}\ (kg/km/pass) = \frac{Fuel\ consumed\ in\ average\ flight\ distance\ (kg)}{Number\ of\ passenge \times Average\ flight\ distance\ (km)} \tag{4-2}$$

The fuel consumption rate of the A319 and B737-800 come from the analysis in the Aircraft Owner's & Operator's Guide: A320 family/ 737NG family (Aircraft commerce, 2006; Aircraft commerce, 2010). In the analysis for the A319, the chosen flight route was between London and Munich which averages a flight distance of 1076.938km and a passenger load of 124 passengers. The experiment record indicated that the average fuel consumption for this route was 1107 US Gallons. Assuming the fuel utilized in the aircraft is the BP Jet A-1, with a density of 804kg/m^3 (Air BP, 2000), and 1 US gallons equals to 0.00379m^3, the average fuel consumption is 3369.112kg. Thus the fuel consumption rate is 0.025 kg/km/pass.

On the other hand, the analysis for the B737-800 selected five routes with an average distance of 1647.9km and a passenger load of 162 passengers. According to the test result, the average fuel consumption was 1920 US Gallons which equals to 5843.464kg. Thus the fuel consumption rate was 0.022 kg/km/pass. In all the analysis, the effect of wind has already been considered.

Secondly, the total fuel consumption can be obtained by multiplying the fuel consumption rates with the total travel passenger numbers and distances. Since this project is targeting at the Chinese aircraft market, the data on passenger numbers and travel distances are primarily from the statistics of Civil Aviation Administration of China (CAAC) and the airlines in China. In order to compare these two aircraft types in the same condition, both will use the same passenger numbers and travel distances based on the statistics of the A319. Since the typical cabin layout of the A319 in China is 128 seats with 2-class (Air China, 2013; China Eastern, 2013; China Southern, 2013), and in 2012, the average

Passenger Load Factor in China is 79.6% (CAAC, 2013), the actual passenger number per flight can be obtained by multiplying these two figures, with the result being 102 passengers approximately. At the same time, according to the route map, the average travel distance of the A319 is 1152.29km per flight (Ctrip.com International, 2013; Star Alliance, 2013), and assuming the aircraft movements during the 24 years are 17520 times, the total travel distance is the product of them – 20188120.8km.

Applying these data to the equation (4-3), the total fuel consumption of these two aircrafts can be calculated as:

$$\begin{aligned} Fuel\ consumption\ (kg) &= Fuel\ consumption_{Per\ passeger}\ (kg/km/Pass) \\ &\times Passenger\ Number \times Travel\ distance\ (km) \end{aligned} \tag{4-3}$$

Finally, the operation processes for the A319 and B737-800 can be created by modifying the existing aircraft operation process in the libraries. The target process chosen in this project is the “Operation, aircraft, passenger, Europe/RER U” process. Since its product amount is 1 personkm, the amount of kerosene should be changed to 0.025km for the A319 and 0.022 for the B737-800 to obtain the proper operation processes.

4.2.3 Disposal stage

The disposal stage is a significant phase in an LCA study to examine the environmental influence of a product. To model the disposal scenarios of the aircrafts, their structures should be explained. Building a disposal scenario consists of three main steps: define waste treatments, build waste scenarios, and establish the disposal scenarios. But it is not necessary to contain all these steps. It depends on the disposal method of the product. The distinctions between these methods are that the disposal scenario refers to product. This means that the information about the assembly of this product is maintained. Hence, except the waste scenarios, it always contains a disassembly and several reuse operations (PRè Consultants, 2008a). On the other hand, the waste scenario refers to material, “without observing any product characteristics” (PRè Consultants, 2008a). It contains how the waste flows are directed to different treatments. Moreover, the waste treatment describes how to manage the waste, including emission information.

Therefore, in order to model the disposal scenario of the retired aircrafts, three elements of information require collection and clarification: the procedures to treat with the end-of-life aircrafts; the data about the whereabouts of the disposed components and materials; and the inputs and outputs of each waste treatment. The first and second step will be clarified in section 4.2.3.1, and the third step is described in section 4.2.3.2.

4.2.3.1 Aircraft end-of-life

The data for this stage is derived mainly from the Process for Advanced Management of End-of-Life of Aircraft (PEMELA) project and previous research (Airbus, 2008b; Howe, 2011). The growing trend of retired aircrafts makes the treatment of end-of-life aircrafts a most significant issue for the reason that, currently, it seems no effective environment friendly disposal process for aircrafts exists. Indeed, the out of service aircrafts are usually discarded and parked in desolate places. In response to this situation, Airbus is conducting extensive research on improving the eco-efficient of aircraft. Airbus also promoted the PEMELA project to recommend a feasible aircraft disposal procedure that may reduce its environmental impact to some extent (Airbus S.A.S., 2012a; Airbus S.A.S., 2012c). The result of the PEMELA project may also propose a possible material recycling rate and standardize the utilization of second - hand materials (Airbus, 2008b; Feldhusen et al., 2011).The PEMELA project took the A300 aircraft as the reference plane. There are three steps for the deconstruction of an aircraft: decommissioning, disassembling, and dismantling (Airbus, 2008b) (Figure 4-10).

Firstly, in the decommissioning stage, the reference plane “was parked, decontaminated and cleaned. The WC water and fuel tanks were emptied and the according liquids were orderly disposed or, concerning the fuel, stored for reuse (Feldhusen et al., 2011) ”.

Subsequently, in the disassembling stage, the Engines, APU (auxiliary power unit), avionic systems, the RAT (ram air turbine), the landing gears, the cabin equipment and some other auxiliary components were dismantled from the aircraft. After the inspection and cleaning processes, some of these parts will be reused according to relevant regulations. The parts that could not be reworked are demolished (Feldhusen et al., 2011).

Finally, in the dismantling stage, “all used materials should be separated and provided for the according recycling channels. Different approaches were tested here” (Feldhusen et al., 2011).

The LCA research of the A319 and B737-800 will mostly examine the treatments of the materials of the end-of-life aircraft. Hence those components which are reused or destroyed integrally will also be considered to the level of material. And the potential waste treatments of this study are: reuse, recycle, landfill and incineration. According to the result of the PEMELA project and previous studies, the disposal scenario per material can be estimated as shown in Table 4-7 and Table 4-8 (Airbus, 2008b; Feldhusen et al., 2011; Asmatulu et al., 2013). The engines and landing gears are assumed to have a 75% and 80% reusable rate. The recycle rate of composite material is assumed to be 50%, which will be explained in section 4.2.3.2. The proportion of each disposal scenario is shown in Figure 4-11 and Figure 4-12. The material weight of each disposal type is shown in Figure 4-13 and Figure 4-14.

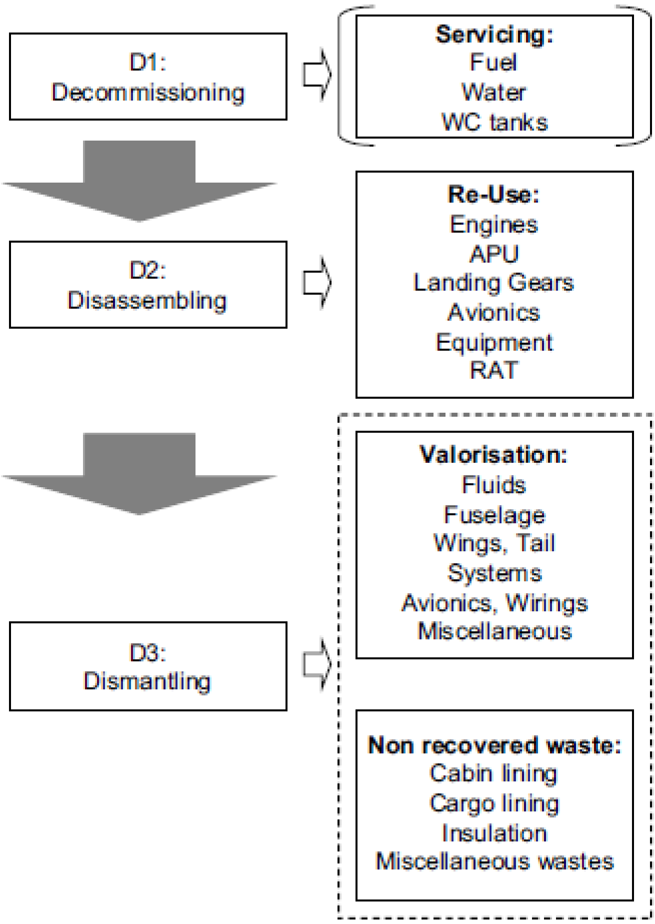


Figure 4-10 Deconstruction of the reference plane (Feldhusen et al., 2011)

Table 4-7 End-of-life scenario for A319

Component	Material	Weight (kg)	Disposal scenario (%)			
			Re-use	Recycle	Incineration	Landfill
Fuselage	Aluminium Alloy	8925		85		15
	Titanium	150			50	50
	steel	100		85		15
	GFRP	1046		50	25	25
	CFRP	145		50	25	25
Wing	Aluminium Alloy	11244		70		30
	Titanium	1340		50		50
	steel	400		75		25
	CFRP	904		50	25	25
Stabilizer	Aluminium Alloy	86		64		36
	GFRP	129		50	25	25
	CFRP	1162		50	25	25

Landing gear	Aluminium Alloy	227	80			20
	Titanium	349	80			20
	steel	2599	80			20
	CFRP	454		50	25	25
Nacelles& Pylons	Steel	1086		80		20
	Titanium Alloy	672			50	50
	GFRP	100		50	25	25
	CFRP	786		50	25	25
Engine	Aluminium Alloy	1000	75			25
	Titanium	1656	75			25
	Steel	400	75			25
	Iron Nickel Chromium Alloy	1100	75			25
	Nickel	1400	75			25

Table 4-8 End-of-life scenario for B737-800

Component	Material	Weight (kg)	Disposal scenario (%)			
			Re-use	Recycle	Incineration	Landfill
Fuselage	Aluminium Alloy	10781		85		15
	Titanium	243			50	50
	GFRP	97		50	25	25
	CFRP	643		50	25	25
Wing	Aluminium Alloy	12628		70		30
	Titanium	350		50		50
	GFRP	272		50	25	25
	CFRP	178		50	25	25
Stabilizer	Aluminium Alloy	1084.6		64		36
	Titanium	20.5		50		50
	GFRP	195.9		50	25	25
	CFRP	218		50	25	25
Landing gear	Aluminium Alloy	450	80			20
	Titanium	1000	80			20

	Steel	1900	80			20
	CFRP	66	80			20
Nacelles& Pylons	Aluminium Alloy	964		85		15
	Titanium	396			50	50
	CFRP	1304		50	25	25
Engine	Aluminium Alloy	1000	75			25
	Titanium	1604	75			25
	Steel	400	75			25
	Iron Nickel Chromium Alloy	1100	75			25
	Nickel	1400	75			25

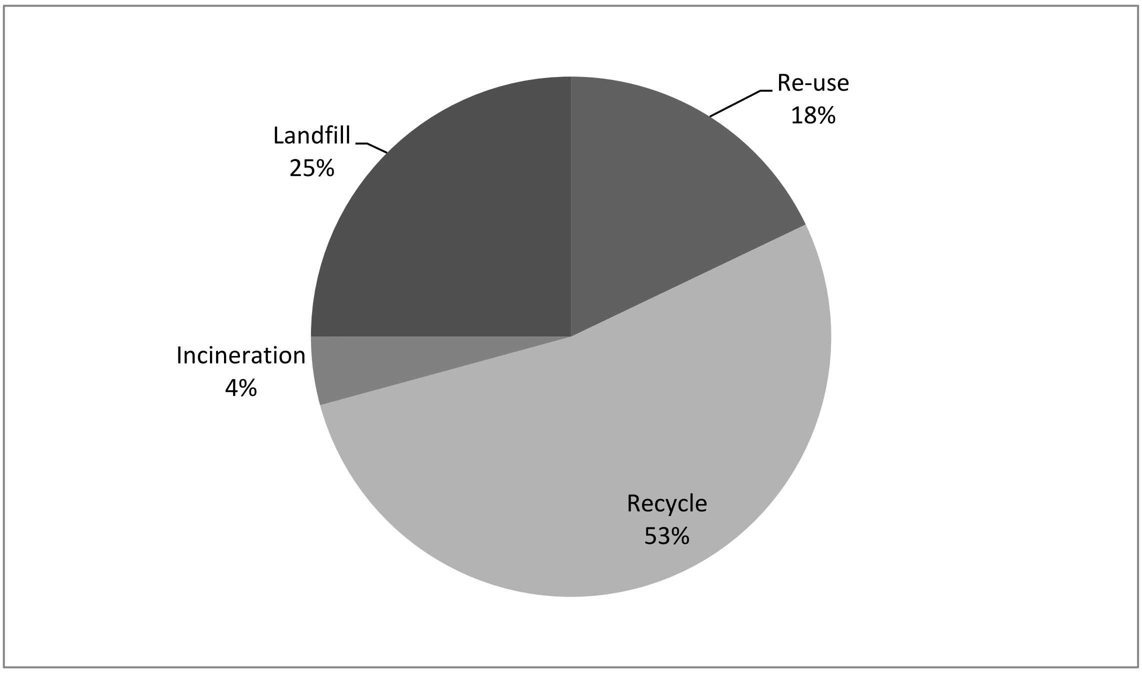


Figure 4-11 Proportion of each disposal scenario for A319

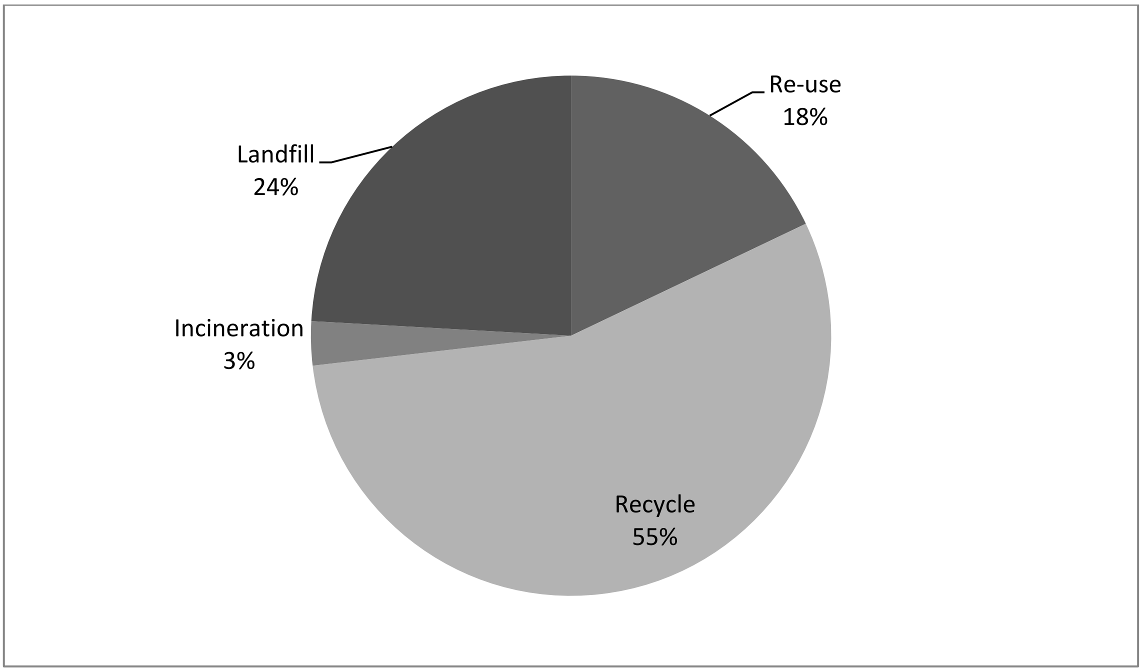


Figure 4-12 Proportion of each disposal scenario for B737-800

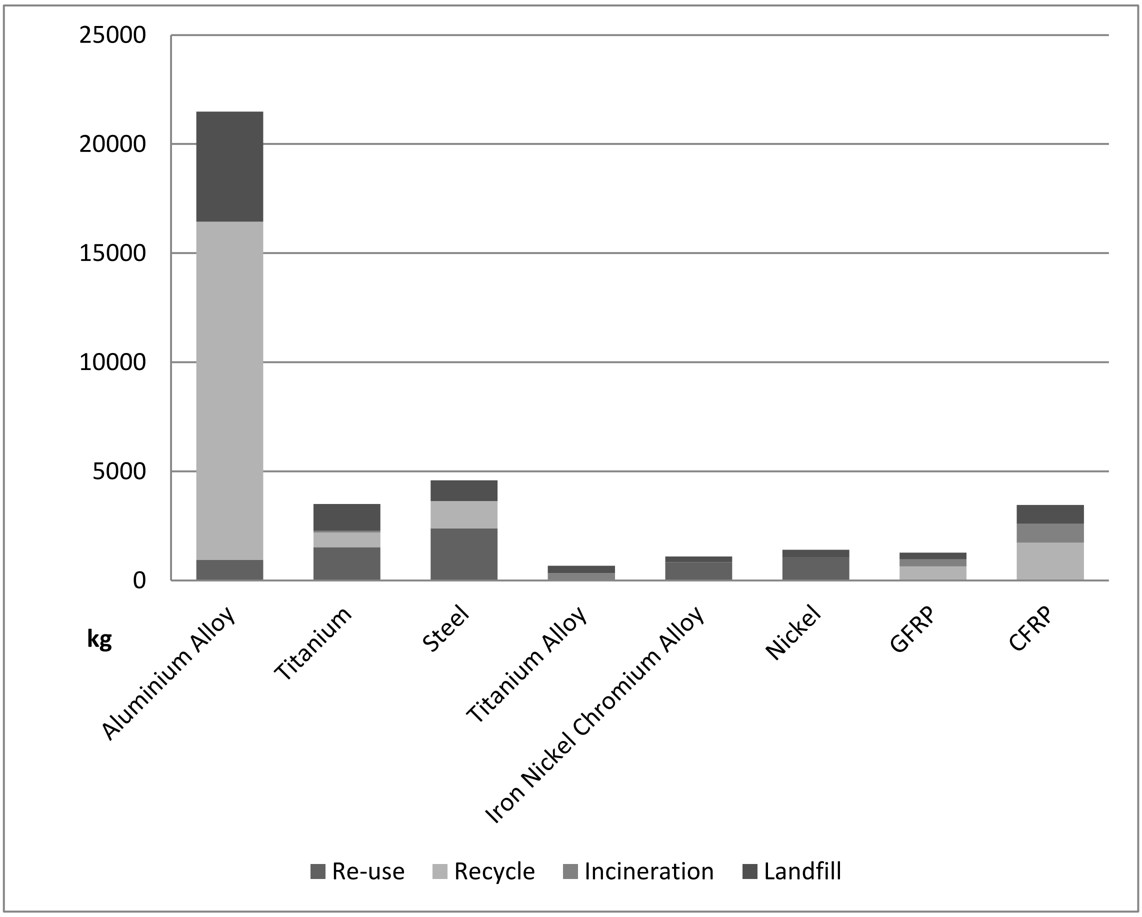


Figure 4-13 Material weight of each disposal type for A319

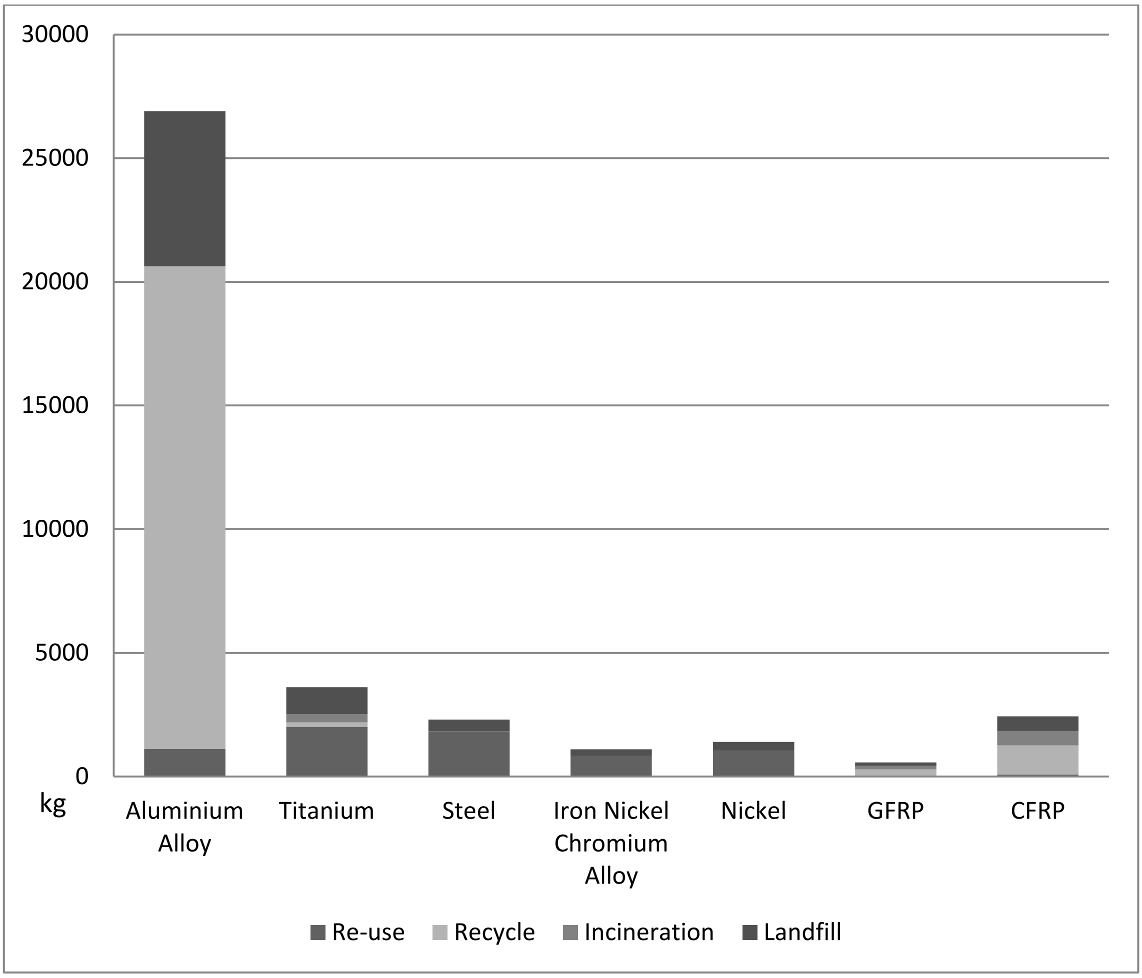


Figure 4-14 Material weight of each disposal type for B737-800

4.2.3.2 Waste treatment processes

With the exception of the composite material, the four waste treatment processes for the other materials can be found from the libraries. Regarding the composite, as it will not flow to the reuse channel, the landfill of this material can be replaced by the plastic landfill process. Accordingly, the processes that require setting up are the recycle and incineration treatments of composite material.

The integral character of thermoset composites makes the recycling of this material quite difficult. The reasons for this are: (1) The cross-linked thermoset polymers utilised in the thermoset composite cannot be re-melted or remoulded. (2) The various hybrid reinforcing materials in the thermoset composites cause it to be a complicated waste type. (3) The standard composition for thermoset composites has not been established. This also contributed to the complication of waste type. (4) Identifying the more appropriate waste type from various compositions is an arduous task (Pickering, 2006). However, there are several potential recycling methods for polymeric composites including mechanical recycling, chemical recycling, fluidised bed thermal process, and pyrolysis techniques.

The mechanical recycling technique usually involves crushing the composite components to scraps. In most cases, this method is used to treat with GFRPs, due to its comparatively low recycle value. Since the fibres recycled from this process are short and not clean enough, they are mainly used as fillers (Yang et al., 2012).

A chemical recycling procedure could recycle fibres by separating it from the polymer matrix (Song et al., 2009). However, this technique has not been developed as maturely as the mechanical technology. It is still at the laboratory stage researching different chemical dissolution systems using various solvents (Yang et al., 2012).

Fluidised bed thermal process can recover monomers from polyester and polyamides composite materials (Song et al., 2009). This process feeds the scrap composites which are about 25mm into a fluidised silica sand bed. The sand is fluidised with a stream of hot air at the temperature range of 450–550 °C. This makes the polymer volatilise from the composite and the fibres and fillers can be obtained. Then a high temperature secondary combustion chamber fully oxidises the polymer. This method can recycle both glass fibre and carbon fibre. The typically fiber length is from 6mm to over 10mm and the fibres retrieved from this procedure are comparatively clean (Yang et al., 2012).

Pyrolysis is a technique that thermally decomposes composite at high temperatures of 300–800 °C in the absence of oxygen to recover long, high modulus fibres. When treated with the polymer-matrix composite, “both the reinforcement fiber and the matrix materials (Yang et al., 2012)” can be recovered.

“Compared to other recycling methods, pyrolysis is the most realistic and practical recycling technology for both carbon and glass fibre reinforced polymer composites” (Yang et al., 2012). And this method is already in the commercial-scale plant whereas others are still in the pilot-scale plant or laboratory scale (Pimenta & Pinho, 2011). In addition, the primary purpose of composite recycle is to obtain fibres. Therefore, the LCA of the A319 and B737-800 research chose pyrolysis as the recycling method of composite. The input and output information of the pyrolysis process is shown in Table 4-9 and Table 4-10 (Pickering, 2006).

The data regarding the incineration process for the composite is listed in Table 4-11 and Table 4-12. For the reason that the main benefit from this process is the energy recovery and the resource about this treatment is difficult to find, the emissions are assumed based on the pyrolysis processes. Nevertheless, the data of the energy in these two tables are relatively accurate as they are obtained from previous research (Witik et al., 2013).

Overall, the disposal and waste scenarios can be created according to the information in Section 4.2.3.1, and the waste treatment processes will be set up utilising the data in Section 4.2.3.2.

Table 4-9 Input and output information of pyrolysis process for CFRP (Pickering, 2006)

Input processes		Output processes							
		Recycled materials		Emissions to air		Emissions to water		Emissions to soil	
Item	Quantity	Item	Quantity (kg)	Item	Quantity (kg)	Item	Quantity (kg)	Item	Quantity (kg)
CFRP	1kg	Carbon fiber	0.393	Propene	0.008526	Acetic acid	0.024156	Xylene	0.00462
Energy	30MJ	Phthalic anhydride	0.148	Water	0.024302	Pyridine	0.024156	Styrene	0.006468
				Sulphur dioxide	0.006264	Phenol	0.020196	Dimethyl formamide	0.000462
				Hydrogen cyanide	0.00319	Aniline	0.292644		
				1-Butene	0.001314	Toluidine hydrochloride	0.033264		
				1,2-Butanediol	0.0029				
				Bromine	0.000812				
				Acetone	0.007772				
				Acetonitrile	0.00145				
				Cyclopentadiene	0.001508				

Table 4-10 Input and output information of pyrolysis process for GFRP (Pickering, 2006)

Input processes		Output processes							
		Recycled materials		Emissions to air		Emissions to water		Emissions to soil	
Item	Quantity	Item	Quantity (kg)	Item	Quantity (kg)	Item	Quantity (kg)	Item	Quantity (kg)
GFRP	1kg	Glass fibre	0.393	Propene	0.008526	Xylene	0.014256	Xylene	0.00462
Energy	30MJ	Styrene	0.104	Water	0.024302	Phthalic anhydride	0.229284	Styrene	0.006468
		Phthalic anhydride	0.148	Sulphur dioxide	0.006264	Dimethyl ether	0.0099	Dimethyl formamide	0.000462
				Hydrogen cyanide	0.00319				
				1-Butene	0.001314				
				1,2-Butanediol	0.0029				
				Bromine	0.000812				
				Acetone	0.007772				
				Acetonitrile	0.00145				
				Cyclopentadiene	0.001508				

Table 4-11 Input and output information of incineration process for CFRP

Input processes		Output processes							
		Recycled materials		Emissions to air		Emissions to water		Emissions to soil	
Item	Quantity	Item	Quantity	Item	Quantity (kg)	Item	Quantity (kg)	Item	Quantity (kg)
CFRP	1kg	Energy	10.51MJ	Propene	0.05	Waste water	0.42	Xylene	0.04
Energy	32MJ			Water	0.05			Styrene	0.03
				Sulphur dioxide	0.05			Dimethyl formamide	0.01
				Hydrogen cyanide	0.05				
				1-Butene	0.05				
				1,2-Butanediol	0.05				
				Bromine	0.05				
				Acetone	0.05				
				Acetonitrile	0.05				
				Cyclopentadiene	0.05				

Table 4-12 Input and output information of incineration process for GFRP

Input processes		Output processes							
		Recycled materials		Emissions to air		Emissions to water		Emissions to soil	
Item	Quantity	Item	Quantity	Item	Quantity (kg)	Item	Quantity (kg)	Item	Quantity (kg)
GFRP	1kg	Energy	3.3MJ	Propene	0.015	Waste water	0.15	Xylene	0.3
Energy	10MJ			Water	0.015			Styrene	0.3
				Sulphur dioxide	0.015			Dimethyl formamide	0.1
				Hydrogen cyanide	0.015				
				1-Butene	0.015				
				1,2-Butanediol	0.015				
				Bromine	0.015				
				Acetone	0.015				
				Acetonitrile	0.015				
				Cyclopentadiene	0.015				

5 IMPACT ASSESSMENT AND RESULT INTERPRETATION

The method selection will be initially introduced; following that, the impact assessment and result interpretation will be conducted in three phases. Firstly, the model network of the aircrafts will be interpreted since they are the basis of the impact analysis. Secondly, the environmental impact of the individual product phase, manufacturing, operation and disposal, will be assessed. Finally, the examination of the whole life cycle of the aircraft will be completed. The findings of this research will then be concluded.

For each phase in the life cycle, the environment impact will be assessed first. Subsequently, according to the impact assessment result, the reasons why particular segments have the most significant impact on the environment will be interpreted and the analysis on both the A319 and B737-800 completed. A comparative analysis of the two types of aircraft is also included in this study. Additionally, the limitations in the study and future suggestions will be stated.

5.1 Impact assessment method

The ISO 14040 standard (British Standards, 2006a) defined the impact assessment as a phase that aimed at evaluating the significance of potential environmental impacts of the product system using the LCI results. In general, LCIA first assigns LCI results to impact categories. Then, for each impact category, a life cycle impact category indicator is selected and the category indicator result calculated (British Standards, 2006a). After that, the collection of indicator results (LCIA results) provides information on the environmental issues associated with the inputs and outputs of the product system.

In most cases, the LCA researchers select assessment methods that have already been published to complete their research instead of developing methodologies. Thus, an appropriate LCA method should be selected under the guidance of the goal of the LCA research.

These methods assess the environmental influence using various impact categories and analyse procedures. The ISO 14040 (British Standards, 2006a) presented the following distinction of these methods:

- **Obligatory elements**: classification and characterisation.
- **Optional elements**: normalisation, ranking, grouping and weighting.

In other words, every LCA must at least include classification and characterisation analyses. Figure 5-1 shows the principle of the impact assessment analysis. From step 1 to step 2 is the essential analysis procedure named characterization. Its theory is to allocate the emissions linked in the product model to the impact categories to analyse the environmental influence. “Traditionally in LCA the emissions and resource extractions are expressed as 10 or more different impact categories, including acidification, ozone layer depletion, ecotoxicity and resource extraction (PRè Consultants, 2008b)”. From step 2 to step 3 is the further analysis process that not every method can organise. These methods will sort the characterization result by damage type to obtain a damage analysis or examine those impacts with a uniform standard named indicator to achieve a normalization analysis. The normalization analysis is used to observe which component has the main environmental effect. It analyses those effects by the environment indicator, such as the environmental effects on people during the same time period and in the same region. Additionally, the analysis can be displayed in another form named single score. It presents the environmental effect of every component. Thus the amount of environment impact one component has can be clearly exposed.

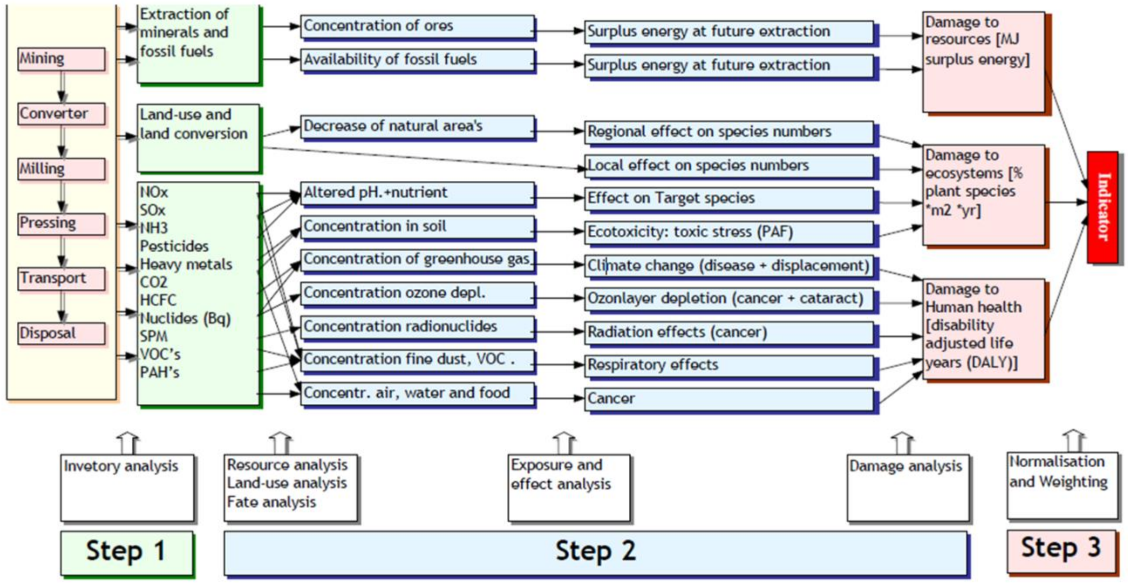


Figure 5-1 Impact assessment method principle (PRè Consultants, 2008b)

The impact assessment method selected in this project is the Eco-indicator 99 (H) V2.07, which is the most widely utilized and complete method. It includes most common impact categories and is able to complete the characterisation, damage assessment, normalisation, weighting and single score analyses.

5.2 Impact assessment and result interpretation

5.2.1 Explanation of the product model

Figure 5-2 shows the life cycle model for the A319. Firstly, the processes and product stages are clearly distinguished in various colours according to the legend on the left hand. Secondly, since the whole life cycle of the aircraft includes nearly three thousand elements, and some processes have little contribution to the whole life cycle, setting up a cut-off value can hide those processes to obtain an effective diagram. The navigator shows that there are 18 processes visible under the 0.005% cut-off. Thirdly, the figure at the left corner of each process indicates the environmental contribution of this process. It can be switched to show the exact environment load value or the percentage. Finally, the “show flow indicator in line width” button has been selected. This means that the width of the lines between the processes reveal the impact degree of those flows. At the same time, the bars at the right side of each process box also reflect the contribution percentage of this process. These both make the chart more intuitive.

As indicated in Figure 5-2, the manufacturing stage contributes just 0.0572% environmental impact on the whole life cycle of the A319 whereas the disposal phase provides 0.0186% positive return, about one third of the manufacturing impact. In comparison, the operation processes represent in total 99.9% of the environment effect of the entire life cycle, in which the proportion of fuel burn phase is 23%. The contribution percentages of these three segments for the B737-800 have the same trend, which is 0.0598% for the manufacturing process, 0.0204% return from the disposal phase and 99.9% of the operation stage, 21.2% of which comes from the fuel burn when the aircraft is flying between airports.

It is obvious that the operation stage provides the most environmental impact over the whole life span. However, the manufacturing and disposal phase are still important for an LCA study of the aircraft. They are the stages most possible to improve. This is because both have numerous processes that offer more opportunity of development.

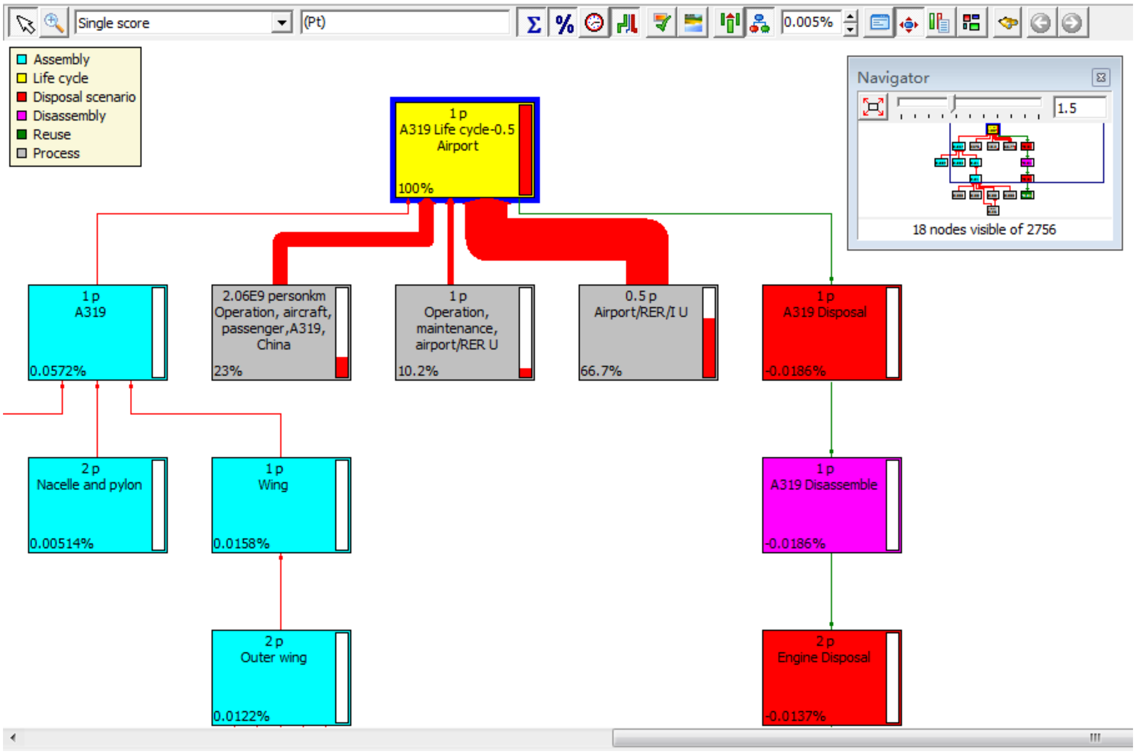


Figure 5-2 Life cycle model for A319

5.2.2 Impact assessment of the individual product phase

5.2.2.1 Impact assessment of the manufacturing phase

The network diagram (Figure 5-3 is a part of the network, the total chart is shown in Appendix C) of the assembly product stage which represents the manufacturing process of the A319 indicates that the engine and wing components contribute more impact than others. Their impact proportions are 31.9% for engine and 27.6% for the wing. The impact of engine manufacturing process is mainly contributed by the production of special material: nickel and titanium. Since these materials are not the focus of this stage, their environmental influence will not be analysed in detail.

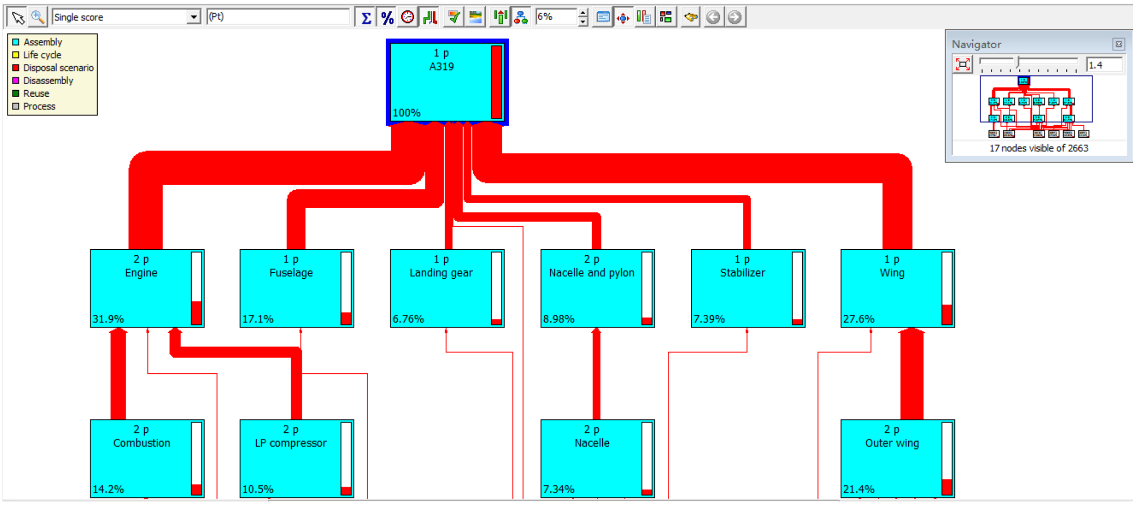


Figure 5-3 Network of A319 assembly

The wing component will be assessed in detail. The impact contribution of various material producing processes to the wing assembly can be realised from Figure 5-4. Table 5-1 shows the comparison between the weights of those materials and their impact contributions. As can be seen from Table 5-1, the weight of CFRP utilized in the wing represents roughly 8% of aluminium alloy, but its impact contribution is approximately one third of aluminium alloy.

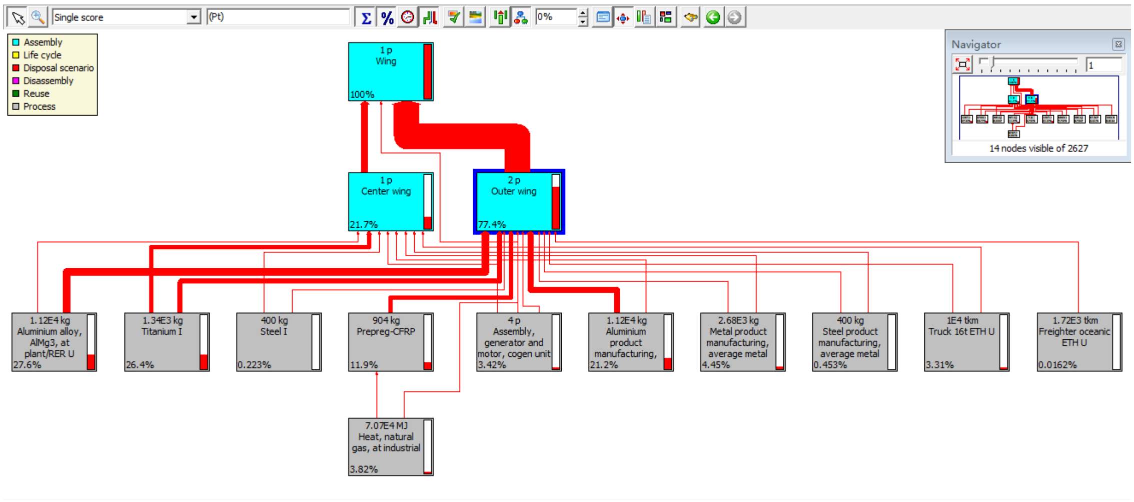


Figure 5-4 Network of Wing manufacturing of A319

Table 5-1 Comparison of material weights and their impact contributions

Material	Weight (kg)	Weight ratio (%)	Contribution ratio (%)
Aluminium Alloy	11244	80.96	48.8
Titanium	1340	9.65	30.85
steel	400	2.88	0.676
CFRP	904	6.51	15.72

This trend is even more obvious in the manufacturing process of the aircraft. As shown in Figure 5-5, the total impact contribution of producing aluminium alloy product is 25.8%, whilst the percentage of composite is 19.38% (the contribution of GFRP which is 6.78% cannot be shown in this figure). Nevertheless, the mass proportions of these two materials are 59.53% for aluminium alloy and 13.1% for composite. It means that, even though the weight of composite occupies just approximately a quarter of aluminium, it provides nearly three quarters of the environmental impact of aluminium. Therefore, it can be inferred that the manufacturing of composite product has more significant negative environment influence then aluminium alloy.

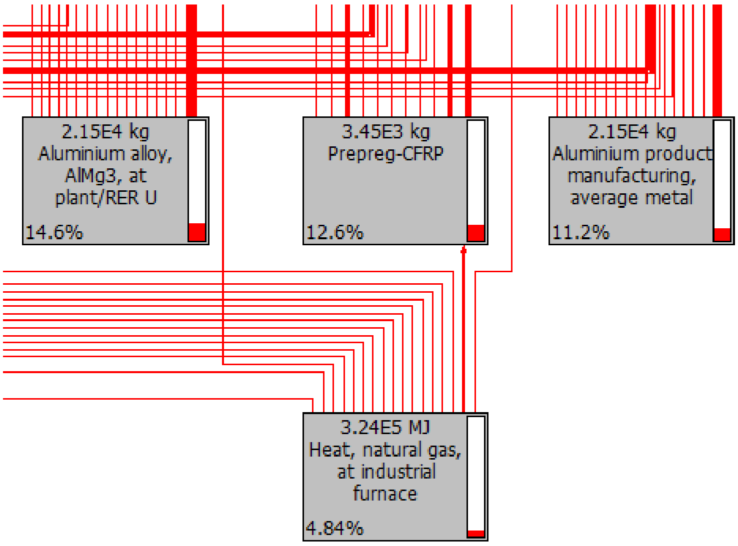


Figure 5-5 Impact contribution of aluminium alloy and CFRP in the manufacturing phase of A319

To further prove this inference, according to the impact assessment result of the climate change category in the characterisation analysis, Figure 5-6 shows the proportion of weight, impact contribution and composite material utilization of each component in the A319. The X axis displays the components and the Y axis represents the percentage. The proportions are compared to the total quantity of each item of the aircraft. From the diagram, it can be seen that the engine, wing and fuselage have the highest impact contribution, along with their mass. On the other hand, the impact contribution of stabilizer, nacelles/pylons and engines are higher than their weight proportion (the figures are: stabilizer: 7.4% to 3.7%, nacelles/pylons: 9% to 7.1% and engines: 31.9% to 14.8%). The possible reason may be that, except the engine which contains numerous nickel and titanium (as referred before), compared to their weight proportion (3.7% for stabilizer and 7.1% for nacelles/pylons), both the stabilizer and nacelles/pylons have a significantly high use rate of composite (27.3% for stabilizer and 18.7% for nacelles/pylons). In particular, the composite use rate of the stabilizer is about seven times its mass proportion. In addition, the composite utilization rate in the stabilizer is significantly higher than the landing gear, thus although the landing gear is approximately triple the weight of the stabilizer, its impact contribution is lower. These appearances also proved the deduction that the manufacturing of composite material appears to have a negative influence on the impact contribution.

Climate change is one of the important environmental issues. Recently, the concept of carbon footprint has been defined as “the amount of carbon dioxide released into the atmosphere as a result of the activities of a particular individual, organization, or community (Oxford University press, 2013)” to assess climate change. Accordingly, the CO_2 emission is the principle indicator to measure this issue. Figure 5-7 illustrates a comparison of CO_2 emission and composite utilization situation between these components. Since the weight differences between components are substantial, in order to get a fair comparison, the CO2 emission of each component is divided by their weight. As can be seen from the chart, with the gradual downward of composite use rate from stabilizer to landing gear, the ratio of CO_2 emission decreased steadily.

This indicated that, compared to the component mass, the CO_2 emission is influenced to some extent by the manufacturing process of composite material.

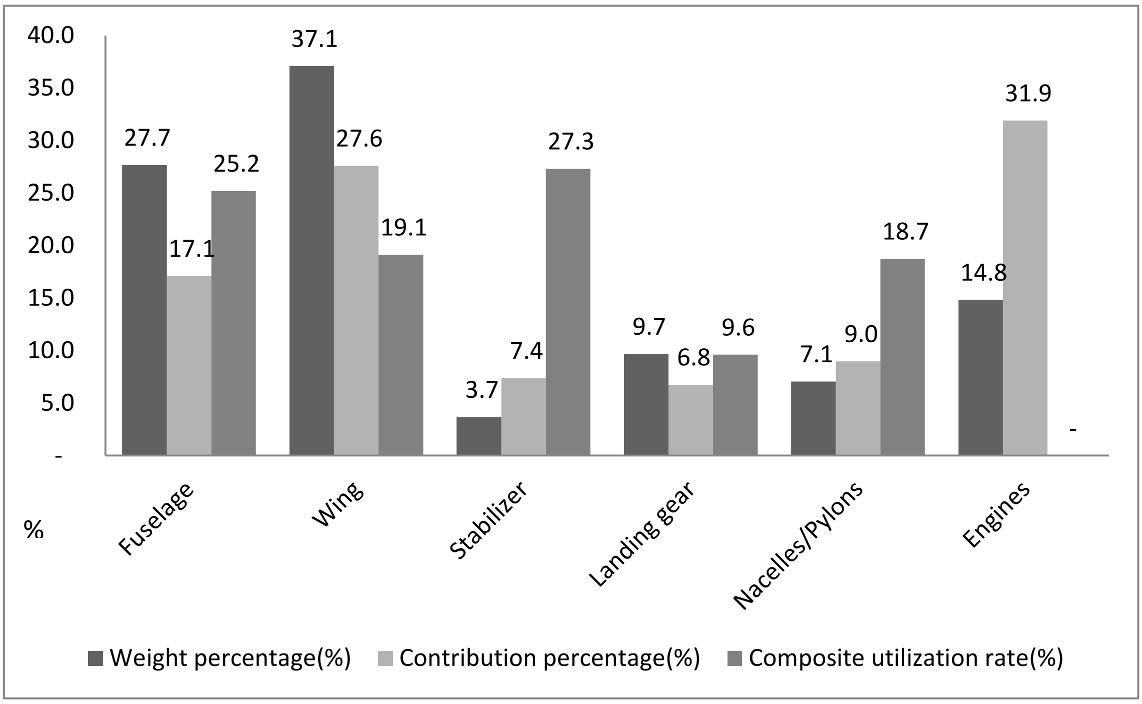


Figure 5-6 Proportion of weight, impact contribution and composite utilization of each component in A319

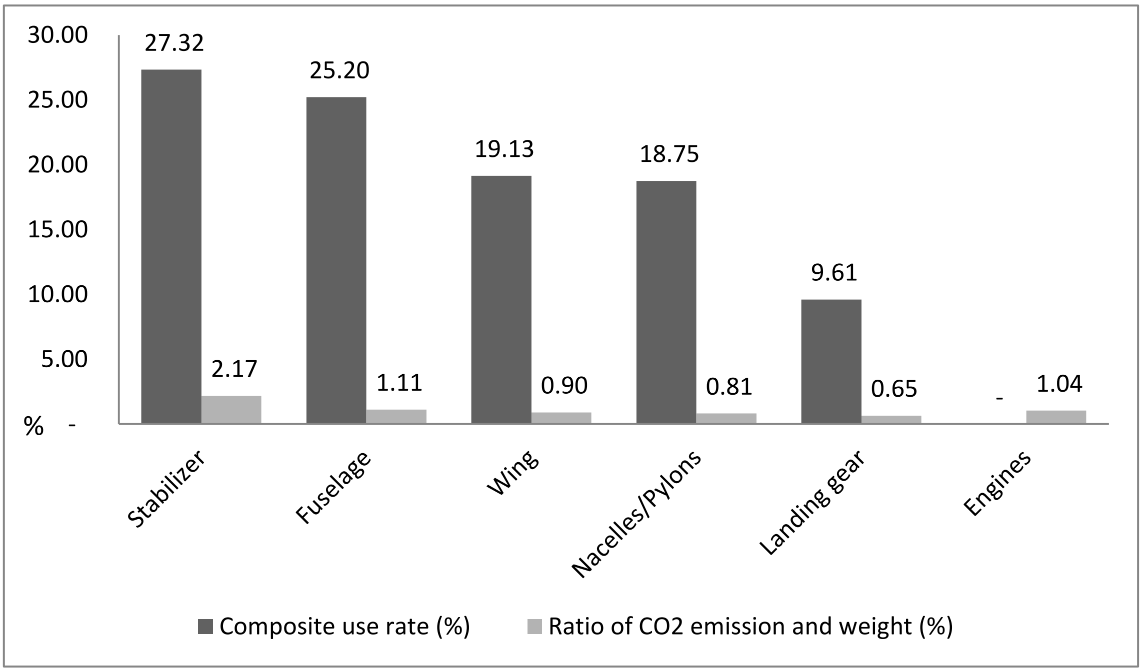


Figure 5-7 Comparison of composite use rate and the ratio of CO_2 emission and weight of each component in A319

When comparing the CO_2 emission between the A319 and B737-800, the significant impact on the environment of the manufacturing of composite becomes clearer. Figure 5-8 shows the relationship between the composite utilization rate, titanium utilization rate and the CO_2 emission rate. These ratios are all based on their corresponding total quantity of the whole aircraft. The X axis also refers to the ratio and the Y axis represents the components, in which “B-” means the components of the B737-800.

It can be seen from the diagram that, when the utilization of titanium is dramatically less than composite, the CO_2 emission rate has the same trend with the composite use rate. Its representative component is the stabilizer. In the A319 aircraft, the composite weight ratio for this component is 93.8% while the titanium ratio is 0%. On the other hand, in the B737-800 aircraft, the figure is 27.3% for composite and 1.4% for titanium. In this situation, the CO_2 emission of the B737-800 stabilizer is slightly less than that of the A319. The 70% reduction of composite use rate decreases just 25% of CO_2 emission.

When comparing other components, the variation of CO_2 emission rate is following the change trend of titanium use rate. Even though in some components (fuselage, landing gear and the engines), the composite use rates between the two aircrafts are in contrast to the variation of titanium, the trend of CO_2 emission remains consistent with titanium. For example, regarding the landing gear, although the figure of composite decreased from 12.5% for the A319 to 1.9% for the B737-800, its CO_2 emission ratio also climbed from 9.6% to 16.9%. This could also be because the ratio of titanium increased from 9.6% to 29.3%.

In order to make a clear comparison with the results of following life cycle phases, the composite weight ratio is changed to the total aircraft scale, and the single score analysis result is used (Figure 5-9) to present the environmental influence. That is 2.4% composite (composite use difference between these two aircraft types)of the total weight of A319 lead to 1210 Pt (Pt is the unit of Eco-indicator point, its value is “one thousandth of the yearly environmental load of one average European inhabitant (Ministry of Housing, 2000)”) total environment impact and 1190 Pt fossil fuel impact. This means that 1% composite reduction can save 504 Pt total environment impact and 496 Pt fossil fuel impact.

It can be concluded that, though the manufacturing process of composite have a slight influence on the environment during the manufacturing stage of the aircraft, it is no more significant than the impact brought by the manufacturing of titanium. It should also be noted that, since the manufacturing of the aircraft has numerous processes and materials, the environmental impact might not just be influenced by these materials. Other materials such as nickel also have a dramatic effect on the LCIA result. Therefore, although the figure listed in this conclusion might not be wholly accurate, the trend should be correct.

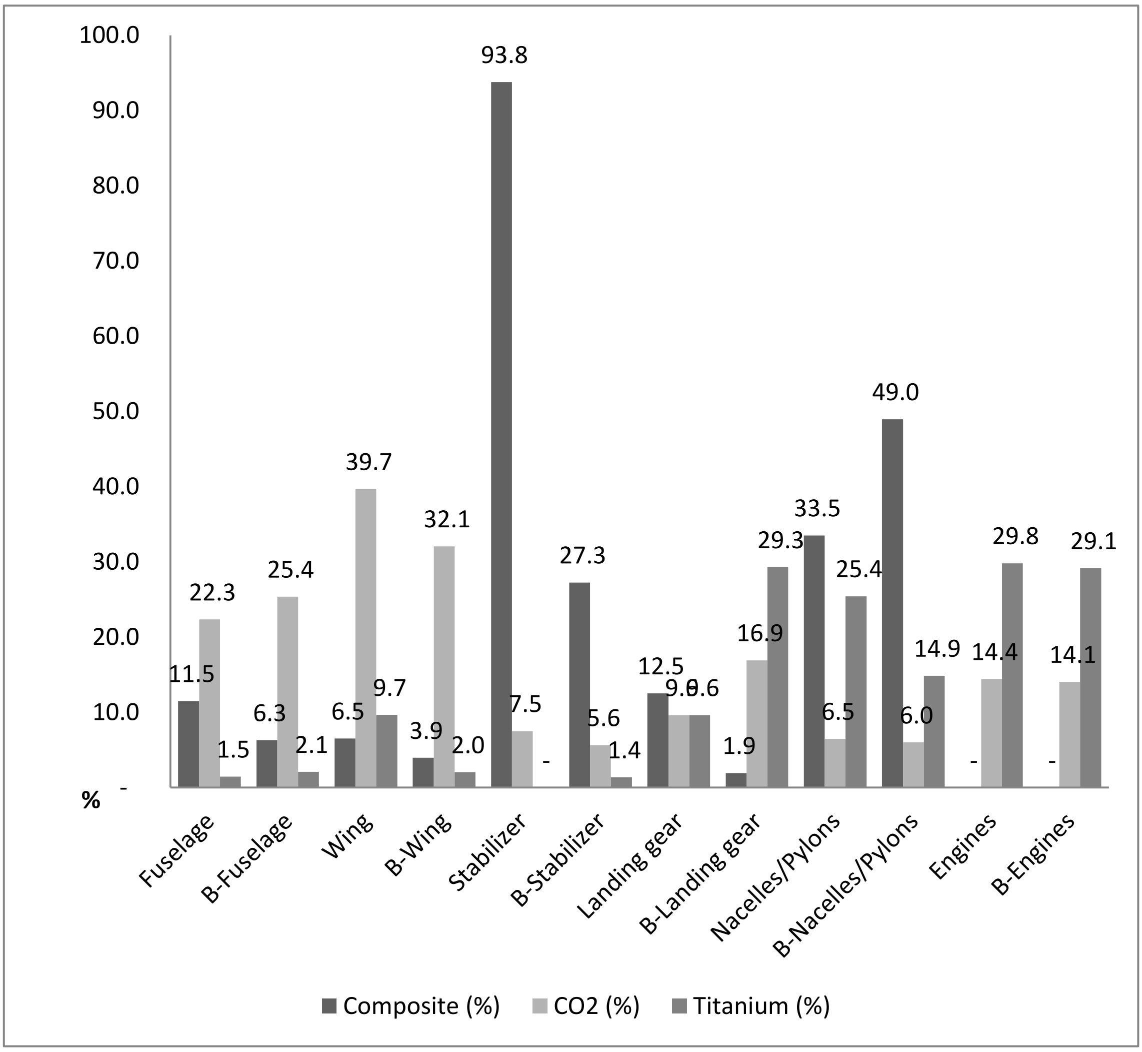


Figure 5-8 Comparison between A319 and B737-800

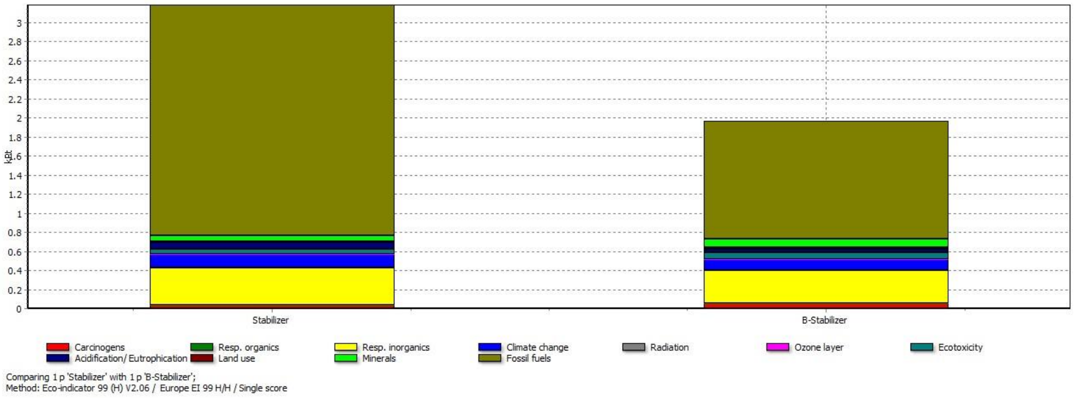
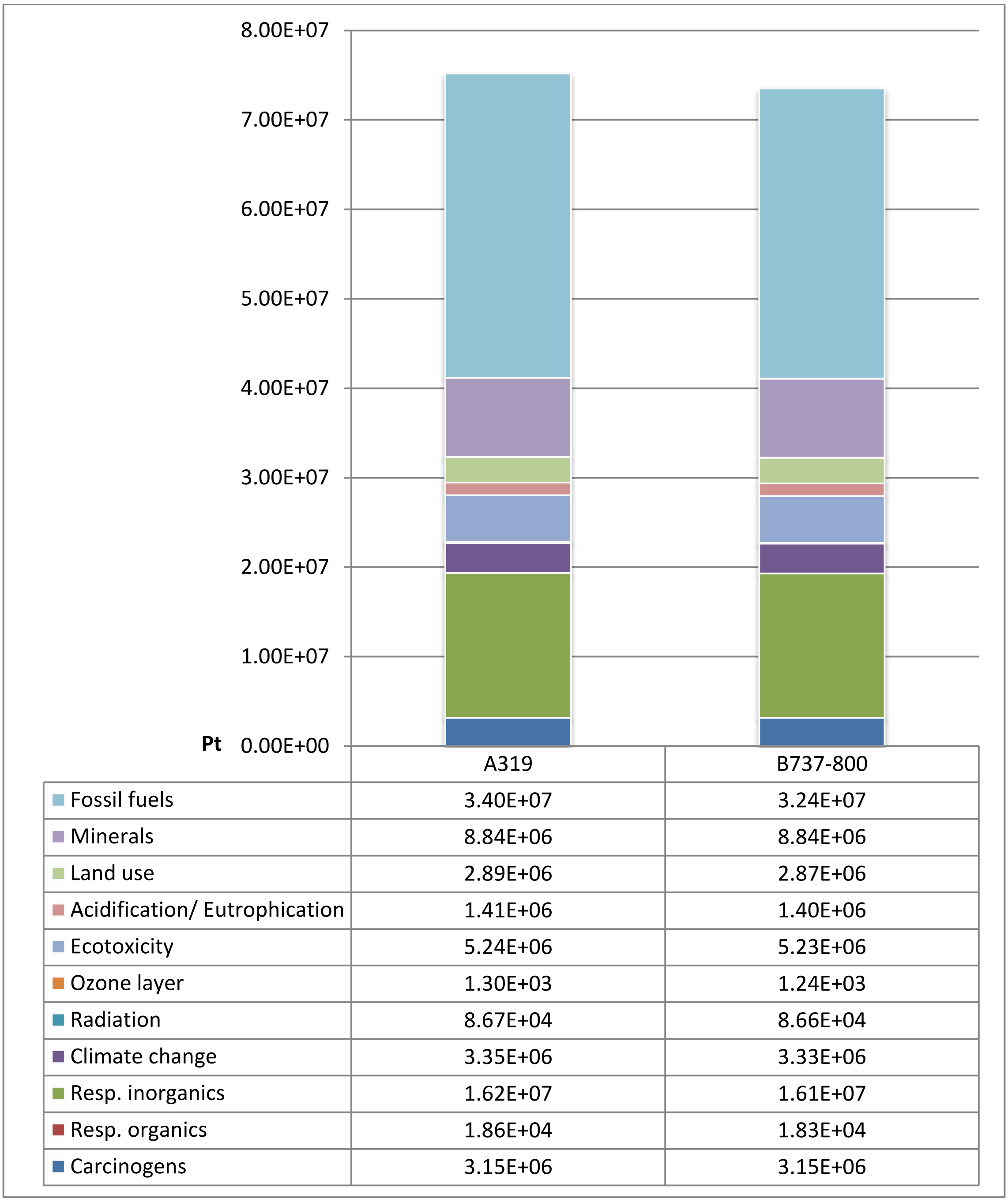


Figure 5-9 Single score result of the comparison of the manufacturing phase for the stabilizers.

5.2.2.2 Impact assessment of the operation phase

In the operation phase, since the construction of the airport and the airport maintenance processes are the same for these two aircraft types, their difference is in the aircraft operation process. Additionally, the principle indicator of the operation process is the fuel consumption rate. As calculated in Section 4.2.2, the fuel consumption rate is 0.025 for the A319 and 0.022 for the B737-800. According to the inventory list, the fuel consumption during the 24 years operation stage is 51479708kg for the A319 and 45302143kg for the B737-800. The fuel saving of the B737-800 is 6177565kg, occupying 12% of the A319 total fuel consumption. As can be seen from Figure 5-10, the single score impact assessment result indicated that the total environment impact of the B737-800 is about 1688800 Pt (2.25%) less than the A319. Additionally, the impact category which has the greatest difference between the two aircraft is the fossil fuel. This impact of A737-800 is 1578400 Pt (4.64%) less than the A319. It represents nearly 93% of the total environment impact difference.



	A319	B737-800
■ Fossil fuels	3.40E+07	3.24E+07
■ Minerals	8.84E+06	8.84E+06
■ Land use	2.89E+06	2.87E+06
■ Acidification/ Eutrophication	1.41E+06	1.40E+06
■ Ecotoxicity	5.24E+06	5.23E+06
■ Ozone layer	1.30E+03	1.24E+03
■ Radiation	8.67E+04	8.66E+04
■ Climate change	3.35E+06	3.33E+06
■ Resp. inorganics	1.62E+07	1.61E+07
■ Resp. organics	1.86E+04	1.83E+04
■ Carcinogens	3.15E+06	3.15E+06

Figure 5-10 Comparison of single score analysis for operation phase

Lee et al (Lee et al., 2001) found that 1% improvement in structure weight of an aircraft can lead to 0.7% reduction in fuel burn. Since the 12% fuel reduction led to 2.25% decrease of the total environment influence and 4.64% fossil fuel impact, the 1% structure weight reduction may contribute 0.13% downward trend of total environmental influence and 0.27% decrease of fossil fuel impact. Although the percentage seems slight, the amount will be significant. Using the data of the A319 as the basic figure, the reduction should be 97756 Pt for the total impact and 91873 Pt for the fossil fuel impact.

As introduced in Chapter 1, compared to aluminium, the use of composite material can reduce the weight by about 20%. For example, the composite utilization rate of the A319 is 13%, thus the total weight reduction caused by using composite should be 2.6%. Moreover, this 13% composite material caused 97756×2.6=254165.6 Pt total environmental impact and 91873×2.6=238869.8 Pt fossil fuel impact. As a further calculation, the impact reduction for 1% increase of composite utilization rate is 19551.2 Pt for total and 18374.6 Pt for fossil fuel.

In conclusion, due to the weight saving property of composite material, it can lead to a large amount of reduction on the environmental impact, especially the fossil fuel category, by decreasing the fuel consumption during the operation stage.

5.2.2.3 Impact assessment of the disposal phase

As shown in Figure 5-2, the disposal phase only provides 0.0186% positive return to the whole life cycle assessment of the A319. It represents approximately one third of the manufacturing phase environmental influence. These positive returns derive mostly from the re-use of landing gear (occupy 16.6%) and engines (occupy 80.1%). And the disposal of composite material contributes in total 2.533% to the overall positive returns. As shown in Figure 5-11, it contributes more to the fossil fuel category (-5480 Pt).

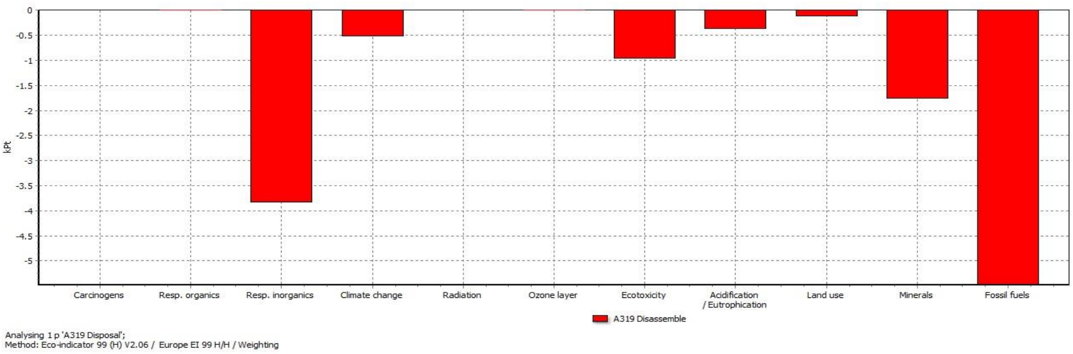


Figure 5-11Weighting analysis for disposal phase of A319

5.2.3 Impact assessment of the whole life cycle

For the reason that the operation stage represents about 99.9% of the environmental impact of the whole life cycle, the result of the life cycle assessment is similar with that of the operation phase. As can be seen from the normalization impact assessment result (Figure 5-12), except in the fossil fuel impact category, the environmental influence during the entire life cycle of both aircraft types is approximately the same. The influence on fossil fuel domain of the A319 is higher than that of the B737-800, which may be caused by its high fuel consumption rate.

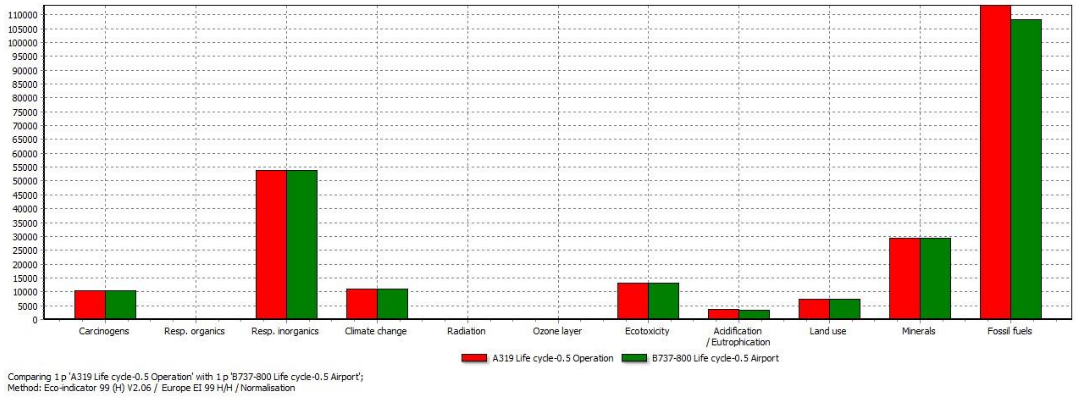


Figure 5-12 Normalized analysis of the comparison between A319 and B737-800

5.3 Discussion

This project has accomplished the life cycle assessment of the A319 and B737-800. To achieve the objectives, the research firstly collected inventory data for the three main phases of the entire life span: manufacturing phase, operation phase and the disposal phase. The impact assessment of the whole life cycle of these two aircraft types was then conducted and compared to analyse the environmental influence of the utilization of composite material. Finally the impact assessment result was interpreted, as follows:

1. The operation stage represents 99.9% of the environmental impact of the whole life cycle. For the A319, the manufacturing stage contributes 0.0572% while the disposal phase provides 0.0186% positive return, about one third of the manufacturing impact. For the B737-800, it is 0.0598% for the manufacturing process and 0.0204% return from the disposal phase, also about one third of the manufacturing impact.
2. The whole life cycle of both aircraft types contribute more to the fossil fuel impact category, which may be caused by its fuel burn during the operation stage.
3. The positive return on the environmental impact from the disposal of composite is still slight.
4. Compared to the total weight of the A319, in the manufacturing phase, 1% composite weight increase can improve 504 Pt total environment impact and 496 Pt fossil fuel impact. However, in the operation phase, the impact reduction for 1% increase of composite utilization rate is 19551.2 Pt for total and 18374.6 Pt for fossil fuel. It is approximately 38 times the impact increase in the manufacturing stage. The use of composite material might reduce the environment impact by its weight reduction property.
5. Compared to the composite material, the titanium seems to have a more significant influence on increasing the environment load during the manufacturing stage.

Overall, result 4 is the key achievement of this project. It indicated that the environmental impact of composite material manufacturing is lower than expected due in part to the weight reduction property that saved on fuel consumption during the operation stage. This might have a significant impact on decreasing the environmental impact during the entire life span of the aircraft. Nevertheless, its recovering efficiency is still quite low due to the immature technology (result 3).

It is not anticipated that the manufacturing of titanium has a greater environmental impact than composite (result 5). This might be because, although titanium is abundant in the earth, it is difficult to isolate it from its minerals and thus could consume a great deal of energy to obtain titanium ingot (Answers, 2013). Equally important, the manufacturing of titanium is comparatively difficult due to its high tensile strength and ductility (Donachie, 2000). The increased duration may also cost more energy. However, its high tensile strength and low density properties make it an ideal structural material for an aircraft. Thus the research on the environmental impact of titanium could be the future work of the LCA study on aircrafts.

It should also be clarified that due to the limitation of data collection and research time as mentioned in Chapter 4, the figures of the impact assessment result might lack accuracy. Nevertheless, the trends of the results should be correct as most inventory data derive from reliable sources and the assumed data have a reasonable basis. Furthermore, the differences are not slight, which means that a low proportion of inaccurate data probably will not change the trends.

6 CONCLUSION AND FUTURE WORK

To conclude, life cycle assessment is an extremely efficient method to manage environment issues. It can clearly address the environmental impact of various aspects during the product life cycle as well as identify the most improvable phase for the researchers to focus on. Nevertheless, its research process, especially the data collection phase, is a complicated procedure. Fortunately, LCA software can help accomplish this complex process, and the libraries and the impact assessment methods involved can effectively improve the efficiency of research as well as reduce duplication of efforts.

With regard to the initial objectives set, although limitations to the research relating to scope and detail remain, this study has made great efforts to accomplish a completed and accurate LCA of the A319 and B737-800 with the inventory data collected from reliable sources. It focused more on the use of composite and examined the potential environmental influence it brought. And the conclusions are obtained by comparing the LCIA result between these two aircrafts type.

The result of this project can be concluded that, during the whole life cycle of the aircraft, the most significant environment influence phase is the operation stage which burns numerous fuels. This appearance also caused the whole life cycle to contribute more to the fossil fuel impact category. And the most important result is that, on aggregate, the utilization of composite material has indeed a positive impact on reducing the environment pollution by decreasing the structural weight of the aircraft. Additionally, since the recycle method of composite is still not mature, the recycle rate of the composite is relatively low and a great deal of energy consumption during the recycle phase remains. Thus the positive return caused by the disposal of composite is slight.

Moreover, in the manufacturing stage, the result that the negative environmental influences caused by titanium manufacturing is more significant than that of composite can be identified as the future research direction. This is heightened by the fact that the use rate of titanium is also rising in the aircraft industry due to its high tensile strength and low density properties which make it an ideal structural material.

Overall, within the scope defined in Chapter 4, the life cycle assessment study of the A319 and B737-800 has been completed. Moreover, the environmental influence of the composite material used on aircraft is analysed clearly. Thus the goal of this project is achieved and the future research direction of this domain is provided.

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Appendix A Weight and material composition of A319

A.1 Fuselage of A319

Secondary Component	Sub-Assembly	Material	Weight (kg)
Nose fwd fuselage	Radome	CFRP	26
	Structure	Aluminium Alloy	1152
		Titanium	150
	Pressure bulkhead	Aluminium Alloy	500
Fwd fuselage	Structure	Aluminium Alloy	1124
	Cabin Floor Structure	GFRP	372
	Cargo Compartment Floor	GFRP	121
Belly fairing		CFRP	119
Centre fuselage	Structure	Aluminium Alloy	1820
	Floor	GFRP	250
Rear fuselage	Cabin floor structure	GFRP	250
	Rear Fuselage Main Structure	Aluminium-alloy	1662
Cone/rear fuselage	Cone/Rear Fuselage Shell Structure	Aluminium Alloy	1295
	Stabilizer Attach Points	Steel	100
Tail cone (apu-compartment)	Fittings	Aluminium Alloy	99
	Service Frame	Aluminium Alloy	270
	Rear pressure bulkhead	Aluminium Alloy	500
Pressurized area Door	2 Cargo compartment doors	Aluminium Alloy	242
	2 Over wing emergency exits	Aluminium Alloy	30
	4 Passenger/crew doors	Aluminium Alloy	194
	4 Avionics compartment	Aluminium Alloy	37
Unpressurized areas Door		GFRP	53

Total weight		**10366**

Material	**Weight (kg)**	**Percentage (%)**
Aluminium Alloy	8925	86.10
Titanium	150	1.45
Steel	100	0.96
GFRP	1046	10.09
CFRP	145	1.40

A.2 Wing of A319

Secondary Component	Sub-Assembly	Sub-Assembly/Part	Sub-Assembly/Part	Material	Weight (kg)
Centre wing	2 Forward and rear spars			Titanium	600
	Upper and lower skin-panels			Aluminium alloy	800
	2 Main frames			Steel	200
	Ribs			Aluminium alloy	600
Outer wing	Wing box	Wing Spars		Aluminium alloy	2000
		27 Ribs		Aluminium alloy	1000
		Skin panels and Stringers		Aluminium alloy	1650
		Wing Root Joint		Titanium	325
		Dry Bays		Steel	100
	Wing tip			CFRP	48
	Leading edge and leading edge devices	Top panels		Aluminium Alloy	88
		Bottom panels		CFRP	12
	Leading Edge Slats	Slats 1-5		Aluminium Alloy	144
	Trailing edge and trailing edge devices	Inner rear-spar trailing-edge	Over wing panel	Aluminium Alloy	20
			Under wing panel	CFRP	35
			Rear false spar	Titanium	25
		Mid and outer rear-spar trailing-edges	Hinge ribs	Titanium	20
			Intermediate ribs	Aluminium Alloy	10
			Top and bottom panels	CFRP	30
			Trailing-edge support structures	Aluminium Alloy	10
	Trailing Edge Flaps			CFRP	236
	Aileron			CFRP	24
	Spoilers			CFRP	67

Single wing weight		**5844**
Centre wing weight		**2200**
Total weight		**13888**

Material	**Weight (kg)**	**Percentage (%)**
Aluminium Alloy	11244	80.96
Titanium	1340	9.65
Steel	400	2.88
CFRP	904	6.51

A.3 Stabilizer of A319

Secondary Component	Sub-Assembly	Material	Weight (kg)
Horizontal stabilizer	LH spar box	CFRP	150.5
	LH leading edge	CFRP	42
	LH trailing edge	CFRP	125
	LH the tips	CFRP	3.00
	LH the aprons	CFRP	3.5
	Centre joint	Aluminium Alloy	61
Elevator assemblies	Elevator structure	CFRP	33
	Elevator leading edge	CFRP	5
	Elevator tips	CFRP	3.5
	Inboard end caps	CFRP	2
	Elevator attach fittings	Aluminium Alloy	5
Vertical stabilizer	Spar box	CFRP	365
	Leading edge	GFRP	48
	Trailing edge	GFRP	33
		CFRP	13
	Tip	GFRP	9
	6Fittings	Aluminium Alloy	15
Rudder assembly	Main structure	CFRP	39
		GFRP	39
	Tip	CFRP	10
Horizontal stabilizer			**709**
Elevator			**97**
Vertical stabilizer			**483**
RUDDER			**88**

Total weight		**1377**

Material	Weight (kg)	Percentage (%)
Aluminium Alloy	86	6.25
GFRP	129	9.37
CFRP	1162	84.39

A.4 Landing gear of A319

Secondary Component	Sub-Assembly	Material	Weight (kg)
2 Main gear and doors	Main gear	Steel	1382
		Aluminium Alloy	120
		Titanium	120
	Main gear doors	CFRP	350
	MLG Leg Fairing	CFRP	32
Nose gear and doors	Nose gear	Steel	213
		Aluminium Alloy	50
		Titanium	50
	Nose gear doors	CFRP	72
2 Extension and retraction systems	Normal Extension and Retraction System	Steel	210
		Aluminium Alloy	10
	Free Fall Extension System	Titanium	132
L/G wheels and their related braking systems	Tires	Steel	794
	Wheels	Aluminium Alloy	47
	Brakes	Titanium	47
Total Weight			**3629**

Material	Weight (kg)	Percentage (%)
Aluminium Alloy	227	6.26
Titanium	349	9.62
Steel	2599	71.62
CFRP	454	12.51

A.5 Nacelles & Pylons of A319

Secondary Component	Sub-Assembly	Sub-Assembly/Part	Material	Weight (kg)
Nacelle	Cowling	Inlet Cowl	CFRP	108.5
		Fan Cowl	Titanium Alloy	108.5
	Thrust Reverser		CFRP	224.5
			Titanium Alloy	227.5
Pylon	Pylon box	Spars	Steel	543
		10 Ribs	CFRP	50
		4 Doors	GFRP	50
	Fairing	Skin	CFRP	10
Single weight				**1322**
Total weight				**2644**

Material	Weight (kg)	Pencentage (%)
Steel	1086	41.07
Titanium Alloy	672	25.42
GFRP	100	3.78
CFRP	786	29.73

A.6 Power plant of A319

Secondary Component	**Sub-Assembly**	**Material**	**Weight (kg)**
Engine	Low Pressure (LP) compressor (fan and booster) assembly	Titanium	828
	High Pressure (HP) compressor	Iron Nickel Chromium Alloy	550
	Combustion section	Nickel	700
	Turbine section	Aluminium Alloy	500
	Accessory drives(gearbox)	Steel	200
Single weight			**2778**
Total weight			**5556**

Material	**Weight (kg)**	**Percentage (%)**
Aluminium Alloy	1000	18.00
Titanium	1656	29.81
Steel	400	7.20
Iron Nickel Chromium Alloy	1100	19.80
Nickel	1400	25.20

Appendix B Weight and material composition of B737-800

B.1 Fuselage of B737-800

Secondary Component	Sub-Assembly	Material	Weight (kg)
Section 41	Structure	Aluminium Alloy	1260
	Bulkhead	Aluminium Alloy	250
	Landing Gear Support Structure	Aluminium Alloy	50
	Door surrounds	Aluminium Alloy	90
	Floor Panels	CFRP	104
	Floor Structure	Aluminium Alloy	100
	4 Seat Tracks	Titanium	140
	Nose Radome	CFRP	26
	Others	Aluminium Alloy	30
		Titanium	10
		CFRP	10
Section 43	Structure	Aluminium Alloy	1120
	Bulkhead	Aluminium Alloy	250
	Beam and Splice	Aluminium Alloy	179
	Forward Cargo Door Surround Structure	Aluminium Alloy	40
	Floor Panels	CFRP	104
	Floor Structure	Aluminium Alloy	100
	12 Seat Tracks	Aluminium Alloy	80
	Wing-to-Body Fairing	GFRP	16
		Aluminium Alloy	16
	Others	Aluminium Alloy	30
		Titanium	10

		CFRP	10
Section 44	Structure	Aluminium Alloy	1820
	Front Spar Bulkhead	Aluminium Alloy	250
	Beam and Splice	Aluminium Alloy	298
	Landing Gear Support Structure	Aluminium Alloy	100
	Exit Door Surround Structure	Aluminium Alloy	50
	Floor Panels	CFRP	150
	Floor Structure	Aluminium Alloy	120
	4 Seat Track Crowns	Aluminium Alloy	120
	Wing-to-Body Fairing	GFRP	10
		CFRP	10
		Aluminium Alloy	12
	Others	Aluminium Alloy	30
		Titanium	10
		CFRP	10
Section 46	Structure	Aluminium Alloy	1750
	Beam	Aluminium Alloy	268
	Aft Cargo Door Surround Structure	Aluminium Alloy	40
	Floor Panel	CFRP	150
	Floor Structure	Aluminium Alloy	120
	4 Seat Tracks	Aluminium Alloy	120
	Wing-to-Body Fairing	GFRP	32
	Others	Aluminium Alloy	40
		Titanium	15
		CFRP	15

Section 47	Structure	Aluminium Alloy	350
	Door Surround Structure	Aluminium Alloy	60
	Floor Panels	CFRP	37
	Floor Structure	Aluminium Alloy	26
	4 Seat Tracks	Titanium	50
	Wing-to-Body Fairing	GFRP	16
		Aluminium Alloy	16
	Others	Aluminium Alloy	15
		Titanium	3
		CFRP	2
Section 48	Structure	Aluminium Alloy	630
	Aft Pressure Bulkhead	Aluminium Alloy	250
	Horizontal Beams	Aluminium Alloy	51
		Aluminium Alloy	51
	Tail cone Fairing	GFRP	23
	Others	Aluminium Alloy	20
		Titanium	5
		CFRP	5
Forward and aft entry doors	Forward entry door	Aluminium Alloy	69
	Aft entry door	Aluminium Alloy	64
Forward and aft galley service doors	Forward galley serivice door	Aluminium Alloy	61
	Aft galley service door	Aluminium Alloy	58
Emergency exit doors		Aluminium Alloy	46
Cargo doors	Aft cargo compartment door	Aluminium Alloy	54
	Forward cargo compartment door	Aluminium Alloy	51
Service doors		Aluminium Alloy	176

		CFRP	10
Total Weight			**11764**

Material	Weight (kg)	Percentage (%)
Aluminium Alloy	10781	91.64
Titanium	243	2.07
GFRP	97	0.82
CFRP	643	5.47

B.2 Wing of B737-800

Secondary Component	Sub-Assembly	Sub-Assembly/Part	Material	Weight (kg)
Centre wing	Spars		Aluminium Alloy	900
	Skin-panels		Aluminium Alloy	1000
	Span wise Beam		Aluminium Alloy	350
Outer wing	Wing box	Skin	Aluminium Alloy	1600
		Rib	Aluminium Alloy	1485
		Spar	Aluminium Alloy	1600
		12 Fittings	Aluminium Alloy	8
	Wing tip		Aluminium Alloy	16
			GFRP	8
	Leading edge	Inboard Fixed Leading Edge	Aluminium Alloy	30
		Outboard Fixed Leading Edge	Aluminium Alloy	20
	Leading Edge Slats	Skin	Aluminium Alloy	150
	Outboard Krueger Flap		Aluminium Alloy	18
			Titanium	25
	Trailing edge	Fixed Trailing Edge Skin	GFRP	65
		Inboard Fixed Trailing Edge Structure	Aluminium Alloy	10
			Titanium	15
		Main Landing Gear Beam	Aluminium Alloy	20
			Titanium	30
		Inboard Wing Trailing Edge Fittings	Aluminium Alloy	10
		Wing Trailing Edge Flap	Titanium	60
			GFRP	63
			Aluminium Alloy	169
			CFRP	43.5

	Aileron		CFRP	45.5
			Aluminium Alloy	10
			Titanium	45
	Spoilers		Aluminium Alloy	43
Single wing				**5589**
Centre wing				**2250**
Total Weight				**13428**

Material	**Weight (kg)**	**Percentage (%)**
Aluminium Alloy	12628	94.04
Titanium	350	2.03
GFRP	272	1.33
CFRP	178	2.61

B.3 Stabilizer of B737-800

Secondary Component	Sub-Assembly	Material	Weight (kg)
Horizontal stabilizer	Spar box	Aluminium Alloy	237
	Leading edge	Aluminium Alloy	18
	Trailing edge	GFRP	8
		CFRP	8
		Aluminium Alloy	20
	Stabilizer Tip	GFRP	0.2
		Aluminium Alloy	0.8
	Horizontal Stabilizer Cove	GFRP	0.6
		Aluminium Alloy	0.4
	Attach fittings	Titanium	2
		Aluminium Alloy	3
	Centre joint	Aluminium Alloy	7.5
		Titanium	9.5
Elevator assemblies	Elevator structure	CFRP	77
	Elevator leading edge	CFRP	3
		GFRP	2
		Aluminium Alloy	3
	Elevator Balance Horn Fairing	GFRP	1
	Elevator attach fittings	Aluminium Alloy	9
Vertical stabilizer	Spar box	Aluminium Alloy	364
		GFRP	100
	Leading edge	Aluminium Alloy	30.7
		GFRP	9.3
	Trailing edge	Aluminium Alloy	42

		GFRP	8
	Dorsal Fin Skin	GFRP	10
		Aluminium Alloy	23
	Vertical Stabilizer Cove	GFRP	2
	Tip	Aluminium Alloy	4
		GFRP	1
	6 Primary attach Fittings	Aluminium Alloy	8
		Titanium	7
Rudder assemblies	Rudder structure	GFRP	32
		CFRP	35
	Rudder leading edge	CFRP	5
		GFRP	5
		Aluminium Alloy	5
	Balance Arm Structure	CFRP	2
		Aluminium Alloy	3
	Rudder Tip Fairing Skin	GFRP	5
	Rudder attach fittings	Aluminium Alloy	15
Horizontal stabilizer			**613**
Elevator			**190**
Vertical stabilizer			**609**
Rudder			**107**
Total Weight			**1519**

Material	Weight (kg)	Percentage (%)
Aluminium Alloy	1084.6	71.40
Titanium	20.5	1.35
GFRP	195.9	12.90
CFRP	218	14.35

B.4 Landing gear of B737-800

Secondary Component	Sub-Assembly	Material	Weight (kg)
2 Main gear and doors	Strut	Steel	500
	Walking beam	Titanium	89
	Links	Aluminium Alloy	89
	MLG doors	CFRP	24
Nose gear and doors	Strut	Steel	240
	Links	Aluminium Alloy	44
	Tow fitting	Titanium	74
	NLG doors.	CFRP	18
L/G wheels and their related braking systems	Tires and wheels	Steel	165
	Hydraulic brake system	Aluminium Alloy	57
	Parking brake system	Titanium	187
Total weight			**3416**

Material	Weight (kg)	Percentage (%)
Aluminium Alloy	450	13.17
Titanium	1000	29.27
Steel	1900	55.62
CFRP	66	1.93

B.5 Nacelles & Pylons

Secondary Component	Sub-Assembly	Material	Weight (kg)
Nacelle	Inlet cowl	Aluminium Alloy	163
	Fan cowl	Aluminium Alloy	82
	Fan duct cowl and thrust reverser	CFRP	510
	Primary exhaust nozzle	Aluminium Alloy	50
	Exhaust plug.	Aluminium Alloy	24
Pylon	Engine Strut Skins	Titanium	46
	Fan Cowl Support Beam Structure	Aluminium Alloy	6
		Titanium	10
	Thumbnail and Forward Fairing Skin Panel	CFRP	5
	Engine Strut Forward Fairing Structure	Aluminium Alloy	44
	Engine Strut-to-Wing Attach Fitting	Aluminium Alloy	13
		Titanium	20
Strut with Systems		Aluminium Alloy	100
		Titanium	122
		CFRP	137
Single weight			**1332**
Total Weight			**2664**

Material	**Weight (kg)**	**Percentage (%)**
Aluminium Alloy	964	36.19
Titanium	396	14.86
CFRP	1304	48.95

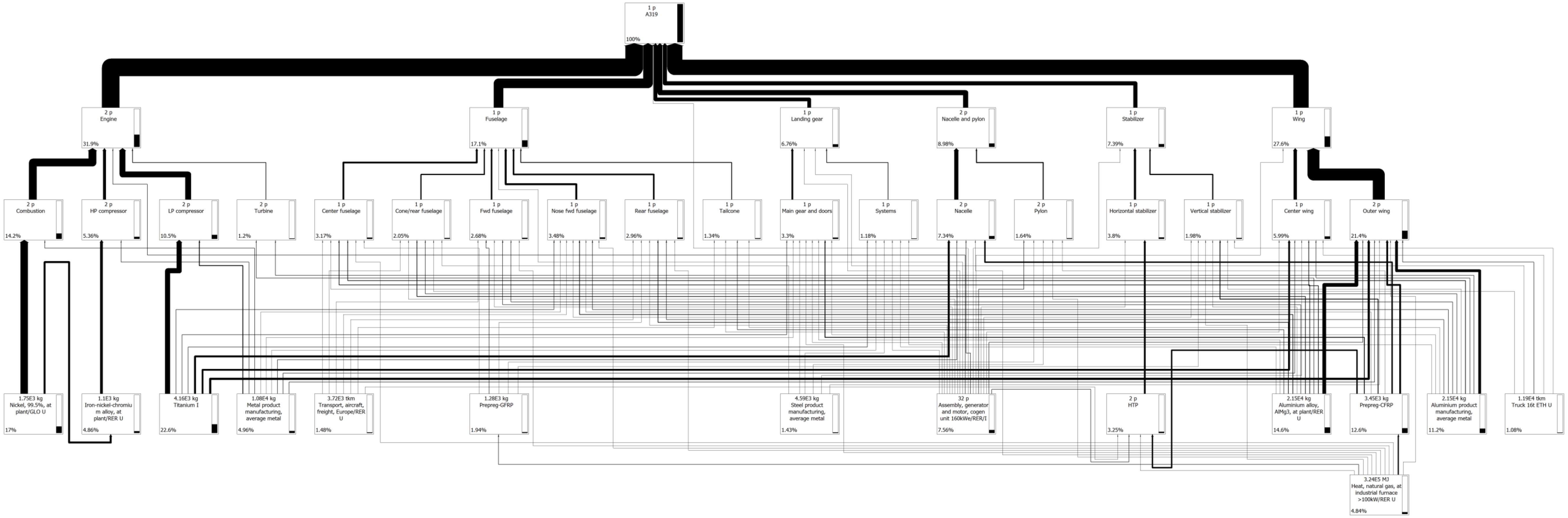
B.6 Power plant of B737-800

Secondary Component	Sub-Assembly	Material	Weight (kg)
Engine	Fan and booster	Aluminium Alloy	500
	High pressure compressor (HPC)	Iron Nickel Chromium Alloy	300
	Combustor	Nickel	700
	High pressure turbine (HPT)	Iron Nickel Chromium Alloy	250
	Low pressure turbine (LPT)	Titanium	802
	Accessory drive.	Steel	200
Single weight			**2752**
Total weight			**5504**

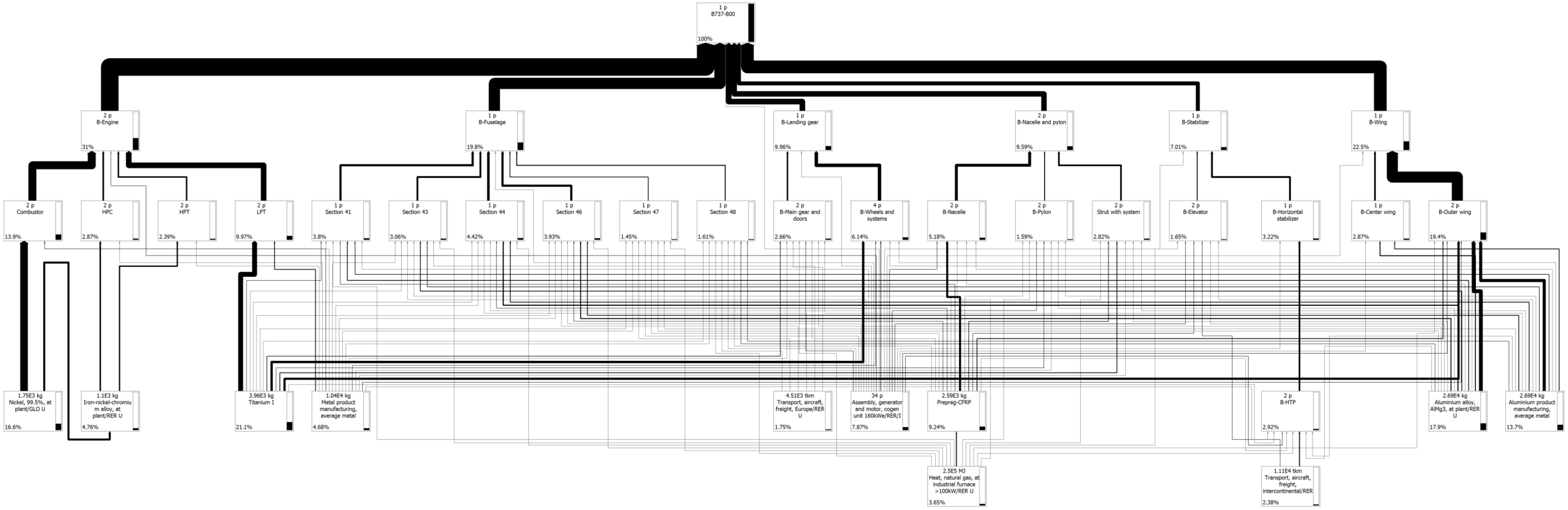
Material	Weight (kg)	Percentage (%)
Titanium	1604	29.14
Iron Nickel Chromium Alloy	1100	19.99
Nickel	1400	25.44
Aluminium Alloy	1000	18.17
Steel	400	7.27

Appendix C Model network of the aircrafts

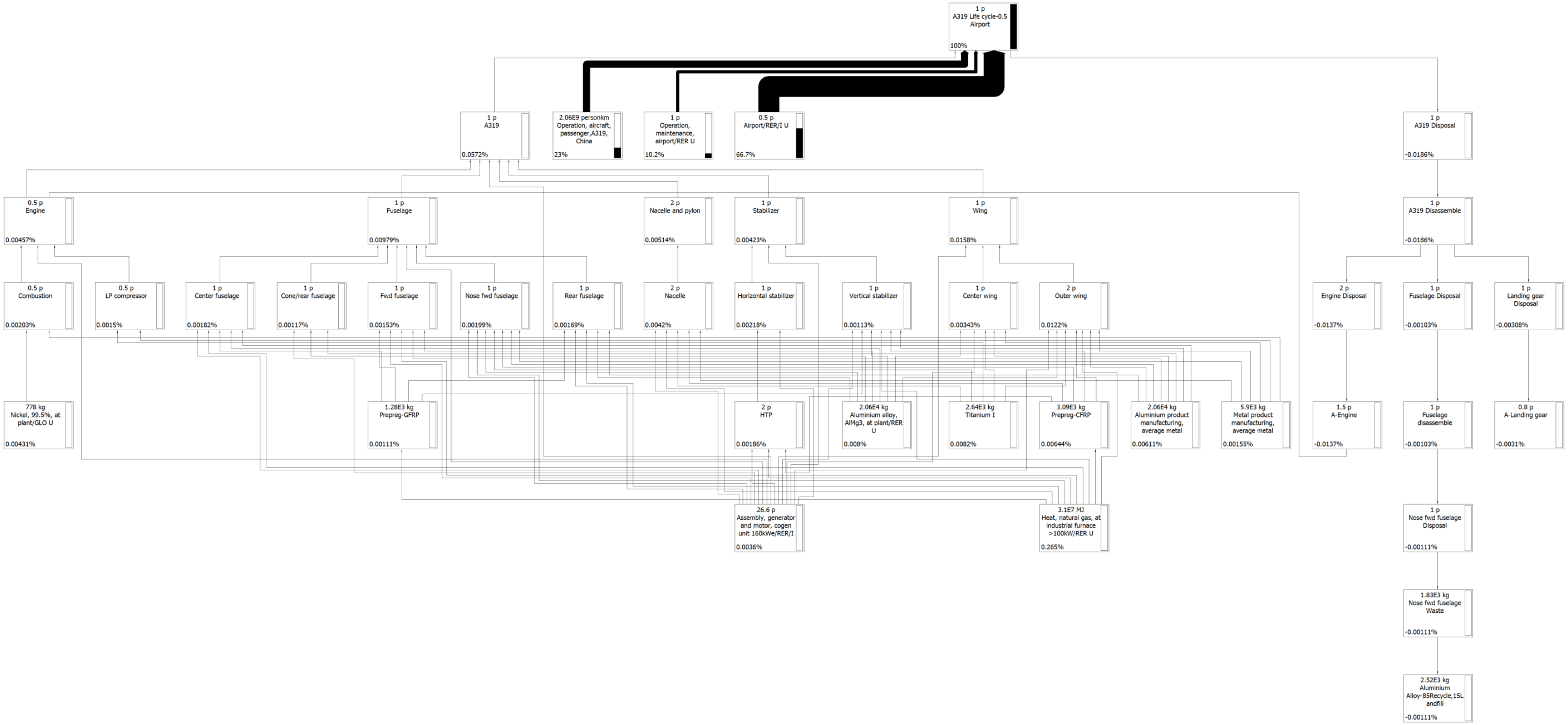
C.1 Network of manufacturing phase of A319 (1% cut off)



C.2 Network of manufacturing phase of B737-800 (1.4% cut off)



C.3 Network of life cycle of A319 (0.001% cut off)



C.4 Network of life cycle of B737-800 (0.001% cut off)